

History of Physics

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Although at the time of Christ's birth Hellenic science had produced nearly all its masterpieces, it was still to give to the world Ptolemy's astronomy, the way for which had been paved for more than a century by the works of Hipparchus. The revelations of Greek thought on the nature of the exterior world ended with the "Almagest", which appeared about A.D. 145, and then began the decline of ancient learning. Those of its works that escaped the fires kindled by Mohammedan warriors were subjected to the barren interpretations of Mussulman commentators and like parched seed, awaited the time when Latin Christianity would furnish a favourable soil in which they could once more flourish and bring forth fruit. Hence it is that the time when Ptolemy put the finishing touches to his "Great Mathematical Syntax of Astronomy" seems the most opportune in which to study the field of ancient physics. An impassable frontier separated this field into two regions in which different laws prevailed. From the moon's orbit to the sphere enclosing the world, extended the region of beings exempt from generation, change, and death, of perfect, divine beings, and these were the star-sphere and the stars themselves. Inside the lunar orbit lay the region of generation and corruption, where the four elements and the mixed bodies generated by their mutual combinations were subject to perpetual change.

The science of the stars was dominated by a principle formulated by Plato and the Pythagoreans, according to which all the phenomena presented to us by the heavenly bodies must be accounted for by combinations of circular and uniform motions. Moreover, Plato declared that these circular motions were reducible to the rotation of solid globes all limited by spherical surfaces concentric with the World and the Earth, and some of these homocentric spheres carried fixed or wandering stars. Eudoxus of Cnidus, Calippus, and Aristotle vied with one another in striving to advance this theory of homocentric spheres, its fundamental hypothesis being incorporated in Aristotle's "Physics" and "Metaphysics". However, the astronomy of homocentric spheres could not explain all celestial phenomena, a considerable number of which showed that the wandering stars did not always remain at an equal distance from the Earth. Heraclides Ponticus in Plato's time, and Aristarchus of Samos about 280 B.C. endeavoured to account for all astronomical phenomena by a heliocentric system, which was an outline of the Copernican mechanics; but the arguments of physics and the precepts of theology proclaiming the Earth's immobility, readily obtained the ascendancy over this doctrine which existed in a mere outline. Then the labours of Apollonius Pergæus (at Alexandria, 205 B.C.), of Hipparchus (who made observation at Rhodes in 128 and 127 B.C.), and finally of Ptolemy (Claudius Ptolemæus of Pelusium) constituted a new astronomical system that claimed the Earth to be immovable in the centre of the universe; a system that seemed, as it were, to reach its completion when, between A.D. 142 and 146, Ptolemy wrote a work called *Megale mathematike syntaxis tes astronomias*, its Arabian title being transliterated by the Christians of the Middle Ages, who named it "Almagest". The astronomy of the "Almagest" explained all astronomical phenomena with a precision which for a long time seemed satisfactory, accounting for them by combinations of circular motions; but, of the circles described, some were eccentric to the World, whilst others were epicyclic circles, the centres of which described deferent circles concentric with or eccentric to the World; moreover, the motion on the deferent was no longer uniform, seeming so only when viewed from the centre of the equant. Briefly, in order to construct a kinematical arrangement by means of which phenomena could be accurately represented, the astronomers whose work Ptolemy completed had to set at naught the properties ascribed to the celestial substance by Aristotle's "Physics", and between this "Physics" and the astronomy of eccentrics and epicycles there ensued a violent struggle which lasted until the middle of the sixteenth century.

In Ptolemy's time the physics of celestial motion was far more advanced than the physics of sublunary bodies, as, in this science of beings subject to generation and corruption, only two chapters had reached any degree of perfection, namely, those on optics (called perspective) and statics. The law of reflection was known as early as the time of Euclid, about 320 B.C., and to this geometrician was attributed, although probably erroneously, a "Treatise on Mirrors", in which the principles of catoptrics were correctly set forth. Dioptrics, being more difficult, was developed less rapidly. Ptolemy already knew that the angle of refraction is not proportional to the angle of incidence, and in order to determine the ratio between the two he undertook experiments the results of which were remarkably exact.

Statics reached a fuller development than optics. The "Mechanical Questions" ascribed to Aristotle were a first attempt to organize that science, and they contained a kind of outline of the principle of virtual velocities, destined to justify the law of the equilibrium of the lever; besides, they embodied the happy idea of referring to the lever theory the theory of all simple machines. An elaboration, in which Euclid seems to have had some part, brought statics to the stage of development in which it was found by Archimedes (about 287-212 B.C.), who was to raise it to a still higher degree of perfection. It will here suffice to mention the works of genius in which the great Syracusan treated the equilibrium of the weights suspended from the two arms of a lever, the search for the centre of gravity, and the equilibrium of liquids and floating bodies. The treatises of Archimedes were too scholarly to be widely read by the mechanics who succeeded

this geometrician; these men preferred easier and more practical writings as, for instance, those on the lines of Aristotle's "Mechanical Questions". Various treatises by Heron of Alexandria have preserved for us the type of these decadent works.

Science and early Christian scholars

Shortly after the death of Ptolemy, Christian science took root at Alexandria with Origen (about 180-253), and a fragment of his "Commentaries on Genesis", preserved by Eusebius, shows us that the author was familiar with the latest astronomical discoveries, especially the precession of the equinoxes. However, the writings in which the Fathers of the Church comment upon the work of the six days of Creation, notably the commentaries of St. Basil and St. Ambrose, borrow but little from Hellenic physics; in fact, their tone would seem to indicate distrust in the teachings of Greek science, this distrust being engendered by two prejudices: in the first place, astronomy was becoming more and more the slave of astrology, the superstitions of which the Church diligently combated; in the second place, between the essential propositions of peripatetic physics and what we believe to be the teaching of Holy Writ, contradictions appeared; thus Genesis was thought to teach the presence of water above the heaven of the fixed stars (the firmament) and this was incompatible with the Aristotelean theory concerning the natural place of the elements. The debates raised by this question gave St. Augustine an opportunity to lay down wise exegetical rules, and he recommended Christians not to put forth lightly, as articles of faith, propositions contradicted by physical science based upon careful experiments. St. Isidore of Seville (d. 636), a bishop, considered it legitimate for Christians to desire to know the teachings of profane science, and he laboured to satisfy this curiosity. His "Etymologies" and "De natura rerum" are merely compilations of fragments borrowed from all the pagan and Christian authors with whom he was acquainted. In the height of the Latin Middle Ages these works served as models for numerous encyclopædias, of which the "De natura rerum" by Bede (about 672-735) and the "De universo" by Rabanus Maurus (776-856) were the best known.

However, the sources from which the Christians of the West imbibed a knowledge of ancient physics became daily more numerous, and to Pliny the Elder's "Natural History", read by Bede, were added Chalcidius's commentary on Plato's "Timæus" and Martianus Capella's "De Nuptiis Philologiæ et Mercurii", these different works inspiring the physics of John Scotus Eriugena. Prior to A.D. 1000 a new Platonic work by Macrobius, a commentary on the "Somnium Scipionis", was in great favour in the schools. Influenced by the various treatises already mentioned, Guillaume of Conches (1080-1150 or 1154) and the unknown author of "De mundi constitutione liber", which, by the way, has been falsely attributed to Bede, set forth a planetary theory making Venus and Mercury satellites of the sun, but Eriugena went still further and made the sun also the centre of the orbits of Mars and Jupiter. Had he but extended this hypothesis to Saturn, he would have merited the title of precursor of Tycho Brahe.

A glance at Arabian physics

The authors of whom we have heretofore spoken had only been acquainted with Greek science through the medium of Latin tradition, but the time came when it was to be much more completely revealed to the Christians of the West through the medium of Mussulman tradition.

There is no Arabian science. The wise men of Mohammedanism were always the more or less faithful disciples of the Greeks, but were themselves destitute of all originality. For instance, they compiled many abridgments of Ptolemy's "Almagest", made numerous observations, and constructed a great many astronomical tables, but added nothing essential to the theories of astronomical motion; their only innovation in this respect, and, by the way, quite an unfortunate one, was the doctrine of the oscillatory motion of the equinoctial points, which the Middle Ages ascribed to Thâbit ibn Kûrrah (836-901), but which was probably the idea of Al-Zarkali, who lived much later and made observations between 1060 and 1080. This motion was merely the adaptation of a mechanism conceived by Ptolemy for a totally different purpose.

In physics, Arabian scholars confined themselves to commentaries on the statements of Aristotle, their attitude being at times one of absolute servility. This intellectual servility to Peripatetic teaching reached its climax in Abul ibn Roshd, whom Latin scholastics called Averroës (about 1120-98) and who said: Aristotle "founded and completed logic, physics, and metaphysics . . . because none of those who have followed him up to our time, that is to say, for four hundred years, have been able to add anything to his writings or to detect therein an error of any importance". This unbounded respect

for Aristotle's work impelled a great many Arabian philosophers to attack Ptolemy's "Astronomy" in the name of Peripatetic physics. The conflict between the hypotheses of eccentrics and epicycles was inaugurated by Ibn Bâdja, known to the scholastics as Avempace (d. 1138), and Abu Bekr ibn el-Tofeil, called Abubacer by the scholastics (d. 1185), and was vigorously conducted by Averroës, the protégé of Abubacer. Abu Ishâk ibn al-Bitrogi, known by the scholastics as Alpetragius, another disciple of Abubacer and a contemporary of Averroës, advanced a theory on planetary motion wherein he wished to account for the phenomena peculiar to the wandering stars, by compounding rotations of homocentric spheres; his treatise, which was more neo-Platonic than Peripatetic, seemed to be a Greek book altered, or else a simple plagiarism. Less inflexible in his Peripateticism than Averroës and Alpetragius, Moses ben Maimun, called Maimonides (1139-1204), accepted Ptolemy's astronomy despite its incompatibility with Aristotelean physics, although he regarded Aristotle's sublunary physics as absolutely true.

Arabian tradition and Latin Scholasticism

It cannot be said exactly when the first translations of Arabic writings began to be received by the Christians of the West, but it was certainly previously to the time of Gerbert (Sylvester II; about 930-1003). Gerbert used treatises translated from the Arabic, and containing instructions on the use of astronomical instruments, notably the astrolabe, to which instrument Hermann the Lame (1013-54) devoted part of his researches. In the beginning of the twelfth century the contributions of Mohammedan science and philosophy to Latin Christendom became more and more frequent and important. About 1120 or 1130 Adelard of Bath translated the "Elements" of Euclid, and various astronomical treatises; in 1141 Peter the Venerable, Abbot of Cluny, found two translators, Hermann the Second (or the Dalmatian) and Robert of Rétines, established in Spain; he engaged them to translate the Koran into Latin, and in 1143 these same translators made Christendom acquainted with Ptolemy's planisphere. Under the direction of Raimond (Archbishop of Toledo, 1130; d. 1150), Domingo Gondisalvi (Gonsalvi; Gundissalinus), Archdeacon of Segovia, began to collaborate with the converted Jew, John of Luna, erroneously called John of Seville (Johannes Hispalensis). While John of Luna applied himself to works in mathematics, he also assisted Gondisalvi in translating into Latin a part of Aristotle's physics, the "De Cælo" and the "Metaphysics", besides treatises by Avicenna, Al-Gazâli, Al-Fârâbi, and perhaps Salomon ibn Gebirol (Avicebron). About 1134 John of Luna translated Al-Fergâni's treatise "Astronomy", which was an abridgement of the "Almagest", thereby introducing Christians to the Ptolemaic system, while at the same time his translations, made in collaboration with Gondisalvi, familiarized the Latins with the physical and metaphysical doctrines of Aristotle. Indeed the influence of Aristotle's "Physics" was already apparent in the writings of the most celebrated masters of the school of Chartres (from 1121 until before 1155), and of Gilbert de la Porrée (1070-1154).

The abridgement of Al-Fergâni's "Astronomy", translated by John of Luna, does not seem to have been the first work in which the Latins were enabled to read the exposition of Ptolemy's system; it was undoubtedly preceded by a more complete treatise, the "De Scientia stellarum" of Albategnius (Al-Battâni), latinized by Plato of Tivoli about 1120. However, the "Almagest" itself was still unknown. Moved by a desire to read and translate Ptolemy's immortal work, Gerard of Cremona (d. 1187) left Italy and went to Toledo, eventually making the translation which he finished in 1175. Besides the "Almagest", Gerard rendered into Latin other works, of which we have a list comprising seventy-four different treatises. Some of these were writings of Greek origin, and included a large portion of the works of Aristotle, a treatise by Archimedes, Euclid's "Elements" (completed by Hypsicles), and books by Hippocrates. Others were Arabic writings, such as the celebrated "Book of Three Brothers", composed by the Beni Mûsa, "Optics" by Ibn Al-Haitam (the Alhazen of the Scholastics), "Astronomy" by Geber, and "De motu octavæ spheræ" by Thâbit ibn Kûrrah. Moreover, in order to spread the study of Ptolemaic astronomy, Gerard composed at Toledo his "Theoricæ planetarum", which during the Middle Ages became one of the classics of astronomical instruction. Beginners who obtained their first cosmographic information through the study of the "Sphæra", written about 1230 by Joannes de Sacrobosco, could acquire a knowledge of eccentrics and epicycles by reading the "Theoricæ planetarum" of Gerard of Cremona. In fact, until the sixteenth century, most astronomical treatises assumed the form of commentaries, either on the "Sphæra", or the "Theoricæ planetarum".

"Aristotle's philosophy", wrote Roger Bacon in 1267, "reached a great development among the Latins when Michael Scot appeared about 1230, bringing with him certain parts of the mathematical and physical treatises of Aristotle and his learned commentators". Among the Arabic writings made known to Christians by Michael Scot (before 1291; astrologer to Frederick II) were the treatises of Aristotle and the "Theory of Planets", which Alpetragius had composed in accordance

with the hypothesis of homocentric spheres. The translation of this last work was completed in 1217. By propagating among the Latins the commentaries on Averroës and on Alpetragius's theory of the planets, as well as a knowledge of the treatises of Aristotle, Michael Scot developed in them an intellectual disposition which might be termed Averroism, and which consisted in a superstitious respect for the word of Aristotle and his commentator.

There was a metaphysical Averroism which, because professing the doctrine of the substantial unity of all human intellects, was in open conflict with Christian orthodoxy; but there was likewise a physical Averroism which, in its blind confidence in Peripatetic physics, held as absolutely certain all that the latter taught on the subject of the celestial substance, rejecting in particular the system of epicycles and eccentrics in order to commend Alpetragius's astronomy of homocentric spheres.

Scientific Averroism found partisans even among those whose purity of faith constrained them to struggle against metaphysical Averroism, and who were very often Peripatetics in so far as was possible without formally contradicting the teaching of the Church. For instance, William of Auvergne (d. 1249), who was the first to combat "Aristotle and his sectarians" on metaphysical grounds, was somewhat misled by Alpetragius's astronomy, which, moreover, he understood but imperfectly. Albertus Magnus (1193 or 1205-1280) followed to a great extent the doctrine of Ptolemy, although he was sometimes influenced by the objections of Averroës or affected by Alpetragius's principles. Vincent of Beauvais in his "Speculum quadruplex", a vast encyclopædic compilation published about 1250, seemed to attach great importance to the system of Alpetragius, borrowing the exposition of it from Albertus Magnus. Finally, even St. Thomas Aquinas gave evidence of being extremely perplexed by the theory (1227-74) of eccentrics and epicycles which justified celestial phenomena by contradicting the principles of Peripatetic physics, and the theory of Alpetragius which honoured these principles but did not go so far as to represent their phenomena in detail.

This hesitation, so marked in the Dominican school, was hardly less remarkable in the Franciscan. Robert Grosseteste or Greathead (1175-1253), whose influence on Franciscan studies was so great, followed the Ptolemaic system in his astronomical writings, his physics being imbued with Alpetragius's ideas. St. Bonaventure (1221-74) wavered between doctrines which he did not thoroughly understand, and Roger Bacon (1214-92) in several of his writings weighed with great care the arguments that could be made to count for or against each of these two astronomical theories, without eventually making a choice. Bacon, however, was familiar with a method of figuration in the system of eccentrics and epicycles which Alhazen had derived from the Greeks; and in this figuration all the motions acknowledged by Ptolemy were traced back to the rotation of solid orbs accurately fitted one into the other. This representation, which refuted most of the objections raised by Averroës against Ptolemaic astronomy, contributed largely to propagate the knowledge of this astronomy, and it seems that the first of the Latins to adopt it and expatiate on its merits was the Franciscan Bernard of Verdun (end of thirteenth century), who had read Bacon's writings. In sublunary physics the authors whom we have just mentioned did not show the hesitation that rendered astronomical doctrines so perplexing, but on almost all points adhered closely to Peripatetic opinions .

The science of observation and its progress -- Astronomers -- The statics of Jordanus -- Thierry of Freiberg -- Pierre of Maricourt

Averroism had rendered scientific progress impossible, but fortunately in Latin Christendom it was to meet with two powerful enemies: the unhampered curiosity of human reason, and the authority of the Church. Encouraged by the certainty resulting from experiments, astronomers rudely shook off the yoke which Peripatetic physics had imposed upon them. The School of Paris in particular was remarkable for its critical views and its freedom of attitude towards the argument of authority. In 1290 William of Saint-Cloud determined with wonderful accuracy the obliquity of the ecliptic and the time of the vernal equinox, and his observations led him to recognize the inaccuracies that marred the "Tables of Toledo", drawn up by Al-Zarkali. The theory of the precession of the equinoxes, conceived by the astronomers of Alfonso X of Castile, and the "Alphonsine Tables" set up in accordance with this theory, gave rise in the first half of the fourteenth century to the observations, calculations, and critical discussions of Parisian astronomers, especially of Jean des Linières and his pupil John of Saxonia or Connaught.

At the end of the thirteenth century and the beginning of the fourteenth, sublunary physics owed great advancement to the

simultaneous efforts of geometricians and experimenters -- their method and discoveries being duly boasted of by Roger Bacon who, however, took no important part in their labours. Jordanus de Nemore, a talented mathematician who, not later than about the beginning of the thirteenth century, wrote treatises on arithmetic and geometry, left a very short treatise on statics in which, side by side with erroneous propositions, we find the law of the equilibrium of the straight lever very correctly established with the aid of the principle of virtual displacements. The treatise, "De ponderibus", by Jordanus provoked research on the part of various commentators, and one of these, whose name is unknown and who must have written before the end of the thirteenth century, drew, from the same principle of virtual displacements, demonstrations, admirable in exactness and elegance, of the law of the equilibrium of the bent lever, and of the apparent weight (*gravitas secundum situm*) of a body on an inclined plane.

Alhazen's "Treatise on Perspective" was read thoroughly by Roger Bacon and his contemporaries, John Peckham (1228-91), the English Franciscan, giving a summary of it. About 1270 Witelo (or Witek; the *Thuringopolonus*), composed an exhaustive ten-volume treatise on optics, which remained a classic until the time of Kepler, who wrote a commentary on it.

Albertus Magnus, Roger Bacon, John Peckham, and Witelo were deeply interested in the theory of the rainbow, and, like the ancient meteorologists, they all took the rainbow to be the image of the sun reflected in a sort of a concave mirror formed by a cloud resolved into rain. In 1300 Thierry of Freiberg proved by means of carefully-conducted experiments in which he used glass balls filled with water, that the rays which render the bow visible have been reflected on the inside of the spherical drops of water, and he traced with great accuracy the course of the rays which produce the rainbows respectively.

The system of Thierry of Freiberg, at least that part relating to the primary rainbow, was reproduced about 1360 by Themon, "Son of the Jew" (*Themo ju d i*), and, from his commentary on "Meteors", it passed on down to the days of the Renaissance when, having been somewhat distorted, it reappeared in the writings of Alessandro Piccolomini, Simon Porta, and Marco and Antonio de Dominis, being thus propagated until the time of Descartes.

The study of the magnet had also made great progress in the course of the thirteenth century; the permanent magnetization of iron, the properties of the magnetic poles, the direction of the Earth's action exerted on these poles or of their action on one another, are all found very accurately described in a treatise written in 1269 by Pierre of Maricourt (Petrus Peregrinus). Like the work of Thierry of Freiberg on the rainbow, the "Epistola de magnete" by Maricourt was a model of the art of logical sequence between experiment and deduction.

The articles of Paris (1277) -- possibility of vacuum

The University of Paris was very uneasy because of the antagonism existing between Christian dogmas and certain Peripatetic doctrines, and on several occasions it combatted Aristotelean influence. In 1277 Etienne Tempier, Bishop of Paris, acting on the advice of the theologians of the Sorbonne, condemned a great number of errors, some of which emanated from the astrology, and others from the philosophy of the Peripatetics. Among these errors considered dangerous to faith were several which might have impeded the progress of physical science, and hence it was that the theologians of Paris declared erroneous the opinion maintaining that God Himself could not give the entire universe a rectilinear motion, as the universe would then leave a vacuum behind it, and also declared false the notion that God could not create several worlds. These condemnations destroyed certain essential foundations of Peripatetic physics; because, although, in Aristotle's system, such propositions were ridiculously untenable, belief in Divine Omnipotence sanctioned them as possible, whilst waiting for science to confirm them as true. For instance, Aristotle's physics treated the existence of an empty space as a pure absurdity; in virtue of the "Articles of Paris" Richard of Middletown (about 1280) and, after him, many masters at Paris and Oxford admitted that the laws of nature are certainly opposed to the production of empty space, but that the realization of such a space is not, in itself, contrary to reason; thus, without any absurdity, one could argue on vacuum and on motion in a vacuum. Next, in order that such arguments might be legitimized, it was necessary to create that branch of mechanical science known as dynamics.

The earth's motion -- Oresme

The "Articles of Paris" were of about the same value in supporting the question of the Earth's motion as in furthering the progress of dynamics by regarding vacuum as something conceivable.

Aristotle maintained that the first heaven (the firmament) moved with a uniform rotary motion, and that the Earth was absolutely stationary, and as these two propositions necessarily resulted from the first principles relative to time and place, it would have been absurd to deny them. However, by declaring that God could endow the World with a rectilinear motion, the theologians of the Sorbonne acknowledged that these two Aristotelean propositions could not be imposed as a logical necessity and thenceforth, whilst continuing to admit that, as a fact, the Earth was immovable and that the heavens moved with a rotary diurnal motion, Richard of Middletown and Duns Scotus (about 1275-1308) began to formulate hypotheses to the effect that these bodies were animated by other motions, and the entire school of Paris adopted the same opinion. Soon, however, the Earth's motion was taught in the School of Paris, not as a possibility, but as a reality. In fact, in the specific setting forth of certain information given by Aristotle and Simplicius, a principle was formulated which for three centuries was to play a great rôle in statics, viz. that every heavy body tends to unite its centre of gravity with the centre of the Earth.

When writing his "Questions" on Aristotle's "De Cælo" in 1368, Albert of Helmstadt (or of Saxony) admitted this principle, which he applied to the entire mass of the terrestrial element. The centre of gravity of this mass is constantly inclined to place itself in the centre of the universe, but, within the terrestrial mass, the position of the centre of gravity is incessantly changing. The principal cause of this variation is the erosion brought about by the streams and rivers that continually wear away the land surface, deepening its valleys and carrying off all loose matter to the bed of the sea, thereby producing a displacement of weight which entails a ceaseless change in the position of the centre of gravity. Now, in order to replace this centre of gravity in the centre of the universe, the Earth moves without ceasing; and meanwhile a slow but perpetual exchange is being effected between the continents and the oceans. Albert of Saxony ventured so far as to think that these small and incessant motions of the Earth could explain the phenomena of the precession of the equinoxes. The same author declared that one of his masters, whose name he did not disclose, announced himself in favour of the daily rotation of the Earth, inasmuch as he refuted the arguments that were opposed to this motion. This anonymous master had a thoroughly convinced disciple in Nicole Oresme who, in 1377, being then Canon of Rouen and later Bishop of Lisieux, wrote a French commentary on Aristotle's treatise "De Cælo", maintaining with quite as much force as clearness that neither experiment nor argument could determine whether the daily motion belonged to the firmament of the fixed stars or to the Earth. He also showed how to interpret the difficulties encountered in "the Sacred Scriptures wherein it is stated that the sun turns, etc. It might be supposed that here Holy Writ adapts itself to the common mode of human speech, as also in several places, for instance, where it is written that God repented Himself, and was angry and calmed Himself and so on, all of which is, however, not to be taken in a strictly literal sense". Finally, Oresme offered several considerations favourable to the hypothesis of the Earth's daily motion. In order to refute one of the objections raised by the Peripatetics against this point, Oresme was led to explain how, in spite of this motion, heavy bodies seemed to fall in a vertical line; he admitted their real motion to be composed of a fall in a vertical line and a diurnal rotation identical with that which they would have if bound to the Earth. This is precisely the principle to which Galileo was afterwards to turn.

Plurality of worlds

Aristotle maintained the simultaneous existence of several worlds to be an absurdity, his principal argument being drawn from his theory of gravity, whence he concluded that two distinct worlds could not coexist and be each surrounded by its elements; therefore it would be ridiculous to compare each of the planets to an earth similar to ours. In 1277 the theologians of Paris condemned this doctrine as a denial of the creative omnipotence of God; Richard of Middletown and Henry of Ghent (who wrote about 1280), Guillaume Varon (who wrote a commentary on the "Sentences" about 1300), and, towards 1320, Jean de Bassols, William of Occam (d. after 1347), and Walter Burley (d. about 1348) did not hesitate to declare that God could create other worlds similar to ours. This doctrine, adopted by several Parisian masters, exacted that the theory of gravity and natural place developed by Aristotle be thoroughly changed; in fact, the following theory was substituted for it. If some part of the elements forming a world be detached from it and driven far away, its tendency will be to move towards the world to which it belongs and from which it was separated; the elements of each world are inclined so to arrange themselves that the heaviest will be in the centre and the lightest on the surface. This theory of gravity appeared in the writings of Jean Buridan of Béthune, who became rector of the University of Paris in 1327,

teaching at that institution until about 1360; and in 1377 this same theory was formally proposed by Oresme. It was also destined to be adopted by Copernicus and his first followers, and to be maintained by Galileo, William Gilbert, and Otto von Guericke.

Dynamics -- theory of impetus -- inertia -- celestial and sublunary mechanics identical

If the School of Paris completely transformed the Peripatetic theory of gravity, it was equally responsible for the overthrow of Aristotelean dynamics. Convinced that, in all motion, the mover should be directly contiguous to the body moved, Aristotle had proposed a strange theory of the motion of projectiles. He held that the projectile was moved by the fluid medium, whether air or water, through which it passed and this, by virtue of the vibration brought about in the fluid at the moment of throwing, and spread through it. In the sixth century of our era this explanation was strenuously opposed by the Christian Stoic, Joannes Philoponus, according to whom the projectile was moved by a certain power communicated to it at the instant of throwing; however, despite the objections raised by Philoponus, Aristotle's various commentators, particularly Averroës, continued to attribute the motion of the projectile to the disturbance of the air, and Albertus Magnus, St. Thomas Aquinas, Roger Bacon, Gilles of Rome, and Walter Burley persevered in maintaining this error. By means of most spirited argumentation, William of Occam made known the complete absurdity of the Peripatetic theory of the motion of projectiles. Going back to Philoponus's thesis, Buridan gave the name *impetus* to the virtue or power communicated to the projectile by the hand or instrument throwing it; he declared that in any given body in motion, this impetus was proportional to the velocity, and that, in different bodies in motion propelled by the same velocity, the quantities of impetus were proportional to the mass or quantity of matter defined as it was afterwards defined by Newton.

In a projectile; impetus is gradually destroyed by the resistance of air or other medium and is also destroyed by the natural gravity of the body in motion, which gravity is opposed to the impetus if the projectile be thrown upward; this struggle explains the different peculiarities of the motion of projectiles. In a falling body, gravity comes to the assistance of impetus which it increases at every instant, hence the velocity of the fall is increasing incessantly.

With the assistance of these principles concerning impetus, Buridan accounts for the swinging of the pendulum. He likewise analyses the mechanism of impact and rebound and, in this connexion, puts forth very correct views on the deformations and elastic reactions that arise in the contiguous parts of two bodies coming into collision. Nearly all this doctrine of impetus is transformed into a very correct mechanical theory if one is careful to substitute the expression *vis viva* for impetus. The dynamics expounded by Buridan were adopted in their entirety by Albert of Saxony, Oresme, Marsile of Inghem, and the entire School of Paris. Albert of Saxony appended thereto the statement that the velocity of a falling body must be proportional either to the time elapsed from the beginning of the fall or to the distance traversed during this time. In a projectile, the impetus is gradually destroyed either by the resistance of the medium or by the contrary tendency of the gravity natural to the body. Where these causes of destruction do not exist, the impetus remains perpetually the same, as in the case of a millstone exactly centred and not rubbing on its axis; once set in motion it will turn indefinitely with the same swiftness. It was under this form that the law of inertia at first became evident to Buridan and Albert of Saxony. The conditions manifested in this hypothetic millstone are realized in the celestial orbs, as in these neither friction nor gravity impedes motion; hence it may be admitted that each celestial orb moves indefinitely by virtue of a suitable impetus communicated to it by God at the moment of creation. It is useless to imitate Aristotle and his commentators by attributing the motion of each orb to a presiding spirit. This was the opinion proposed by Buridan and adopted by Albert of Saxony; and whilst formulating a doctrine from which modern dynamics was to spring, these masters understood that the same dynamics governs both celestial and sublunary bodies. Such an idea was directly opposed to the essential distinction established by ancient physics between these two kinds of bodies. Moreover, following William of Occam, the masters of Paris rejected this distinction; they acknowledged that the matter constituting celestial bodies was of the same nature as that constituting sublunary bodies and that, if the former remained perpetually the same, it was not because they were, by nature, incapable of change and destruction, but simply because the place in which they were contained no agent capable of corrupting them. A century elapsed between the condemnations pronounced by Etienne Tempier (1277) and the editing of the "Traité du Ciel et du Monde" by Oresme (1377) and, within that time, all the essential principles of Aristotle's physics were undermined, and the great controlling ideas of modern science formulated. This revolution was mainly the work of Oxford Franciscans like Richard of Middletown, Duns Scotus, and

William of Occam, and of masters in the School of Paris, heirs to the tradition inaugurated by these Franciscans; among the Parisian masters Buridan, Albert of Saxony, and Oresme were in the foremost rank.

Propagation of the doctrines of the school of Paris in Germany and Italy -- Purbach and Regiomontanus -- Nicholas of Cusa -- Vinci

The great Western Schism involved the University of Paris in politico-religious quarrels of extreme violence; the misfortunes brought about by the conflict between the Armagnacs and Burgundians and by the Hundred Years' War, completed what these quarrels had begun, and the wonderful progress made by science during the fourteenth century in the University of Paris suddenly ceased. However, the schism contributed to the diffusion of Parisian doctrines by driving out of Paris a large number of brilliant men who had taught there with marked success. In 1386 Marsile of Inghem (d. 1396), who had been one of the most gifted professors of the University of Paris, became rector of the infant University of Heidelberg, where he introduced the dynamic theories of Buridan and Albert of Saxony.

About the same time, another master, reputedly of Paris, Heinrich Heimbuch of Langenstein, or of Hesse, was chiefly instrumental in founding the University of Vienna and, besides his theological knowledge, brought thither the astronomical tradition of Jean des Linières and John of Saxony. This tradition was carefully preserved in Vienna, being magnificently developed there throughout the fifteenth century, and paving the way for Georg Purbach (1423-61) and his disciple Johann Müller of Königsberg, surnamed Regiomontanus (1436-76). It was to the writing of theories calculated to make the Ptolemaic system known, to the designing and constructing of exact instruments, to the multiplying of observations, and the preparing of tables and almanacs (ephemerides), more accurate than those used by astronomers up to that time, that Purbach and Regiomontanus devoted their prodigious energy. By perfecting all the details of Ptolemy's theories, which they never called in question, they were most helpful in bringing to light the defects of these theories and in preparing the materials by means of which Copernicus was to build up his new astronomy.

Averroism flourished in the Italian Universities of Padua and Bologna, which were noted for their adherence to Peripatetic doctrines. Still from the beginning of the fifteenth century the opinions of the School of Paris began to find their way into these institutions, thanks to the teaching of Paolo Nicoletti of Venice (flourished about 1420). It was there developed by his pupil Gaetan of Tiene (d. 1465). These masters devoted special attention to propagating the dynamics of impetus in Italy.

About the time that Paola of Venice was teaching at Padua, Nicholas of Cusa came there to take his doctorate in law. Whether it was then that the latter became initiated in the physics of the School of Paris matters little, as in any event it was from Parisian physics that he adopted those doctrines that smacked least of Peripateticism. He became thoroughly conversant with the dynamics of impetus and, like Buridan and Albert of Saxony, attributed the motion of the celestial spheres to the impetus which God had communicated to them in creating them, and which was perpetuated because, in these spheres, there was no element of destruction. He admitted that the Earth moved incessantly, and that its motion might be the cause of the precession of the equinoxes. In a note discovered long after his death, he went so far as to attribute to the Earth a daily rotation. He imagined that the sun, the moon, and the planets were so many systems, each of which contained an earth and elements analogous to our Earth and elements, and to account for the action of gravity in each of these systems he followed closely the theory of gravity advanced by Oresme.

Leonardo da Vinci (1452-1519) was perhaps more thoroughly convinced of the merits of the Parisian physics than any other Italian master. A keen observer, and endowed with insatiable curiosity, he had studied a great number of works, amongst which we may mention the various treatises of the School of Jordanus, various books by Albert of Saxony, and in all likelihood the works of Nicholas of Cusa; then, profiting by the learning of these scholars, he formally enunciated or else simply intimated many new ideas. The statics of the School of Jordanus led him to discover the law of the composition of concurrent forces stated as follows: the two component forces have equal moments as regards the direction of the resultant, and the resultant and one of the components have equal moments as regards the direction of the other component. The statics derived from the properties which Albert of Saxony attributed to the centre of gravity caused Vinci to recognize the law of the polygon of support and to determine the centre of gravity of a tetrahedron. He also presented the law of the equilibrium of two liquids of different density in communicating tubes, and the principle of

virtual displacements seems to have occasioned his acknowledgement of the hydrostatic law known as Pascal's. Vinci continued to meditate on the properties of impetus, which he called *impeto* or *forza*, and the propositions that he formulated on the subject of this power very often showed a fairly clear discernment of the law of the conservation of energy. These propositions conducted him to remarkably correct and accurate conclusions concerning the impossibility of perpetual motion. Unfortunately he misunderstood the pregnant explanation, afforded by the theory of impetus, regarding the acceleration of falling bodies, and like the Peripatetics attributed this acceleration to the impulsion of the encompassing air. However, by way of compensation, he distinctly asserted that the velocity of a body that falls freely is proportional to the time occupied in the fall, and he understood in what way this law extends to a fall on an inclined plane. When he wished to determine how the path traversed by a falling body is connected with the time occupied in the fall, he was confronted by a difficulty which, in the seventeenth century, was likewise to baffle Baliani and Gassendi.

Vinci was much engrossed in the analysis of the deformations and elastic reactions which cause a body to rebound after it has struck another, and this doctrine, formulated by Buridan, Albert of Saxony, and Marsile of Inghem he applied in such a way as to draw from it the explanation of the flight of birds. This flight is an alternation of falls during which the bird compresses the air beneath it, and of rebounds due to the elastic force of this air. Until the great painter discovered this explanation, the question of the flight of birds was always looked upon as a problem in statics, and was likened to the swimming of a fish in water. Vinci attached great importance to the views developed by Albert of Saxony in regard to the Earth's equilibrium. Like the Parisian master, he held that the centre of gravity within the terrestrial mass is constantly changing under the influence of erosion and that the Earth is continually moving so as to bring this centre of gravity to the centre of the World. These small, incessant motions eventually bring to the surface of the continents those portions of earth that once occupied the bed of the ocean and, to place this assertion of Albert of Saxony beyond the range of doubt, Vinci devoted himself to the study of fossils and to extremely cautious observations which made him the creator of Stratigraphy. In many passages in his notes Vinci asserts, like Nicholas of Cusa that the moon and the other wandering stars are worlds analogous to ours, that they carry seas upon their surfaces, and are surrounded by air; and the development of this opinion led him to talk of the gravity binding to each of these stars the elements that belonged to it. On the subject of this gravity he professed a theory similar to Oresme's. Hence it would seem that, in almost every particular, Vinci was a faithful disciple of the great Parisian masters of the fourteenth century, of Buridan, Albert of Saxony, and Oresme.

Italian Averroism and its tendencies to routine -- attempts at restoring the astronomy of homocentric spheres

Whilst, through the anti-Peripatetic influence of the School of Paris, Vinci reaped a rich harvest of discoveries, innumerable Italians devoted themselves to the sterile worship of defunct ideas with a servility that was truly astonishing. The Averroists did not wish to acknowledge as true anything out of conformity with the ideas of Aristotle as interpreted by Averroës; with Pompanazzi (1462-1526), the Alexandrists, seeking their inspiration further back in the past, refused to understand Aristotle otherwise than he had been understood by Alexander of Aphrodisias; and the Humanists, solicitous only for purity of form, would not consent to use any technical language whatever and rejected all ideas that were not sufficiently vague to be attractive to orators and poets; thus Averroists, Alexandrists, and Humanists proclaimed a truce to their vehement discussions so as to combine against the "language of Paris", the "logic of Paris", and the "physics of Paris". It is difficult to conceive the absurdities to which these minds were led by their slavish surrender to routine. A great number of physicists, rejecting the Parisian theory of impetus, returned to the untenable dynamics of Aristotle, and maintained that the projectile was moved by the ambient air. In 1499 Nicolò Vernias of Chieti, an Averroist professor at Padua, taught that if a heavy body fell it was in consequence of the motion of the air surrounding it.

A servile adoration of Peripateticism prompted many so-called philosophers to reject the Ptolemaic system, the only one which, at that time, could satisfy the legitimate exigencies of astronomers, and to readopt the hypothesis of homocentric spheres. They held as null and void the innumerable observations that showed changes in the distance of each planet from the Earth. Alessandro Achillini of Bologna (1463-1512), an uncompromising Averroist and a strong opponent of the theory of impetus and of all Parisian doctrines, inaugurated, in his treatise "De orbibus" (1498), a strange reaction against Ptolemaic astronomy; Agostino Nifo (1473-1538) laboured for the same end in a work that has not come down to us; Girolamo Fracastorio (1483-1553) gave us, in 1535, his book "De homocentricis", and Gianbattista Amico (1536), and Giovanni Antonio Delfino (1559) published small works in an endeavour to restore the system of homocentric spheres.

The Copernican revolution

Although directed by tendencies diametrically opposed to the true scientific spirit, the efforts made by Averroists to restore the astronomy of homocentric spheres were perhaps a stimulus to the progress of science, inasmuch as they accustomed physicists to the thought that the Ptolemaic system was not the only astronomical doctrine possible, or even the best that could be desired. Thus, in their own way, the Averroists paved the way for the Copernican revolution. The movements forecasting this revolution were noticeable in the middle of the fourteenth century in the writings of Nicholas of Cusa, and in the beginning of the fifteenth century in the notes of Vinci, both of these eminent scientists being well versed in Parisian physics.

Celio Calcagnini proposed, in his turn, to explain the daily motion of the stars by attributing to the Earth a rotation from West to East, complete in one sidereal day. His dissertation, "Quod c lum stet, terra vero moveatur", although seeming to have been written about 1530, was not published until 1544, when it appeared in a posthumous edition of the author's works. Calcagnini declared that the Earth, originally in equilibrium in the centre of the universe, received a first impulse which imparted to it a rotary motion, and this motion, to which nothing was opposed, was indefinitely preserved by virtue of the principle set forth by Buridan and accepted by Albert of Saxony and Nicholas of Cusa. According to Calcagnini the daily rotation of the Earth was accompanied by an oscillation which explained the movement of the precession of the equinoxes. Another oscillation set the waters of the sea in motion and determined the ebb and flow of the tides. This last hypothesis was to be maintained by Andrea Cesalpino (1519-1603) in his "Quæstiones peripateticæ" (1569), and to inspire Galileo, who, unfortunately, was to seek in the phenomena of the tides his favourite proof of the Earth's rotation.

The "De revolutionibus orbium c lestium libri sex" were printed in 1543, a few months after the death of Copernicus (1473-1543), but the principles of the astronomic system proposed by this man of genius had been published as early as 1539 in the "Narratio prima" of his disciple, Joachim Rhæticus (1514-76). Copernicus adhered to the ancient astronomical hypotheses which claimed that the World was spherical and limited, and that all celestial motions were decomposable into circular and uniform motions; but he held that the firmament of fixed stars was immovable, as also the sun, which was placed in the centre of this firmament. To the Earth he attributed three motions: a circular motion by which the centre of the Earth described with uniform velocity a circle situated in the plane of the ecliptic and eccentric to the sun; a daily rotation on an axis inclined towards the ecliptic, and finally, a rotation of this axis around an axis normal to the ecliptic and passing through the centre of the Earth. The time occupied by this last rotation was a little longer than that required for the circular motion of the centre of the Earth which produced the phenomenon of the precession of the equinoxes. To the five planets Copernicus ascribed motions analogous to those with which the Earth was provided, and he maintained that the moon moved in a circle around the Earth.

Of the Copernican hypotheses, the newest was that according to which the Earth moved in a circle around the sun. From the days of Aristarchus of Samos and Seleucus no one had adopted this view. Medieval astronomers had all rejected it, because they supposed that the stars were much too close to the Earth and the sun, and that an annual circular motion of the Earth might give the stars a perceptible parallax. Still, on the other hand, we have seen that various authors had proposed to attribute to the Earth one or the other of the two motions which Copernicus added to the annual motion. To defend the hypothesis of the daily motion of the Earth against the objections formulated by Peripatetic physics, Copernicus invoked exactly the same reasons as Oresme, and in order to explain how each planet retains the various parts of its elements, he adopted the theory of gravity proposed by the eminent master. Copernicus showed himself the adherent of Parisian physics even in the following opinion, enunciated accidentally: the acceleration of the fall of heavy bodies is explained by the continual increase which impetus receives from gravity.

Fortunes of the Copernican system in the sixteenth century

Copernicus and his disciple Rhæticus very probably regarded the motions which their theory ascribed to the Earth and the planets, the sun's rest and that of the firmament of fixed stars, as the real motions or real rest of these bodies. The "De revolutionibus orbium cælestium libri sex" appeared with an anonymous preface which inspired an entirely different idea. This preface was the work of the Lutheran theologian Osiander (1498-1552), who therein expressed the opinion that the

hypotheses proposed by philosophers in general, and by Copernicus in particular, were in no wise calculated to acquaint us with the reality of things: "Neque enim necesse est eas hypotheses esse veras, imo, ne verisimiles quidem, sed sufficit hoc unum si calculum observationibus congruentem exhibeant". Osiander's view of astronomical hypotheses was not new. Even in the days of Grecian antiquity a number of thinkers had maintained that the sole object of these hypotheses was to "save appearances", *sozein ta phainomena*; and in the Middle Ages, as well as in antiquity, this method continued to be that of philosophers who wished to make use of Ptolemaic astronomy whilst at the same time upholding the Peripatetic physics absolutely incompatible with this astronomy. Osiander's doctrine was therefore readily received, first of all by astronomers who, without believing the Earth's motion to be a reality, accepted and admired the kinetic combinations conceived by Copernicus, as these combinations provided them with better means than could be offered by the Ptolemaic system for figuring out the motion of the moon and the phenomena of the precession of the equinoxes.

One of the astronomers who most distinctly assumed this attitude in regard to Ptolemy's system was Erasmus Reinhold (1511-53), who, although not admitting the Earth's motion, professed a great admiration for the system of Copernicus and used it in computing new astronomical tables, the "Prutenicæ tabulæ" (1551), which were largely instrumental in introducing to astronomers the kinetic combinations originated by Copernicus. The "Prutenicæ tabulæ" were especially employed by the commission which in 1582 effected the Gregorian reform of the calendar. Whilst not believing in the Earth's motion, the members of this commission did not hesitate to use tables founded on a theory of the precession of the equinoxes and attributing a certain motion to the earth.

However, the freedom permitting astronomers to use all hypotheses qualified to account for phenomena was soon restricted by the exigencies of Peripatetic philosophers and Protestant theologians. Osiander had written his celebrated preface to Copernicus's book with a view to warding off the attacks of theologians, but in this he did not succeed. Martin Luther, in his "Tischrede", was the first to express indignation at the impiety of those who admitted the hypothesis of solar rest. Melancthon, although acknowledging the purely astronomical advantages of the Copernican system, strongly combatted the hypothesis of the Earth's motion (1549), not only with the aid of arguments furnished by Peripatetic physics but likewise, and chiefly, with the assistance of numerous texts taken from Holy Writ. Kaspar Peucer (1525-1602), Melancthon's son-in-law, whilst endeavouring to have his theory of the planets harmonize with the progress which the Copernican system had made in this regard, nevertheless rejected the Copernican hypotheses as absurd (1571).

It then came to be exacted of astronomical hypotheses that not only, as Osiander had desired, the result of their calculations be conformable to facts, but also that they be not refuted "either in the name of the principles of physics or in the name of the authority of the Sacred Scriptures". This criterion was explicitly formulated in 1578 by a Lutheran, the Danish astronomer Tycho Brahe (1546-1601), and it was precisely by virtue of these two requirements that the doctrines of Galileo were to be condemned by the Inquisition in 1616 and 1633. Eager not to admit any hypothesis that would conflict with Aristotelean physics or be contrary to the letter of the Sacred Scriptures, and yet most desirous to retain all the astronomical advantages of the Copernican system, Tycho Brahe proposed a new system which virtually consisted in leaving the Earth motionless and in moving the other heavenly bodies in such a way that their displacement with regard to the Earth might remain the same as in the system of Copernicus. Moreover, although posing as the defender of Aristotelean physics, Tycho Brahe dealt it a disastrous blow. In 1572 a star, until then unknown, appeared in the constellation of Cassiopeia, and in showing accurate observations that the new astral body was really a fixed star, Tycho Brahe proved conclusively that the celestial world was not, as Aristotle would have had us believe, formed of a substance exempt from generation and destruction.

The Church had not remained indifferent to the hypothesis of the Earth's motion until the time of Tycho Brahe, as it was amongst her members that this hypothesis had found its first defenders, counting adherents even in the extremely orthodox University of Paris. At the time of defending this hypothesis, Oresme was Canon of Rouen, and immediately after he was promoted to the Bishopric of Lisieux; Nicholas of Cusa was Bishop of Brixen and cardinal, and was entrusted with important negotiations by Eugenius IV, Nicholas V, and Pius II; Calcagnini was prothonotary Apostolic; Copernicus was Canon of Thorn, and it was Cardinal Schomberg who urged him to publish his work, the dedication of which was accepted by Paul III. Besides, Oresme had made clear how to interpret the Scriptural passages claimed to be opposed to the Copernican system, and in 1584 Didacus a Stunica of Salamanca found in Holy Writ texts which could be invoked with just as much certainty in favour of the Earth's motion. However, in 1595 the Protestant senate of the University of Tübingen compelled Kepler to retract the chapter in his "Mysterium cosmographicum", in which he had endeavoured to make the Copernican system agree with Scripture.

Christopher Clavius (1537-1612), a Jesuit, and one of the influential members of the commission that reformed the Gregorian Calendar, seemed to be the first Catholic astronomer to adopt the double test imposed upon astronomical hypotheses by Tycho Brahe, and to decide (1581) that the suppositions of Copernicus were to be rejected, as opposed both to Peripatetic physics and to Scripture; on the other hand, at the end of his life and under the influence of Galileo's discoveries, Clavius appeared to have assumed a far more favourable attitude towards Copernican doctrines. The enemies of Aristotelean philosophy gladly adopted the system of Copernicus, considering its hypotheses as so many propositions physically true, this being the case with Pierre de La Ramée, called Petrus Ramus (1502-72), and especially with Giordano Bruno (about 1550-1600). The physics developed by Bruno, in which he incorporated the Copernican hypothesis, proceeded from Nicole Oresme, and Nicholas of Cusa; but chiefly from the physics taught in the University of Paris in the fourteenth century. The infinite extent of the universe and the plurality of worlds were admitted as possible by many theologians at the end of the thirteenth century, and the theory of the slow motion which gradually causes the central portions of the Earth to work to the surface had been taught by Albert of Saxony before it attracted the attention of Vinci. The solution of Peripatetic arguments against the Earth's motion and the theory of gravity called forth by the comparison of the planets with the Earth would appear to have been borrowed by Bruno from Oresme. The apostasy and heresies for which Bruno was condemned in 1600 had nothing to do with the physical doctrines he had espoused, which included in particular Copernican astronomy. In fact it does not seem that, in the sixteenth century, the Church manifested the slightest anxiety concerning the system of Copernicus.

Theory of the tides

It is undoubtedly to the great voyages that shed additional lustre on the close of the fifteenth century that we must attribute the importance assumed in the sixteenth century by the problem of the tides, and the great progress made at that time towards the solution of this problem. The correlation existing between the phenomenon of high and low tide and the course of the moon was known even in ancient times. Posidonius accurately described it; the Arabian astronomers were also familiar with it, and the explanation given of it in the ninth century by Albumazar in his "Introductorium magnum ad Astronomiam" remained a classic throughout the Middle Ages. The observation of tidal phenomena very naturally led to the supposition that the moon attracted the waters of the ocean and, in the thirteenth century, William of Auvergne compared this attraction to that of the magnet for iron. However, the mere attraction of the moon did not suffice to account for the alternation of spring and neap tides, which phenomenon clearly indicated a certain intervention of the sun. In his "Questions sur les livres des Météores", which appeared during the latter half of the fourteenth century, Themon, "Son of the Jew", introduced in a vague sort of way the idea of superposing two tides, the one due to the sun and the other to the moon.

In 1528 this idea was very clearly endorsed by Federico Grisogone of Zara, a Dalmatian who taught medicine at Padua. Grisogone declared that, under the action of the moon exclusively, the sea would assume an ovoid shape, its major axis being directed towards the centre of the moon; that the action of the sun would also give it an ovoid shape, less elongated than the first, its major axis being directed towards the centre of the sun; and that the variation of sea level, at all times and in all places, was obtained by adding the elevation or depression produced by the solar tide to the elevation or depression produced by the lunar tide. In 1557 Girolamo Cardano accepted and briefly explained Grisogone's theory. In 1559 a posthumous work by Delfino gave a description of the phenomena of the tides, identical with that deduced from the mechanism conceived by Grisogone. The doctrine of the Dalmatian physician was reproduced by Paolo Gallucci in 1588, and by Annibale Raimondo in 1589; and in 1600 Claude Duret, who had plagiarized Delfino's treatise, published in France the description of the tides given in that work.

Statics in the sixteenth century -- Stevinus

When writing on statics Cardano drew upon two sources, the writings of Archimedes and the treatises of the School of Jordanus; besides, he probably plagiarized the notes left by Vinci, and it was perhaps from this source that he took the theorem: a system endowed with weight is in equilibrium when the centre of gravity of this system is the lowest possible.

Nicolo Tartaglia (about 1500-57), Cardano's antagonist, shamelessly purloined a supposedly forgotten treatise by one of Jordanus's commentators. Ferrari, Cardano's faithful disciple, harshly rebuked Tartaglia for the theft, which nevertheless had the merit of re-establishing the vogue of certain discoveries of the thirteenth century, especially the law of the

equilibrium of a body supported by an inclined plane. By another and no less barefaced plagiarism, Tartaglia published under his own name a translation of Archimedes's "Treatise on floating bodies" made by William of Moerbeke at the end of the thirteenth century. This publication, dishonest though it was, helped to give prominence to the study of Archimedes's mechanical labours, which study exerted the greatest influence over the progress of science at the end of the sixteenth century, the blending of Archimedean mathematics with Parisian physics, generating the movement that terminated in Galileo's work. The translation and explanation of the works of Archimedes enlisted the attention of geometers such as Francesco Maurolycus of Messina (1494-1575) and Federico Commandino of Urbino (1509-75), and these two authors, continuing the work of the great Syracusan, determined the position of the centre of gravity of various solids; in addition Commandino translated and explained Pappus's mathematical "Collection", and the fragment of "Mechanics" by Heron of Alexandria appended thereto. Admiration for these monuments of ancient science inspired a number of Italians with a profound contempt for medieval statics. The fecundity of the principle of virtual displacements, so happily employed by the School of Jordanus, was ignored; and, deprived of the laws discovered by this school and of the additions made to them by Vinci, the treatises on statics written by over-enthusiastic admirers of the Archimedean method were notably deficient. Among the authors of these treatises Guidobaldo dal Monte (1545-1607) and Giovanni Battista Benedetti (1530-90) deserve special mention.

Of the mathematicians who, in statics, claimed to follow exclusively the rigorous methods of Archimedes and the Greek geometers, the most illustrious was Simon Stevinus of Bruges (1548-1620). Through him the statics of solid bodies recovered all that had been gained by the School of Jordanus and Vinci, and lost by the contempt of such men as Guidobaldo del Monte and Benedetti. The law of the equilibrium of the lever, one of the fundamental propositions of which Stevinus made use, was established by him with the aid of an ingenious demonstration which Galileo was also to employ, and which is found in a small anonymous work of the thirteenth century. In order to confirm another essential principle of his theory, the law of the equilibrium of a body on an inclined plane, Stevinus resorted to the impossibility of perpetual motion, which had been affirmed with great precision by Vinci and Cardano. Stevinus's chief glory lay in his discoveries in hydrostatics; and the determining of the extent and point of application of the pressure on the slanting inner side of a vessel by the liquid contained therein was in itself sufficient to entitle this geometer from Bruges to a foremost place among the creators of the theory of the equilibrium of fluids. Benedetti was on the point of enunciating the principle known as Pascal's Law, and an insignificant addition permitted Mersenne to infer this principle and the idea of the hydraulic press from what the Italian geometer had written. Benedetti had justified his propositions by using as an axiom the law of the equilibrium of liquids in communicating vessels, and prior to this time Vinci had followed the same logical proceeding.

Dynamics in the sixteenth century

The geometers who, in spite of the stereotyped methods of Averroism and the banter of Humanism, continued to cultivate the Parisian dynamics of impetus, were rewarded by splendid discoveries. Dissipating the doubt in which Albert of Saxony had remained enveloped, Vinci had declared the velocity acquired by a falling body to be proportional to the time occupied by the fall, but he did not know how to determine the law connecting the time consumed in falling with the space passed over by the falling body. Nevertheless to find this law it would have sufficed to invoke the following proposition: in a uniformly varied motion, the space traversed by the moving body is equal to that which it would traverse in a uniform motion whose duration would be that of the preceding motion, and whose velocity would be the same as that which affected the preceding motion at the mean instant of its duration. This proposition was known to Oresme, who had demonstrated it exactly as it was to be demonstrated later by Galileo; it was enunciated and discussed at the close of the fourteenth century by all the logicians who, in the University of Oxford, composed the school of William of Heytesbury, Chancellor of Oxford in 1375; it was subsequently examined or invoked in the fifteenth century by all the Italians who became the commentators of these logicians; and finally, the masters of the University of Paris, contemporaries of Vinci, taught and demonstrated it as Oresme had done.

This law which Vinci was not able to determine was published in 1545 by a Spanish Dominican, Domingo Soto (1494-1560), an alumnus of the University of Paris, and professor of theology at Alcalá de Henares, and afterwards at Salamanca. He formulated these two laws thus:

The velocity of a falling body increases proportionally to the time of the fall.

The space traversed in a uniformly varied motion is the same as in a uniform motion occupying the same time, its velocity being the mean velocity of the former.

In addition Soto declared that the motion of a body thrown vertically upward is uniformly retarded. It should be mentioned that all these propositions were formulated by the celebrated Dominican as if in relation to truths generally admitted by the masters among whom he lived.

The Parisian theory, maintaining that the accelerated fall of bodies was due to the effect of a continual increase of impetus caused by gravity, was admitted by Julius Cæsar Scaliger (1484-1558), Benedetti, and Gabriel Vasquez (1551-1604), the celebrated Jesuit theologian. The first of these authors presented this theory in such a way that uniform acceleration of motion seemed naturally to follow from it.

Soto, Tartaglia, and Cardano made strenuous efforts, after the manner of Vinci, to explain the motion of projectiles by appealing to the conflict between impetus and gravity, but their attempts were frustrated by a Peripatetic error which several Parisian masters had long before rejected. They believed that the motion of the projectile was accelerated from the start, and attributed this initial acceleration to an impulse communicated by the vibrating air. Indeed, throughout the sixteenth century, the Italian Averroists continued to attribute to the ambient air the very transportation of the projectile. Tartaglia empirically discovered that a piece of artillery attained its greatest range when pointed at an angle of forty-five degrees to the horizon. Bruno insisted upon Oresme's explanation of the fact that a body appears to fall in a vertical line in spite of the Earth's motion; to obtain the trajectory of this body it is necessary to combine the action of its weight with the impetus which the Earth has imparted to it. It was as follows that Benedetti set forth the law followed by such an impetus. A body whirled in a circle and suddenly left to itself will move in a straight line tangent to the circle at the very point where the body happened to be at the moment of its release. For this achievement Benedetti deserves to be ranked among the most valuable contributors to the discovery of the law of inertia. In 1553 Benedetti advanced the following argument: in air, or any fluid whatever, ten equal stones fall with the same velocity as one of their number; and if all were combined they would still fall with the same velocity; therefore, in a fluid two stones, one of which is ten times heavier than the other, fall with the same velocity. Benedetti lauded the extreme novelty of this argument with which, in reality, many scholastics had been familiar, but which they had all claimed was not conclusive, because the resistance which the air offered to the heavier stone could certainly not be ten times that which it opposed to the lighter one. Achillini was one of those who clearly maintained this principle. That it might lead to a correct conclusion, Benedetti's argument had to be restricted to the motion of bodies in a vacuum, and this is what was done by Galileo.

Galileo's work

Galileo Galilei (1564-1642) had been in youth a staunch Peripatetic, but was later converted to the Copernican system, and devoted most of his efforts to its defence. The triumph of the system of Copernicus could only be secured by the perfecting of mechanics, and especially by solving the problem presented by the fall of bodies, when the earth was supposed to be in motion. It was towards this solution that many of Galileo's researches were directed, and to bring his labours to a successful issue he had to adopt certain principles of Parisian dynamics. Unfortunately, instead of using them all, he left it to others to exhaust their fecundity.

Galilean statics was a compromise between the incorrect method inaugurated in Aristotle's "Mechanical Questions" and the correct method of virtual displacements successfully applied by the School of Jordanus. Imbued with ideas that were still intensely Peripatetic, it introduced the consideration of a certain *impeto* or *momento*, proportional to the velocity of the moving body and not unlike the impetus of the Parisians. Galilean hydrostatics also showed an imperfect form of the principle of virtual displacements, which seemed to have been suggested to the great Pisan by the effectual researches made on the theory of running water by his friend Benedetto Castelli, the Benedictine (1577-1644). At first Galileo asserted that the velocity of a falling body increased proportionally to the space traversed, and afterwards, by an ingenious demonstration, he proved the utter absurdity of such a law. He then taught that the motion of a freely falling body was uniformly accelerated; in favour of this law, he contented himself with appealing to its simplicity without considering the continual increase of impetus under the influence of gravity. Gravity creates, in equal periods, a new and uniform impetus which, added to that already acquired, causes the total impetus to increase in arithmetical progression according to the time occupied in the fall; hence the velocity of the falling body. This argument towards which all Parisian tradition had been tending and which, in the last place, had been broached by Scaliger, leads to our modern law: a constant force

produces uniformly accelerated motion. In Galileo's work there is no trace either of the argument or of the conclusion deduced therefrom; however, the argument itself was carefully developed by Galileo's friend, Giambattista Baliani (1582-1666).

From the very definition of velocity, Baliani endeavoured to deduce the law according to which the space traversed by a falling body is increased proportionally to the time occupied in the fall. Here he was confronted by a difficulty that had also baffled Vinci; however, he eventually anticipated its solution, which was given, after similar hesitation, by another of Galileo's disciples, Pierre Gassendi (1592-1655). Galileo had reached the law connecting the time occupied in the fall with the space traversed by a falling body, by using a demonstration that became celebrated as the "demonstration of the triangle". It was textually that given by Oresme in the fourteenth century and, as we have seen, Soto had thought of using Oresme's proposition in the study of the accelerated fall of bodies. Galileo extended the laws of freely falling bodies to a fall down an inclined plane and subjected to the test of experiment the law of the motion of a weight on an inclined plane.

A body which, without friction or resistance of any kind, would describe the circumference of a circle concentric with the Earth would retain an invariable *impeto* or *momento*, as gravity would in no wise tend to increase or destroy this *impeto*: this principle which belonged to the dynamics of Buridan and Albert of Saxony, was acknowledged by Galileo. On a small surface, a sphere concentric with the Earth is apparently merged into a horizontal plane; a body thrown upon a horizontal plane and free from all friction would therefore assume a motion apparently rectilinear and uniform. It is only under this restricted and erroneous form that Galileo recognized the law of inertia and in this he was the faithful disciple of the School of Paris.

If a heavy body moved by an *impeto* that would make it describe a circle concentric with the Earth is, moreover, free to fall, the *impeto* of uniform rotation and gravity are component forces. Over a small extent the motion produced by this *impeto* may be assumed to be rectilinear, horizontal, and uniform; hence the approximate law may be enunciated as follows: a heavy body, to which a horizontal initial velocity has been imparted at the very moment that it is abandoned to the action of gravity, assumes a motion which is sensibly the combination of a uniform horizontal motion with the vertical motion that it would assume without initial velocity. Galileo then demonstrated that the trajectory of this heavy body is a parabola with vertical axis. This theory of the motion of projectiles rests upon principles in no wise conformable to an exact knowledge of the law of inertia and which are, at bottom, identical with those invoked by Oresme when he wished to explain how, despite the Earth's rotation, a body seems to fall vertically. The argument employed by Galileo did not permit him to state how a projectile moves when its initial velocity is not horizontal.

Evangelista Torricelli (1608-47), a disciple of Castelli and of Galileo, extended the latter's method to the case of a projectile whose initial velocity had a direction other than horizontal, and proved that the trajectory remained a parabola with a vertical axis. On the other hand Gassendi showed that in this problem of the motion of projectiles, the real law of inertia which had just been formulated by Descartes should be substituted for the principles admitted by the Parisian dynamics of the fourteenth century.

Mention should be made of Galileo's observations on the duration of the oscillation of the pendulum, as these observations opened up to dynamics a new field. Galileo's progress in dynamics served as a defence of the Copernican system and the discoveries which, with the aid of the telescope, he was able to make in the heavens contributed to the same end. The spots on the sun's surface and the mountains, similar to those upon the Earth, that hid from view certain portions of the lunar disc, gave ample proof of the fact that the celestial bodies were not, as Aristotelean physics had maintained, formed of an incorruptible substance unlike sublunary elements; moreover, the rôle of satellite which, in this heliocentric astronomy, the moon played in regard to the Earth was carried out in relation to Jupiter by the two "Medicean planets", which Galileo had been the first to discover. Not satisfied with having defeated the arguments opposed to the Copernican system by adducing these excellent reasons, Galileo was eager to establish a positive proof in favour of this system. Inspired perhaps by Calcagnini, he believed that the phenomenon of the tides would furnish him the desired proof and he consequently rejected every explanation of ebb and flow founded on the attraction of the sun and the moon, in order to attribute the motion of the seas to the centrifugal force produced by terrestrial rotation. Such an explanation would connect the period of high tide with the sidereal instead of the lunar day, thus contradicting the most ordinary and ancient observations. This remark alone ought to have held Galileo back and prevented him from producing an argument better calculated to overthrow the doctrine of the Earth's rotation than to establish and confirm it.

On two occasions, in 1616 and 1633, the Inquisition condemned what Galileo had written in favour of the system of Copernicus. The hypothesis of the Earth's motion was declared *falsa in Philosophia et ad minus erronea in fide*; the hypothesis of the sun being stationary was adjudged *falsa in Philosophia et formaliter hæretica*. Adopting the doctrine formulated by Tycho Brahe in 1578, the Holy Office forbade the use of all astronomical hypotheses that did not agree both with the principles of Aristotelean physics, and with the letter of the Sacred Scriptures.

Initial attempts in celestial mechanics -- Gilbert -- Kepler

Copernicus had endeavoured to describe accurately the motion of each of the celestial bodies, and Galileo had striven to show that the views of Copernicus were correct; but neither Copernicus nor Galileo had attempted to extend to the stars, what they knew concerning the dynamics of sublunary motions, or to determine thereby the forces that sustain celestial motions. They were satisfied with holding that the daily rotation of the Earth is perpetuated by virtue of an impetus given once for all; that the various parts of an element belonging to a star tend towards the centre of this star by reason of a gravity peculiar to each of the celestial bodies through which the body is enabled to preserve its entireness. Thus, in celestial mechanics, these two great scientists contributed scarcely anything to what had already been taught by Buridan, Oresme, and Nicholas of Cusa. About Galileo's time we notice the first attempts to constitute celestial mechanics, that is to say, to explain the motion of the stars by the aid of forces analogous to those the effects of which we feel upon earth; the most important of these initial attempts were made by William Gilbert (1540-1603), and Johann Kepler (1571-1631).

To Gilbert we are indebted for an exhaustive treatise on magnetism, in which he systematically incorporated what was known in medieval times of electrical and magnetic phenomena, without adding thereto anything very essential; he also gave the result of his own valuable experiments. It was in this treatise that he began to expound his "Magnetic Philosophy", that is to say his celestial mechanics, but the work in which he fully developed it was not published until 1651, long after his death. Like Oresme and Copernicus, Gilbert maintained that in each star there was a particular gravity through which the material parts belonging to this star, and these only, tended to rejoin the star when they had been separated from it. He compared this gravity, peculiar to each star, to the action by which a piece of iron flies towards the magnet whose nature it shares. This opinion, held by so many of Gilbert's predecessors and adopted by a great number of his imitators, led Francis Bacon astray. Bacon was the enthusiastic herald of the experimental method which, however, he never practised and of which he had an utterly false conception. According to Gilbert, the Earth, sun, and the stars were animated, and the animating principle of each communicated to the body the motion of perpetual rotation. From a distance, the sun exerted an action perpendicular to the radius vector which goes from the centre of the sun to a planet, and this action caused the planet to revolve around the sun just as a horse turns the horse-mill to which it is yoked.

Kepler himself admitted that in his first attempts along the line of celestial mechanics he was under the influence of Nicholas of Cusa and Gilbert. Inspired by the former of these authors, he attributed the Earth's rotation on its axis to an impetus communicated by the Creator at the beginning of time; but, under the influence of Gilbert's theory, he declared that this impetus ended by being transformed into a soul or an animating principle. In Kepler's earliest system, as in Gilbert's, the distant sun was said to exercise over each planet a power perpendicular to the radius vector, which power produced the circular motion of the planet. However, Kepler had the happy thought of submitting a universal attraction for the magnetic attraction that Gilbert had considered peculiar to each star. He assumed that every material mass tended towards every other material mass, no matter to what celestial body each one of them belonged; that a portion of matter placed between two stars would tend towards the larger and nearer one, although it might never have belonged to it; that, at the moment of high tide, the waters of the sea rose towards the moon, not because they had any special affinity for this humid star, but by virtue of the general tendency that draws all material masses towards one another.

In the course of numerous attempts to explain the motion of the stars, Kepler was led to complicate his first celestial mechanics. He assumed that all celestial bodies were plunged into an ethereal fluid, that the rotation of the sun engendered a vortex within this fluid the reactions of which interposed to deflect each planet from the circular path. He also thought that a certain power, similar to that which directs the magnetic needle, preserved invariable in space the direction of the axis around which the rotation of each planet is effected. The unstable and complicated system of celestial mechanics taught by Kepler sprang from very deficient dynamics which, on many points, was more akin to that of the Peripatetics than to that of the Parisians. However, these many vague hypotheses exerted an incontestable influence on the attempts of scientists from Kepler to Newton to determine the forces that move the stars. If, indeed, Kepler prepared the

way for Newton's work, it was mainly by the discovery of the three admirable laws that have immortalized his name; and, by teaching that the planets described ellipses instead of circles he produced in astronomy a revolution greater by far than that caused by Copernicus; he destroyed the last time-honoured principle of ancient physics, according to which all celestial motions were reducible to circular motion.

Controversies concerning geostatics

The "magnetic" philosophy adopted and developed by Gilbert was not only rejected by Kepler but badly abused in a dispute over the principles of statics. A number of the Parisian Scholastics of the fourteenth century, and Albert of Saxony in particular, had accepted the principle that in every body there is a fixed, determined point which tends to join the centre of the World, this point being identical with the centre of gravity as considered by Archimedes. From this principle various authors, notably Vinci, deduced corollaries that retained a place in statics. The Copernican revolution had modified this principle but little, having simply substituted, for the centre of the universe, a particular point in each star, towards which point tended the centre of gravity of each mass belonging to this star. Copernicus, Galileo, and Gilbert admitted the principle thus modified, but Kepler rejected it. In 1635 Jean de Beaugrand deduced from this principle a paradoxical theory on the gravity of bodies, and particularly on the variation in the weight of a body whose distance from the centre of the universe changes. Opinions similar to those proposed by Beaugrand in his geostatics were held in Italy by Castelli, and in France by Pierre Fermat (1608-65). Fermat's doctrine was discussed and refuted by Etienne Pascal (1588-1651) and Gilles Persone de Roberval (1602-75), and the admirable controversy between these authors and Fermat contributed in great measure to the clear exposition of a certain number of ideas employed in statics, amongst them, that of the centre of gravity. It was this controversy which led Descartes to revive the question of virtual displacements in precisely the same form as that adopted by the School of Jordanus, in order that the essential propositions of statics might be given a stable foundation. On the other hand, Torricelli based all his arguments concerning the laws of equilibrium on the axiom quoted above, viz.: a system endowed with weight is in equilibrium when the centre of gravity of all the bodies forming it is the lowest possible. Cardano and perhaps Vinci had derived this proposition from the doctrine of Albert of Saxony, but Torricelli was careful to use it only under circumstances in which all verticals are considered parallel to one another and, in this way he severed all connexion between the axiom that he admitted and the doubtful hypotheses of Parisian physics or magnetic philosophy. Thenceforth the principles of statics were formulated with accuracy, John Wallis (1616-1703), Pierre Varignon (1654-1722), and Jean Bernoulli (1667-1748) having merely to complete and develop the information provided by Stevinus, Roberval, Descartes, and Torricelli.

Descartes's work

We have just stated what part Descartes took in the building of statics by bringing forward the method of virtual displacements, but his active interest in the building up of dynamics was still more important. He clearly formulated the law of inertia as observed by Benedetti: every moving body is inclined, if nothing prevent it, to continue its motion in a straight line and with constant velocity; a body cannot move in a circle unless it be drawn towards the centre, by centripetal movement in opposition to the centrifugal force by which this body tends to fly away from the centre. Because of the similarity of the views held by Descartes and Benedetti concerning this law, we may conclude that Descartes's discovery was influenced by that of Benedetti, especially as Benedetti's works were known to Marin Mersenne (1588-1648), the faithful friend and correspondent of Descartes. Descartes connected the following truth with the law of inertia: a weight constant in size and direction causes a uniformly accelerated motion. Besides we have seen how, with the aid of Descartes's principles, Gassendi was able to rectify what Galileo had taught concerning falling bodies and the motion of projectiles.

In statics a heavy body can very often be replaced by a material point placed at its centre of gravity; but in dynamics the question arises whether the motion of a body be treated as if this body were entirely concentrated in one of these points, and also which point this is? This question relative to the existence and finding of a centre of impulsion had already engrossed the attention of Vinci and after him, of Bernardino Baldi (1553-1617). Baldi asserted that, in a body undergoing a motion of translation, the centre of impulsion does not differ from the centre of gravity. Now, is there a centre of impulsion and, if so, where is it to be found in a body undergoing a motion other than that of translation, for instance, by a rotation around an axis? In other words, is there a simple pendulum that moves in the same way as a given compound pendulum? Inspired, no doubt, by reading Baldi, Mersenne laid this problem before Roberval and Descartes,

both of whom made great efforts to solve it but became unfriendly to each other because of the difference in their respective propositions. Of the two, Descartes came nearer to the truth, but the dynamic principles that he used were not sufficiently accurate to justify his opinion in a convincing manner; the glory was reserved to Christian Huygens.

The Jesuits, who at the College of La Flèche had been the preceptors of Mersenne and Descartes, did not teach Peripatetic physics in its stereotyped integrity, but Parisian physics; the treatise that guided the instruction imparted at this institution being represented by the "Commentaries" on Aristotle, published by the Jesuits of Coimbra at the close of the seventeenth century. Hence it can be understood why the dynamics of Descartes had many points in common with the dynamics of Buridan and the Parisians. Indeed, so close were the relations between Parisian and Cartesian physics that certain professors at La Flèche, such as Etienne Noël (1581-1660), became Cartesians. Other Jesuits attempted to build up a sort of a combination of Galilean and Cartesian mechanics with the mechanics taught by Parisian Scholasticism, and foremost among these men must be mentioned Honoré Fabri (1606-88), a friend of Mersenne.

In every moving body Descartes maintained the existence of a certain power to continue its motion in the same direction and with the same velocity and this power, which he called the quantity of motion, he measured by estimating the product of the mass of the moving body by the velocity that impels it. The affinity is close between the rôle which Descartes attributed to this quantity of motion, and that which Buridan ascribed to impetus. Fabri was fully aware of this analogy and the momentum that he discussed was at once the impetus of the Parisians, and Descartes's quantity of motion. In statics he identified this momentum with what Galileo called *momento* or *impeto*, and this identification was certainly conformable to the Pisan's idea. Fabri's synthesis was well adapted to make this truth clear, that modern dynamics, the foundations of which were laid by Descartes and Galileo, proceeded almost directly from the dynamics taught during the fourteenth century in the University of Paris.

If the special physical truths demonstrated or anticipated by Descartes were easily traceable to the philosophy of the fourteenth century, the principles on which the great geometrician wished to base these truths were absolutely incompatible with this philosophy. In fact, denying that in reality there existed anything qualitative, Descartes insisted that matter be reduced to extension and to the attributes of which extension seemed to him susceptible, namely, numerical proportions and motion; and it was by combinations of different figures and motions that all the effects of physics could be explained according to his liking. Therefore the power by virtue of which a body tends to preserve the direction and velocity of its motion is not a quality distinct from motion, such as the impetus recognized by the scholastics; it is nothing else than the motion itself as was taught by William of Occam at the beginning of the fourteenth century. A body in motion and isolated would always retain the same quantity of motion, but there is no isolated body in a vacuum, because matter being identical with extension, vacuum is inconceivable, as is also compressibility. The only conceivable motions are those which can be produced in the midst of incompressible matter, that is to say, vortical motions confined within their own bulk.

In these motions bodies drive one another from the place they have occupied and, in such a transmission of motion, the quantity of motion of each of these bodies varies; however, the entire quantity of motion of all the bodies that impinge on one another remains constant, as God always maintains the same sum total of motion in the world. This transmission of motion by impact is the only action that bodies can exert over one another and in Cartesian, as well as in Aristotelean physics, a body cannot put another in motion unless it touch it, immediate action at a distance being beyond conception.

There are various species of matter, differing from one another only in the size and shape of the contiguous particles of which they are formed. The space that extends between the different heavenly bodies is filled with a certain subtile matter, the very fine particles of which easily penetrate the interstices left between the coarser constituents of other bodies. The properties of subtile matter play an important part in all Cartesian cosmology. The vortices in which subtile matter moves, and the pressure generated by these vortical motions, serve to explain all celestial phenomena. Leibniz was right in supposing that for this part of his work Descartes had drawn largely upon Kepler. Descartes also strove to explain, with the aid of the figures and motions of subtile and other matter, the different effects observable in physics, particularly the properties of the magnet and of light. Light is identical with the pressure which subtile matter exerts over bodies and, as subtile matter is incompressible, light is instantly transmitted to any distance, however great.

The suppositions by the aid of which Descartes attempted to reduce all physical phenomena to combinations of figures and motions had scarcely any part in the discoveries that he made in physics; therefore the identification of light with the pressure exerted by subtile matter plays no part in the invention of the new truths which Descartes taught in optics.

Foremost amongst these truths is the law of the refraction of light passing from one medium to another, although the question still remains whether Descartes discovered this law himself, or whether, as Huygens accused him of doing, he borrowed it from Willebrord Snellius (1591-1626), without any mention of the real author. By this law Descartes gave the theory of refraction through a prism, which permitted him to measure the indices of refraction; moreover, he greatly perfected the study of lenses, and finally completed the explanation of the rainbow, no progress having been made along this line from the year 1300, when Thierry of Freiberg had given his treatise on it. However, the reason why the rays emerging from the drops of water are variously coloured was no better known by Descartes than by Aristotle; it remained for Newton to make the discovery.

Progress of experimental physics

Even in Descartes's work the discoveries in physics were almost independent of Cartesianism. The knowledge of natural truths continued to advance without the influence of this system and, at times, even in opposition to it, although those to whom this progress was due were often Cartesians. This advancement was largely the result of a more frequent and skilful use of the experimental method. The art of making logically connected experiments and of deducing their consequences is indeed very ancient; in a way the works produced by this art were no more perfect than the researches of Pierre of Maricourt on the magnet or Thierry of Freiberg on the rainbow. However, if the art remained the same, its technic continued to improve; more skilled workmen and more powerful processes furnishing physicists with more intricate and better made instruments, and thus rendering possible more delicate experiments. The rather imperfect tests made by Galileo and Mersenne in endeavouring to determine the specific weight of air mark the beginning of the development of the experimental method, which was at once vigorously pushed forward by discussions in regard to vacuum.

In Peripatetic physics the possibility of an empty space was a logical contradiction; but, after the condemnation pronounced at Paris in 1277 by Tempier, the existence of a vacuum ceased to be considered absurd. It was simply taught as a fact that the powers of nature are so constructed as to oppose the production of an empty space. Of the various conjectures proposed concerning the forces which prevent the appearance of a vacuum, the most sensible and, it would seem, the most generally received among sixteenth-century Parisians, was the following: contiguous bodies adhere to one another, and this adhesion is maintained by forces resembling those by which a piece of iron adheres to the magnet which it touches. In naming this force *horror vacui*, there was no intention of considering the bodies as animate beings. A heavy piece of iron detaches itself from the magnet that should hold it up, its weight having conquered the force by which the magnet retained it; in the same way, the weight of too heavy a body can prevent the *horror vacui* from raising this body. This very logical corollary of the hypothesis we have just mentioned was formulated by Galileo, who saw therein the explanation of a fact well-known to the cistern makers of his time; namely, that a suction-pump could not raise water higher than thirty-two feet. This corollary entailed the possibility of producing an empty space, a fact known to Torricelli who, in 1644, made the celebrated experiment with mercury that was destined to immortalize his name. However, at the same time, he anticipated a new explanation of this experiment; the mercury is supported in the tube not by the *horror vacui* that does not exist, but by the pressure which the heavy air exerts on the exterior surface of the basin.

Toricelli's experiment quickly attracted the attention of physicists. In France, thanks to Mersenne, it called forth on his part, and on that of those who had dealings with him, many experiments in which Roberval and Pascal (1623-62) vied with each other in ingenuity, and in order to have the resources of technic more easily at his disposal, Pascal made his startling experiments in a glass factory at Rouen. Among the numerous inquirers interested in Torricelli's experiment some accepted the explanation offered by the "column of air", and advanced by the great Italian geometrician himself; whereas others, such as Roberval, held to the ancient hypothesis of an attraction analogous to magnetic action. At length, with a view to settling the difference, an experiment was made which consisted in measuring at what height the mercury remained suspended in Torricelli's tube; observing it first of all at the foot of a mountain and then at its summit. The idea of this experiment seemed to have suggested itself to several physicists, notably Mersenne, Descartes, and Pascal and through the instrumentality of the last named and the courtesy of Périer, his brother-in-law, it was made between the base and summit of Puy-de-Dôme, 19 Sept., 1648. The "Traité de l'équilibre de liqueurs et de la pesanteur de la masse de l'air", which Pascal subsequently composed, is justly cited as a model of the art of logically connected experiments with deductions. Between atomists and Cartesians there were many discussions as to whether the upper part of Torricelli's tube was really empty or filled with subtile matter; but these discussions bore little fruit. However, fortunately for physics, the

experimental method so accurately followed by Torricelli, Pascal, and their rivals continued to progress.

Otto von Guericke (1602-86) seems to have preceded Torricelli in the production of an empty space, since, between 1632 and 1638, he appears to have constructed his first pneumatic machine, with the aid of which instrument he made in 1654 the celebrated Magdeburg experiments, published in 1657 by his friend Caspar Schoot, S.J. (1608-60). Informed by Schoot of Guericke's researches, Robert Boyle (1627-91) perfected the pneumatic machine and, assisted by Richard Townley, his pupil, pursued the experiments that made known the law of the compressibility of perfect gases. In France these experiments were taken up and followed by Mariotte (1620-84). The use of the dilatation of a fluid for showing the changes of temperature was already known to Galileo, but it is uncertain whether the thermoscope was invented by Galileo or by some one of the numerous physicists to whom the priority is attributed, among these being Santorio, called Sanctorius (1560-1636), Fra Paolo Sarpi (1552-1623), Cornelis van Drebbel (1572-1634), and Robert Fludd (1574-1637). Although the various thermoscopes for air or liquid used in the very beginning admitted of only arbitrary graduation, they nevertheless served to indicate the constancy of the temperature or the direction of its variations, and consequently contributed to the discovery of a number of the laws of physics. Hence this apparatus was used in the Accademia del Cimento, opened at Florence 19 June, 1657, and devoted to the study of experimental physics. To the members of this academy we are especially indebted for the demonstration of the constancy of the point of fusion of ice and of the absorption of heat accompanying this fusion. Observations of this kind, made by means of the thermoscope, created an ardent desire for the transformation of this apparatus into a thermometer, by the aid of a definite graduation so arranged that everywhere instruments could be made which would be comparable with one another. This problem, one of the most important in physics, was not solved until 1702 when Guillaume Amontons (1663-1705) worked it out in the most remarkable manner. Amontons took as a starting-point these two laws discovered or verified by him the boiling point of water under atmospheric pressure is constant. The pressures sustained by any two masses of air, heated in the same way in any two constant volumes, have a relation independent of the temperature. These two laws enabled Amontons to use the air thermometer under constant volume and to graduate it in such a way that it gave what we today call absolute temperature. Of all the definitions of the degree of temperature given since Amontons's time, he, at the first stroke, found the most perfect. Equipped with instruments capable of measuring pressure and registering temperature, experimental physics could not but make rapid progress, this being still further augmented by reason of the interest shown by the learned societies that had been recently founded. The Accademia del Cimento was discontinued in 1667, but the Royal Society of London had begun its sessions in 1663 and the Académie des Sciences at Paris was founded or rather organized by Colbert in 1666. These different academies immediately became the enthusiastic centres of scientific research in regard to natural phenomena.

Undulatory theory of light

It was to the Académie des Sciences of Paris that, in 1678, Christian Huygens (1629-95) presented his "Treatise on Light". According to the Cartesian system, light was instantly transmitted to any distance through the medium of incompressible subtile matter. Descartes did not hesitate to assure Fermat that his entire philosophy would give way as soon as it should be demonstrated that light is propagated with a limited velocity. In 1675 Ole Rømer (1644-1710), the Danish astronomer, announced to the Académie des Sciences the extent of the considerable but finite velocity with which light traverses the space that separates the planets from one another, the study of the eclipses of Jupiter's satellites having brought him to this conclusion. Descartes's optical theory was destroyed, and Huygens undertook to build up a new theory of light. He was constantly guided by the supposition that, in the midst of compressible ether, substituted for incompressible subtile matter, light is propagated by waves exactly similar to those which transmit sound through a gaseous medium. This comparison led him to an explanation, which is still the standard one, of the laws of reflection and refraction. In this explanation the index of the refraction of light passing from one medium to another equals the ratio of the velocity of propagation in the first medium to the velocity of propagation in the second. In 1850 this fundamental law was confirmed by Foucault's experiments.

However, Huygens did not stop here. In 1669 Erasmus Berthelsen, known as Bartholinus (1625-98), discovered the double refraction of Iceland spar. By a generalization, as ingenious as it was daring, of the theory he had given for non-crystallized media, Huygens succeeded in tracing the form of the surface of a luminous wave inside of a crystal such as spar or quartz, and in defining the apparently complex laws of the double refraction of light in the interior of these crystals. At the same time, he called attention to the phenomena of polarization which accompany this double refraction;

he was, however, unable to draw from his optical theory the explanation of these effects. The comparison between light and sound caused Malebranche (1638-1715) to make some very effective conjectures in 1699. He assumed that light is a vibratory motion analogous to that produced by sound; the greater or less amplitude of this motion, as the case may be, generates a greater or less intensity but, whilst in sound each period corresponds to a particular note, in light it corresponds to a particular colour. Through this analogy Malebranche arrived at the idea of monochromatic light, which Newton was to deduce from admirably conducted experiments; moreover, he established between simple colour and the period of the vibration of light, the connexion that was to be preserved in the optics of Young and Fresnel.

Developments of dynamics

Both Cartesians and atomists maintained that impact was the only process by which bodies could put one another in motion; hence, to Cartesians and atomists, the theory of impact seemed like the first chapter of rational physics. This theory had already enlisted the attention of Galileo, Marcus Marci (1639), and Descartes when, in 1668, the Royal Society of London proposed it as the subject of a competition and, of the three important memoirs submitted to the criticism of this society by John Wallis, Christopher Wren (1632-1723), and Huygens, the last is the only one that we can consider. In his treatise Huygens adopted the following principle: if a material body, subject merely to the action of gravity, starts from a certain position, with initial velocity equal to zero, the centre of gravity of this body can at no time rise higher than it was at the outset of the motion. Huygens justified this principle by observing that, if it were false, perpetual motion would be possible. To find the origin of this axiom it would be necessary to go back to "De Subtilitate" by Cardano, who had probably drawn it from the notes of Vinci; the proposition on which Torricelli had based his statics was a corollary from this postulate. By maintaining the accuracy of this postulate, even in the case where parts of the system clash; by combining it with the law of the accelerated fall of bodies, taken from Galileo's works, and with another postulate on the relativity of motion, Huygens arrived at the law of the impact of hard bodies. He showed that the quantity the value of which remains constant in spite of this impact is not, as Descartes declared, the total quantity of motion, but that which Leibniz called the quantity of *vis viva* (living force).

The axiom that had so happily served Huygens in the study of the impact of bodies he now extended to a body oscillating around a horizontal axis and his "Horologium oscillatorium", which appeared in 1673, solved in the most elegant and complete manner the problem of the centres of oscillation previously handled by Descartes and Roberval. That Huygens's axiom was the subversion of Cartesian dynamics was shown by Leibniz in 1686. If, like Descartes, we measure the efficiency of a force by the work that it does, and if, moreover, we admit Huygens's axiom and the law of falling bodies, we find that this efficiency is not measured by the increase in the quantity of motion of the moving body, but by the increase in half the product of the mass of the moving body and the square of its velocity. It was this product that Leibniz called *vis viva*. Huygens's "Horologium oscillatorium" not only gave the solution of the problem of the centre of oscillation but likewise a statement of the laws which, in circular motion, govern the magnitude of centrifugal force, and thus it was that the eminent physicist prepared the way for Newton, the lawgiver of dynamics.

Newton's work

Most of the great dynamical truths had been discovered between the time of Galileo and Descartes, and that of Huygens and Leibniz. The science of dynamics required a Euclid who would organize it as geometry had been organized, and this Euclid appeared in the person of Isaac Newton (1642-1727) who, in his "Philosophiæ naturalis principia mathematica", published in 1687, succeeded in deducing the entire science of motion from three postulates: inertia; the independence of the effects of previously acquired forces and motions; and the equality of action and reaction. Had Newton's "Principia" contained nothing more than this co-ordination of dynamics into a logical system, they would nevertheless have been one of the most important works ever written; but, in addition, they gave the grandest possible application of this dynamics in utilizing it for the establishment of celestial mechanics. In fact, Newton succeeded in showing that the laws of bodies falling to the surface of the earth, the laws that preside over the motion of planets around the sun, and of satellites around the planets which they accompany, finally, the laws that govern the form of the Earth and of the other stars, as also the high and low tides of the sea, are but so many corollaries from this unique hypothesis: two bodies, whatever their origin or nature, exert over each other an attraction proportional to the product of their masses and in inverse ratio to the square of the distance that separates them.

The dominating principle of ancient physics declared the essential distinction between the laws that directed the motions of the stars -- beings exempt from generation, change, and death -- and the laws presiding over the motions of sublunary bodies subject to generation and corruption. From the birth of Christian physics and especially from the end of the thirteenth century, physicists had been endeavouring to destroy the authority of this principle and to render the celestial and sublunary worlds subject to the same laws the doctrine of universal gravitation being the outcome of this prolonged effort. In proportion as the time approached, when Newton was to produce his system, attempts at cosmology were multiplied, so many forerunners, as it were, of this discovery. When in 1672 Guericke again took up Kepler's celestial mechanics, he made but one correction therein, which unfortunately caused the disappearance of the only proposition by which this work led up to Newton's discoveries. Kepler had maintained that two material masses of any kind attract each other, but, in imitation of Copernicus, Gilbert, and Galileo, Guericke limited this mutual attraction to parts of the same star, so that, far from being attracted by the Earth, portions of the moon would be repelled by the Earth if placed upon its surface. But, in 1644, under the pseudonym of Aristarchus of Samos, Roberval published a system of celestial mechanics, in which the attraction was perhaps mutual between two masses of no matter what kind; in which, at all events, the Earth and Jupiter attracted their satellites with a power identical with the gravity with which they endow their own fragments. In 1665, on the pretence of explaining the motions of Jupiter's satellites, Giovanni Alfonso Borelli (1608-79) tried to advance a theory which simultaneously comprised the motions of the planets around the sun and of the satellites around the planets. He was the first of modern scientists (Plutarch having preceded him) to hold the opinion that the attraction which causes a planet to tend towards the sun and a satellite to tend towards the star which it accompanies, is in equilibrium with the centrifugal force produced by the circular motion of the planet or satellite in question. In 1674 Robert Hooke (1635-1702) formulated the same idea with great precision. Having already supposed the attraction of two masses to vary inversely as the square of their distance, he was in possession of the fundamental hypotheses of the theory of universal gravitation, which hypotheses were held by Wren about the same time. However, neither of these scientists was able to deduce therefrom celestial mechanics, as both were still unacquainted with the laws of centrifugal force, published just at this time by Huygens. In 1684 Edmund Halley (1656-1742) strove to combine Huygens's theories with Hooke's hypotheses, but, before his work was finished, Newton presented his "Principia" to the Royal Society, having for twenty years silently pursued his meditations on the system of the world. Halley, who could not forestall Newton, had the glory of broadening the domain of universal gravitation by making it include comets (1705).

Not satisfied with creating celestial mechanics, Newton also contributed largely to the progress of optics. From ancient times the colouring of the spectrum, produced by the passage of white light through a glass prism, had elicited the wonder of observers and appealed to the acumen of physicists without, however, being satisfactorily explained. Finally, a complete explanation was given by Newton who, in creating a theory of colours, accomplished what all the philosophers from Aristotle down had laboured in vain to achieve. The theory advanced by the English physicist agreed with that proposed by Malebranche at the same time. However, Malebranche's theory was nothing more than a hypothesis suggested by the analogy between light and sound, whereas Newton's explanation was drawn from experiments, as simple as they were ingenious, its exposition by the author being one of the most beautiful examples of experimental induction. Unfortunately Newton disregarded this analogy between sound and light that had furnished Huygens and Malebranche with such fruitful discoveries. Newton's opinion was to the effect that light is formed of infinitely small projectiles thrown off with extreme velocity by incandescent bodies. The particles of the medium in which these projectiles move exert over them an attraction similar to universal attraction; however, this new attraction does not vary inversely as the square of the distance but according to another function of the distance, and in such a way that it exercises a very great power between a material particle and a luminous corpuscle that are contiguous. Nevertheless this attraction becomes altogether insensible as soon as the two masses between which it operates are separated from each other by a perceptible interval.

This action exerted by the particles of a medium on the luminous corpuscles pervading them changes the velocity with which these bodies move and the direction which they follow at the moment of passing from one medium to another; hence the phenomenon of refraction. The index of refraction is the ratio of the velocity of light in the medium which it enters, to the velocity it had in the medium which it leaves. Now, as the index of refraction so understood was precisely the reverse of that attributed to it by Huygens's theory, in 1850 Foucault submitted both to the test of experiment, with the result that Newton's theory of emission was condemned. Newton explained the experimental laws that govern the colouring of thin laminæ, such as soap bubbles, and succeeded in compelling these colours, by suitable forms of these thin laminæ, to assume the regular order known as "Newton's Rings". To explain this phenomenon he conceived that luminous projectiles have a form that may, at the surface of contact of two media, either pass easily or be easily reflected, according to the manner of their presentation at the moment of passage; a rotary motion causes them to pass alternately

by "fits of easy transmission or of easy reflection".

Newton thought that he had accounted for the principal optical phenomena by supposing that, besides this universal attraction, there existed an attraction, sensible only at a very short distance, exerted by the particles of bodies on luminous corpuscles, and naturally he came to believe that these two kinds of attraction would suffice to explain all physical phenomena. Action extending to a considerable distance, such as electric and magnetic action, must follow laws analogous to those which govern universal gravity; on the other hand, the effects of capillarity and cohesion, chemical decomposition and reaction must depend on molecular attraction extending only to extremely small distances and similar to that exerted over luminous corpuscles. This comprehensive hypothesis proposed by Newton in a "question" placed at the end of the second edition of his "Optics" (1717) gave a sort of outline of the programme which eighteenth-century physics was to attempt to carry out.

Progress of general and celestial mechanics in the eighteenth century

This programme made three demands: first, that general mechanics and celestial mechanics advance in the way indicated by Newton; secondly, that electric and magnetic phenomena be explained by a theory analogous to that of universal gravitation; thirdly, that molecular attraction furnish the detailed explanations of the various changes investigated by physics and chemistry.

Many followed in the path outlined by Newton and tried to extend the domain of general and celestial mechanics, but there were three who seem to have surpassed all the others: Alexis-Claude Clairaut (1713-65), Jean-Baptiste gRond d'Alembert (1717-83), and Leonhard Euler (1707-83). The progress which, thanks to these three able men, was made in general mechanics, may be summed up as follows: In 1743, by his principle of the equilibrium of channels, which was easily connected with the principle of virtual displacements, Clairaut obtained the general equations of the equilibrium of liquids. In the same year d'Alembert formulated a rule whereby all problems of motion were reduced to problems of equilibrium and, in 1744, applied this rule to the equation of hydrostatics given by Clairaut and arrived at the equations of hydrodynamics. Euler transformed these equations and, in his studies on the motion of liquids, was enabled to obtain results no less important than those which he had obtained by analysing the motion of solids. Clairaut extended the consequences of universal attraction in all directions, and, in 1743, the equations of hydrostatics that he had established enabled him to perfect the theory of the figure of the earth. In 1752 he published his theory of lunar inequalities, which he had at first despaired of accounting for by Newton's principles. The methods that he devised for the study of the perturbations which the planets produce on the path of a star permitted him, in 1758, to announce with accuracy the time of the return of Halley's Comet. The confirmation of this prediction in which Clairaut had received assistance from Lalande (1732-1807) and Mme. Lepaute, both able mathematicians, placed beyond doubt the applicability of Newton's hypotheses to comets.

Great as were Clairaut's achievements in perfecting the system of universal attraction, they were not as important as those of d'Alembert. Newton could not deduce from his suppositions a satisfactory theory of the precession of the equinoxes, and this failure marred the harmony of the doctrine of universal gravitation. In 1749 d'Alembert deduced from the hypothesis of gravitation the explanation of the precession of the equinoxes and of the nutation of the earth's axis; and soon afterwards Euler, drawing upon the admirable resources of his mathematical genius, made still further improvements on d'Alembert's discovery. Clairaut, d'Alembert, and Euler were the most brilliant stars in an entire constellation of mechanical theorists and astronomers, and to this group there succeeded another, in which shone two men of surpassing intellectuality, Joseph-Louis Lagrange (1736-1813) and Pierre-Simon Laplace (1749-1827). Laplace was said to have been born to complete celestial mechanics, if, indeed, it were in the nature of a science to admit of completion; and quite as much could be said of Lagrange with regard to general mechanics. In 1787 Lagrange published the first edition of his "Mécanique analytique"; the second, which was greatly enlarged, was published after the author's death. Laplace's "Mécanique céleste" was published from 1799 to 1805, and both of these works give an account of the greater part of the mechanical conquests made in the course of the eighteenth century, with the assistance of the principles that Newton had assigned to general mechanics and the laws that he had imposed upon universal gravitation. However exhaustive and effective these two treatises are, they do not by any means include all the discoveries in general and celestial mechanics for which we are indebted to their authors. To do Lagrange even meagre justice his able researches should be placed on a

par with his "Mécanique analytique"; and our idea of Laplace's work would be very incomplete were we to omit the grand cosmogonic hypothesis with which, in 1796, he crowned his "Exposition du système du monde". In developing this hypothesis the illustrious geometrician was unaware that in 1755 Kant had expressed similar suppositions which were marred by serious errors in dynamic theories.

Establishment of the theory of electricity and magnetism

For a long time the study of electric action was merely superficial and, in the beginning of the eighteenth century, it was still in the condition in which Thales of Miletus had left it, remaining far from the point to which the study of magnetic attraction and repulsion had been carried in the time of Pierre of Maricourt. When, in 1733 and 1734, Charles-François de Cisternay du Fay distinguished two kinds of electricity, resinous and vitreous, and when he proved that bodies charged with the same kind of electricity repel one another, whereas those charged with different kinds attract one another, electrical science was brought up to the level that magnetic science had long before attained, and thenceforth these two sciences, united by the closest analogy, progressed side by side. They advanced rapidly as, in the eighteenth century, the study of electrical phenomena became a popular craze. Physicists were not the only ones devoted to it; men of the world crowded the salons where popularizers of the science, such as the Abbé Nollet (1700-70), enlisted as votaries dandified marquesses and sprightly marchionesses. Numberless experimentalists applied themselves to multiplying observations on electricity and magnetism, but we shall restrict ourselves to mentioning Benjamin Franklin (1706-90) who, by his logically-conducted researches, contributed more than any other man to the formation of the theories of electricity and magnetism. The researches of Henry Cavendish (1731-1810) deserve to be placed in the same rank as Franklin's, though they were but little known before his death.

By means of Franklin's experiments and his own, Æpinus (Franz Ulrich Theodor Hoch, 1724-1802) was the first to attempt to solve the problem suggested by Newton and, by the hypothesis of attractive and repellent forces, to explain the distribution of electricity and magnetism over the bodies which they affect. His researches could not be pushed very far, as it was still unknown that these forces depend upon the distance at which they are exerted. Moreover, Æpinus succeeded in drawing still closer the connexion already established between the sciences of electricity and magnetism, by showing the polarization of each of the elements of the insulating plate which separates the two collecting plates of the condenser. The experiment he made in this line in 1759 was destined to suggest to Coulomb the experiment of the broken magnets and the theory of magnetic polarization, which is the foundation of the study of magnets; and was also to be the starting-point of an entire branch of electrical science, namely the study of dielectric bodies, which study was developed in the nineteenth century by Michael Faraday and James Clerk-Maxwell.

Their analogy to the fertile law of universal gravitation undoubtedly led physicists to suppose that electrical and magnetic forces vary inversely as the square of the distance that separates the acting elements; but, so far, this opinion had not been confirmed by experiment. However, in 1780 it received this confirmation from Charles-Augustin de Coulomb with the aid of the torsion balance. By the use of this balance and the proof plane, he was enabled to make detailed experiments on the subject of the distribution of electricity over conductive bodies, no such tests having been previously made. Although Coulomb's experiments placed beyond doubt the elementary laws of electricity and magnetism, it still remained to be established by mathematical analysis how electricity was distributed over the surface of conductive bodies of given shape, and how a piece of soft iron was magnetized under given circumstances. The solution of these problems was attempted by Coulomb and also in 1787 by Haüy, but neither of these two savants pushed his tests very far. The establishment of principles which would permit of an analysis of the distribution of electricity on conductors, and of magnetism on soft iron, required the genius of Simon-Denis Poisson (1781-1840).

In 1812 Poisson showed how the investigation of the distribution of electricity in equilibrium on conductors belonged to the domain of analysis, and he gave a complete solution of this problem in the case of two conductive spheres influencing each other, whether placed at given distances or in contact. Coulomb's experiments in connexion with contiguous spheres established the truth of Poisson's theory. In 1824 Poisson established on the subject of hollow conductors limited either interiorly or exteriorly by a spherical cavity, theorems which, in 1828, were extended by George Green (1793-1841) to all kinds of hollow conductors and which Faraday was subsequently to confirm through experimentation. Between 1813 and 1824 Poisson took up the study of magnetic forces and magnetization by impulsion and, in spite of a few inaccuracies which the future was to correct, the formulæ which he established remain at the basis of all the research of which

magnetism has meanwhile been the object. Thanks to Poisson's memoirs, the theory of the forces exercised in inverse ratio to the square of the distance, by annexing the domain of static electricity and magnetism, markedly enlarged the field which at first included only celestial mechanics. The study of the action of the electric current was to open up to this theory a new and fertile territory.

The discoveries of Aloisio Galvani (1737-98) and Alessandro Volta (1745-1827) enriched physics with the voltaic battery. It would be impossible to enumerate, even briefly, the researches occasioned by this discovery. All physicists have compared the conductor, the seat of a current, to a space in which a fluid circulates. In his works on hydrodynamics Euler had established general formulæ which apply to the motion of all fluids and, imitating Euler's method, Jean-Baptiste-Joseph Fourier (1768-1830) began the study of the circulation of heat-then considered a fluid and called caloric-within conductive bodies. The mathematical laws to which he had recourse once more showed the extreme importance of the mathematical methods inaugurated by Lagrange and Laplace in the study of universal attraction, and at the same time extended by Poisson to the study of electrostatics. In order to treat mathematically of the circulation of electric fluid in the interior of conductive bodies, it sufficed to take up Fourier's analysis almost textually, substituting the word electricity for the word heat, this being done in 1827 by Georg Simon Ohm (1789-1854).

Meanwhile on 21 July, 1820, Hans Christian Oersted (1777-1851) had discovered the action of the electric current on the magnetic needle. To this discovery André-Marie Ampère (1775-1836) added that of the action exerted over each other by two conductors carrying electric currents and, to the study of electro-dynamic and electro-magnetic forces, he applied a method similar to that used by Newton when studying universal attraction. In 1826 Ampère gave the complete theory of all these forces in his "Mémoire sur la théorie mathématique des phénomènes électro-dynamiques uniquement déduite de l'expérience", a work that can stand the test of comparison with the "Philosophiæ naturalis principia mathematica" and not be found wanting.

Not wishing to carry the history of electricity and magnetism beyond this date, we shall content ourselves with making another comparison between the two works we have just mentioned. As Newton's treatise brought about numerous discoveries on the part of his successors, Ampère's memoir gave the initial impetus to researches which have greatly broadened the field of electro-dynamics and electro-magnetism. Michael Faraday (1791-1867), an experimentalist whose activity, skill, and good fortune have perhaps never been equalled, established in 1831 the experimental laws of electro-dynamic and electro-magnetic induction, and, between 1845 and 1847, Franz Ernst Neumann (1798-1895) and Wilhelm Weber (1804-91), by closely following Ampère's method of studying electro-dynamic force, finally established the mathematical theory of these phenomena of induction. Michael Faraday was opposed to Newtonian doctrines, and highly disapproved the theory of action at a distance; in fact, when he applied himself to analysing the polarization of insulated media, which he called dielectrics, he hoped to eliminate the hypothesis of such action. Meantime by extending to dielectric bodies the formulæ that Poisson, Ampère, and Neumann had established for magnets and conductive bodies, James Clerk-Maxwell (1831-79) was enabled to create a new branch of electro-dynamics, and thereby bring to light the long-sought link connecting the sciences of electricity and optics. This wonderful discovery was not one of the least important conquests of the method defined and practised by Newton.

Molecular attraction

While universal attraction, which varies proportionally as the product of the masses and inversely as the square of the distance, was being established throughout the science of astronomy, and while, thanks to the study of other forces also varying inversely as the square of the distance, electricity and magnetism were being organized, other parts of physics received no less light from another Newtonian hypothesis, namely, the supposition that, between two material particles, there is an attraction distinct from universal attraction and extremely powerful, while the two particles are contiguous, but ceasing to be appreciable as soon as the two masses which it acts upon are separated by a sensible distance. Among the phenomena to be explained by such attractions, Newton had already signaled the effect of capillarity in connexion with which Francis Hauksbee (d. 1705) had made interesting experiments. In 1718 James Jurin (1684-1750) tried to follow Newton's idea but without any marked success, and it was Clairaut who, in 1743, showed how hydrostatic methods permitted the application of this idea to the explanation of capillary phenomena. Unfortunately his able reasoning led to no important result, as he had ascribed too great a value to the extent of molecular action.

Chemical action also was one of the actions which Newton made subject to molecular attraction, and John Keill (1671-

1721), John Freind (1675-1728), and Pierre-Joseph Macquer (1718-84) believed in the fruitfulness of this Newtonian opinion. The hypothesis of molecular attraction proved a great annoyance to a man whose scientific mediocrity had not prevented him from acquiring great influence, we mean Georges-Louis-Leclerc de Buffon (1707-88). Incapable of understanding that an attraction could be other than inversely proportional to the square of the distance, Buffon entered into a discussion of the subject with Clairaut, and fondly imagined that he had triumphed over the modest learning of his opponent. Ruggiero Giuseppe Boscovich, S.J.* (1711-87), published a detailed exposition of the views attacked by Buffon and defended by Clairaut, and, inspired alike by the opinions of Newton and Leibniz, he conceived a cosmology in which the universe is composed solely of material points, these being attracted to each other in pairs. When these points are separated by a sensible distance, their attraction is reduced to mere universal attraction, whereas when they are in very close proximity it assumes a dominant importance. Boscovich's cosmology provided physical theory with a programme which the geometers of the eighteenth century, and of a great portion of the nineteenth, laboured assiduously to carry out.

The efforts of Johann Andreas von Segner (1704-77), and subsequently of Thomas Young (1773-1829) again drew attention to capillary phenomena, and with the assistance of the hypothesis of molecular attraction, as also of Clairaut's method Laplace advanced in 1806 and 1807 an admirable theory which Karl Friedrich Gauss (1777-1855) improved in 1829. Being a thoroughly-convinced partisan of Boscovich's cosmological doctrine, Laplace communicated his convictions to numerous geometers, who surrendered to the ascendancy of his genius; we shall only mention Claude-Louis-Marie Navier (1785-1836), Poisson, and Augustin Cauchy (1789-1857). In developing the consequences of the hypothesis of molecular attraction Navier, Poisson, and Cauchy succeeded in building up the theory of the equilibrium and small motions of elastic bodies, one of the finest and most fruitful theories of modern physics. The discredit into which the progress of present-day thermodynamics has brought Boscovich's cosmology has, however, affected scarcely anything of what Laplace, Gauss, Navier, Poisson, Cauchy, and many others have deduced from the principles of this cosmology. The theories which they established have always been readily justified with the assistance of new methods, the way of bringing about this justification having been indicated by Cauchy himself and George Green. After Macquer, many chemists used the hypothesis of molecular attraction in an attempt to disentangle the laws of reaction which they studied, and among these scientists we may mention Torbern Bergman (1735-1784), and above all Claude-Louis Berthollet (1784-1822). When the latter published his "Statique chimique" in 1803, he believed that the science of chemical equilibria, subject at last to Newton's method, had found its true direction; however, it was not to enter upon this direction until much later on, when it would be guided by precepts altogether different and which were to be formulated by thermodynamics.

Revival of the undulatory theory of light

The emission theory of light not only led Newton to conceive the hypothesis of molecular attraction, but seemed to provide this hypothesis with an opportunity for further success by permitting Laplace to find, in the emission system, the laws of the double refraction of Iceland spar, which laws Huygens had discovered by the use of the undulatory theory. In this way Newton's optics appeared to rob Huygens's optics of the one advantage in which it glorified. However, at the very moment that Laplace's discovery seemed to ensure the triumph of the emission system, the undulatory theory carried off new and dazzling victories, won mainly through the efforts of Thomas Young and Augustin-Jean Fresnel (1788-1827). Between 1801 and 1803 Young made the memorable discoveries which provoked this revival of undulatory optics. The comparison of the ether that vibrates in a ray of light to the air that vibrates in a resonant tube led him to explain the alternately light and dark fringes that show in a place illumined by two equal beams slightly inclined to each other. The principle of interference, thus justified, allowed him to connect with the undulatory theory the explanation of the colours of thin laminæ that Newton had demanded of the "fits of easy transmission and easy reflection" of the particles of light.

In 1815 Fresnel, who combined this principle of interference with the methods devised by Huygens, took up the theory of the phenomena of diffraction which had been discovered by Francesco Maria Grimaldi, S.J.* (1618-63), and had remained a mystery to opticians. Fresnel's attempts at explaining these phenomena led him to draw up in 1818 a memoir which in a marked degree revealed the essential character of his genius, namely, a strange power of divination exercised independently of all rules of deductive reasoning. Despite the irregularity of his procedure, Fresnel made known very complicated formulæ, the most minute details of which were verified by experiment, and long afterwards justified according to the logical method of mathematicians. Never did physicist conquer more important and more unthought-of

truths, and yet never was there employed a method more capable of leading the common mind into error. Up to this time the vibrations of ether in a ray of light had been supposed to be longitudinal, as it is in the air of a resonant tube, but in 1808 Etienne-Louis Malus (1775-1812) discovered the polarization of light when reflected on glass, and, in 1817, when studying this phenomenon, Young was led to suppose that luminous vibrations are perpendicular to the ray which transmits them. Fresnel, who had conceived the same idea, completed an experiment (1816) in collaboration with Arago (1786-1853), which proved the view that luminous vibrations are transverse to the direction of propagation.

The hypothesis of transverse vibrations was, for Fresnel, the key to all the secrets of optics, and from the day that he adopted it he made discoveries with great rapidity. Among these discoveries were:

- The complete theory of the phenomena of polarization accompanying the reflection or refraction of light on the surface of contact of two isotropic media. The peculiarities which accompany total reflection gave Fresnel an opportunity to display in a most striking manner his strange power of divination and thus throw out a veritable challenge to logic. This divination was no less efficient in the second discovery.
- In studying double refraction, Huygens limited himself to determining the direction of luminous rays in the interior of crystals now called uniaxial, without, however, being able to account for the polarization of these rays; but with the aid of the wave-surface, Fresnel succeeded in giving the most elegant form to the law of the refraction of rays in biaxial crystals, and in formulating rules by which rays polarize in the interior of all crystals, uniaxial as well as biaxial.

Although all these wonderful theories destroyed the theory of emission, the hypothesis of molecular attraction was far from losing ground. In fact Fresnel thought he could find in the elasticity of the ether, which transmits luminous vibrations, the explanation of all the optical laws that he had verified by experiment, and he sought the explanation of this elasticity and its laws in the attraction which he believed to exist between the contiguous particles of this fluid. Being too little of a mathematician and too little of a mechanician to go very far in the analysis of such a problem, he left its solution to his successors. To this task, so clearly defined by Fresnel, Cauchy devoted the most powerful efforts of his genius as an algebraist and, thanks to this pupil of Laplace, the Newtonian physics of molecular attraction became an active factor in the propagation of the theory of undulatory optics. Fresnel's discoveries did not please all Newtonians as much as they did Cauchy. Arago could never admit that luminous vibrations were transverse, notwithstanding that he had collaborated with Fresnel in making the experiment by which this point was verified, and Jean-Baptiste Biot (1774-1862), whose experimental researches were numerous and skilful, and who had furnished recent optics with very valuable matter, remained strongly attached to the system of emission by which he endeavoured to explain all the phenomena that Fresnel had discovered and explained by the undulatory system. Moreover, Biot would not acknowledge himself defeated, or regard the system of emission as condemned until Foucault (1819-68) proved that light is propagated much more quickly in air than in water.

Theories of heat

The idea of the quantity of heat and the invention of the calorimeter intended for measuring the amount of heat emitted or absorbed by a body under given circumstances are due to Joseph Black (1728-99) and Adair Crawford (1749-95), who, by joining calorimetry with thermometry, veritably created the science of heat, which science remained unborn as long as the only thing done was the comparison of temperatures. Like Descartes, Newton held that heat consisted in a very lively agitation of the smallest parts of which bodies are composed. By showing that a certain quantity of heat is furnished to ice which melts, without however raising the temperature of the ice, that this heat remains in a "latent state" in the water resulting from the melting and that it again becomes manifest when the water returns to ice, the experiments of Black and Crawford led physicists to change their opinion concerning the nature of heat. In it they beheld a certain fluid which combines with other matter when heat passes into the latent state, and separates from it when heat is liberated again, and, in the new nomenclature that perpetuated the revolution brought about by Antoine-Laurent Lavoisier (1743-94), this imponderable fluid was assigned a place among simple bodies and named caloric.

Air becomes heated when it is compressed, and cools again when rarefied under the receiver of the pneumatic machine. Johann Heinrich Lambert (1728-77), Horace de Saussure (1740-79), and John Dalton (1766-1844) recognized the importance of this already old experiment, but it is to Laplace that we are indebted for a complete explanation of this phenomenon. The experiment proved to Laplace that, at a given temperature, a mass of air contains a quantity of caloric

proportional to its volume. If we admit the accuracy of the law of compressibility enunciated by Boyle and Mariotte, this quantity of heat combined with a given mass of air, also of given temperature, is proportional to the volume of this air. In 1803 Laplace formulated these propositions in a short note inserted in Berthollet's "Statique chimique". In order to verify the consequences which Laplace deduced therefrom concerning the expansion of gases, Louis-Joseph Gay-Lussac (1778-1850) began researches on this subject, and in 1807 on the variations of temperature produced when a gas contained in a receiver enters another receiver previously empty.

Laplace's views entail an evident corollary; to raise to a certain number of degrees the temperature of a gas of a fixed volume, the communication of less heat is required than if this gas were expanded under an invariable pressure. Hence a gas admits of two distinct kinds of specific heat which depend on whether it is heated at constant volume or under constant pressure; the specific heat being greater in the latter case than in the former. Through these remarks the study of the specific heat of gases was signalized as one of the most important in which experimenters could engage. The Institute made this study the subject of a competition which called forth two notable memoirs, one by Delaroché and Bérard on the measurement of the specific heats of various gases under constant pressure; and the other by Desormes and Clément, published in 1812, on the determination of the increase of heat due to a given compression in a given mass of air. The experiments of Desormes and Clément enabled Laplace to deduce, in the case of air, the ratio of specific heat under constant pressure to specific heat under constant volume, and hence to test the ideas he had formed on the propagation of sound. In applying to air the law of compressibility discovered by Boyle, Newton had attempted to calculate the velocity of the propagation of sound in this fluid, and the formula which he had established gave values very inferior to those furnished by experimental determination. Lagrange had already shown that, by modifying Boyle's law of compressibility, this disagreement could be overcome; however, the modification was to be justified not by what Lagrange said but by what Laplace discovered. When sound is propagated in air by alternate condensations and rarefactions, the temperature at each point instead of remaining unchanged, as Boyle's law supposed, is alternately raised and lowered about a mean value. Hence velocity of sound was no longer expressed by the formula Newton had proposed; this expression had to be multiplied by the square root of the ratio of specific heat under constant pressure to specific heat under constant volume. Laplace had this thought in mind in 1803 (Berthollet, "Statique chimique"); its consequences being developed in 1807 by Poisson, his disciple. In 1816 Laplace published his new formula; fresh experiments by Desormes and Clément, and analogous experiments by Gay-Lussac and Welter gave him tolerably exact values of the relation of the specific heats of gases. Henceforth the great geometrician could compare the result given by his formula with that furnished by the direct determination of the velocity of sound, the latter, in metres per second, being represented by the number 340-889, and the former by the number 337 715. This agreement seemed a very strong confirmation of the hypothesis of caloric and the theory of molecular action, to both of which it was attributable. It would appear that Laplace had a right to say: "The phenomena of the expansion of heat and vibration of gases lead back to the attractive and repellent forces sensible only at imperceptible distances. In my theory on capillary action, I have traced to similar forces the effects of capillarity. All terrestrial phenomena depend upon this species of force, just as celestial phenomena depend upon universal gravitation, and the study of these forces now seems to me the principal object of mathematical philosophy" (written in 1823).

In 1824 a new truth was formulated from which was to be developed a doctrine which was to overturn, to a great extent, natural philosophy as conceived by Newton and Boscovich and carried out by Laplace and his disciples. However, Sadi Carnot (1796-1832), the author of this new truth, still assumed the correctness of the theory of caloric. He proposed to extend to heat-engines the principle of the impossibility of perpetual motion recognized for engines of unchanging temperature, and was led to the following conclusion: In order that a certain quantity of caloric may produce work of the kind that human industry requires, this caloric must pass from a hot to a cold body; when the quantity of caloric is given, as well as the temperatures to which these two bodies are raised, the useful work produced admits of a superior limit independent of the nature of the substances which transmit the caloric and of the device by means of which the transmission is effected. The moment that Carnot formulated this fertile truth, the foundations of the theory of caloric were shaken. However, in the hypothesis of caloric, how could the generation of heat by friction be explained? Two bodies rubbed together were found to be just as rich in caloric as they had been; therefore, whence came the caloric evolved by friction?

As early as 1783 Lavoisier and Laplace were much troubled by the problem, which also arrested the attention of physicists; as in 1798 when Benjamin Thompson, Count Rumford (1753-1814) made accurate experiments on the heat evolved by friction, and, in 1799, when similar experiments were made by Sir Humphrey Davy (1778-1829). In 1803, beside the notes in which Laplace announced some of the greatest conquests of the doctrine of caloric, Berthollet, in his

"Statique chimique", gave an account of Rumford's experiments, trying in vain to reconcile them with the prevailing opinion. Now these experiments, which were incompatible with the hypothesis that heat is a fluid contained in a quantity in each body, recalled to mind the supposition of Descartes and Newton, which claimed heat to be a very lively agitation of the small particles of bodies. It was in favour of this view that Rumford and Davy finally declared themselves.

In the last years of his life Carnot consigned to paper a few notes which remained unpublished until 1878. In these notes he rejected the theory of caloric as inconsistent with Rumford's experiments. "Heat", he added, "is therefore the result of motion. It is quite plain that it can be produced by the consumption of motive power and that it can produce this power. Wherever there is destruction of motive power there is, at the same time, production of heat in a quantity exactly proportional to the quantity of motive power destroyed; and inversely, wherever there is destruction of heat, there is production of motive power".

In 1842 Robert Mayer (1814-78) found the principle of the equivalence between heat and work, and showed that once the difference in two specific heats of a gas is known, it is possible to calculate the mechanical value of heat. This value differed little from that found by Carnot. Mayer's pleasing work exerted scarcely any more influence on the progress of the theory of heat than did Carnot's unpublished notes. However, in 1843 James Prescott Joule (1818-89) was the next to discover the principle of the equivalence between heat and work, and conducted several of the experiments which Carnot in his notes had requested to have made. Joule's work communicated to the new theory a fresh impetus. In 1849 William Thomson, afterwards Lord Kelvin (1824-1907), indicated the necessity of reconciling Carnot's principle with the thenceforth incontestable principle of the mechanical equivalent of heat; and in 1850 Rudolf Clausius (1822-88) accomplished the task; thus the science of thermodynamics was founded. When in 1847 Hermann von Helmholtz published his small work entitled "Ueber die Erhaltung der Kraft", he showed that the principle of the mechanical equivalent of heat not only established a bond between mechanics and the theory of heat, but also linked the studies of chemical reaction, electricity, and magnetism, and in this way physics was confronted with the carrying-out of an entirely new programme, whose results are at present too incomplete to be judged even by scientists.

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