A. PANNEKOEK

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CHAPTER 26

NEWTON

The concept of attraction was not introduced for the first time by Newton. Copernicus had already spoken of the mutual attraction of the parts of the earth as the cause of its spherical shape; he assumed this faculty to be present in other celestial bodies too, causing their particles to be compressed into a sphere. Kepler, too, had spoken of gravity as a tendency of cognate bodies to approach and join one another. To him the tides were a proof that the moon exerted an attraction upon the water of the earth: 'if the earth ceased to attract the waters, all the sea water would be drawn upward and would flow to the moon'.[132] He compared gravity with magnetism: 'the earth draws along the bodies flying in the air, because they are chained to her as though by a magnetic force, just as if there existed a contact between them.'[133] This attraction had nothing to do with orbital motion; the sun, as quoted above, did not exert an attractive force upon the planets but a directive force, dragging the planets along with its rotation. Gravity and orbital motion were two different and entirely separate fields.

Nor did the seventeenth century see any connection between the vortices, which moved the planets in their circles, and gravity, working at the surface of the earth and doubtless also at the surface of the sun and the other planets. Huygens made an attempt to establish such a connection in a lecture held, in 1669, at the Paris Academy, 'On the Cause of Gravity'. Whereas Descartes had assumed that the ethereal fluid, by rotating uniformly about a certain axis through the earth, carried the moon along, Huygens made the thin fluid matter in rapid rotation move in all directions about the earth's surface. As a consequence of their centrifugal force directed outward, i.e. upward, the fine particles pressed down the larger particles of the coarse-grained visible matter, which did not participate in the rotations. This origin of gravity implied that the thin fluid matter passed freely through all heavy objects and filled the space between their particles. The velocity of this whirling motion had to be 17 times greater than the velocity of the equator, because, with a rotation of the earth 17 times more rapid than the actual one, the objects at the equator would lose their gravity.

The actual progress of science, however, went in exactly the opposite direction, not in explaining gravity by circular orbits but in explaining circular orbits by gravity. The development of the fundamental principles of mechanics had made this possible. Galileo had explained the constant velocity of a horizontal movement in the absence of friction by pointing out that such movement was part of a circular orbit about the earth's centre, which had always been considered uniform by nature. He had not been able to overcome this conception; but his researches had so perfectly cleared the way that pupils and younger scientists, like Cavalieri (1632) and Torricelli (1644), could express the 'principle of inertia' in modern form: when acting forces are absent, the motion is rectilinear with constant velocity. Then the next step was the realization that a circular orbit is not simply a natural motion—as all the preceding centuries had supposed—but a complex enforced motion. A circular motion is the result of a force directed towards the centre, continuously preventing the body from following the rectilinear motion along the tangent. This tendency to follow the tangent and move with increasing rapidity away from the centre was observed as a 'centrifugal force', a tension in the string when an object is swung around. In his work on the Jupiter satellites, Borelli in 1665 had expressed himself in this way: that the centrifugal force of the orbital motion was exactly in equilibrium with the attractive force of Jupiter. The complete theory of the centrifugal force was given by Huygens in 1673 in his work *Horologium oscillatorium*, in which he, in connection with his invention of the pendulum clock, treated a number of related mathematical and mechanical problems. He deduced that the centrifugal force is proportional to the square of the velocity and to the inverse of the radius of the circle.

So the idea became dominant that an attraction directed toward the centre of their orbit works upon the planets and the moon. It might be expected that this force decreases with increasing distance; but in what ratio? The answer to this question was given by Newton (plate 7).

Isaac Newton, a farmer's son from the hamlet of Woolsthorpe, in Lincolnshire, born in 1642, went to study in Cambridge in 1661. When the university was closed for a couple of years because of a pestilence in the town, he returned in 1665 to his native village. Here he made his first studies in what were to become the most important subjects of his later work: mathematics (the theory of fluxions), optics (the discovery that common light is composed of numerous kinds of simple light, all of different colours and refrangibility), and gravitation. The falling of bodies toward the earth caught his attention (the anecdote relates that, seeing an apple fall from the tree, he began to ponder over the cause of this falling) and raised the question as to what height gravity extended. To the moon perhaps? If so, could gravity be the force that kept the moon

in its circular orbit? To settle it, he had to know in what ratio gravity decreases with distance from the earth. For this problem Kepler's third law could give a valuable indication. According to this law, a four times larger circular orbit has an eight times larger period, hence a two times smaller velocity; therefore, the centrifugal force, according to Huygens's formula, is 16 times smaller. Generally in such a planetary system the centrifugal force must be as the inverse square of the distance. Gravity compensating it must vary in the same ratio.

The moon's distance being 60 times the earth's radius, its gravity must be 3,600 times smaller than that of a stone falling on the earth's surface, or, as it was sometimes expressed, the moon falls in a minute as far as a stone falls in a second. Newton, in making the computation, assumed an arc of one degree on earth to be 60 miles, as given in a sailor's manual, the only book at hand—even today an English nautical mile is always taken to equal one minute of arc. Assuming this to be the usual 'Statute mile' of 5,280 feet, equal to 4,954 Paris feet, he computed the moon's acceleration per second to be 0.0073 feet, per minute 26.3 feet. Through Galileo's experiments, however, afterwards repeated more accurately by others, the acceleration of freely falling bodies per second was known to be 30 feet. The two values are of the same order of magnitude, but the difference, one-eighth of the amount, is too great to be acceptable. Disappointed, the story runs, he abandoned his apparently so brilliant idea. In the years that followed he occupied himself with optical and mathematical studies.

He could have used a better value, because Snellius's result, which gave, for an arc of 1°, a length of a good 69 English miles, could already be found in English books. It was confirmed by the more extensive and accurate determination of Picard in France, published in 1671, giving, for 1°, 57,065 toises or 69 English miles. Performed with this value, the new computation gave complete agreement. Thus the law of gravitational attraction, decreasing as the inverse square of the distance, was established.

Newton was not the only man to formulate this law of variation of force with distance. Part of his mathematical deductions were found in Huygens's work published in 1673. Robert Hooke, that acute and versatile but jealous scientist, asserted afterward that he had known the law for a long time—which was quite possible—and even that Newton had got the idea from him. Probably Hooke, by facing him with the problem of what the orbit of a body would be, if affected by such an attractive force, was a strong factor in drawing Newton's attention to this matter. But he himself could do nothing with the mere idea. Halley and Wren discussed the same questions, without being able to solve them. What was necessary was to demonstrate all arguments and derive all consequences of this law for the celestial orbits with exact mathematics. Newton was the only man able to do so by means of the mathematical methods he himself had constructed.

In 1684 the theory was ready in its main part; and in 1685, by solving the problem of the attraction of a solid sphere and demonstrating that it was exactly equal to the attraction by its mass if concentrated in the centre, he removed the last difficulty in the argument. Another year of severest mental exertion was needed, in which he was so entirely absorbed by his problems that dinner and sleep often were neglected and his health was badly shaken; the many anecdotes about his absent-mindedness relate to this period. Then the first part could be presented to the Royal Society in 1686. That the manuscript was not buried for a long time in its archives, was due to the unremitting care of his friend Halley, at that time assistant secretary (called 'Clerk') of the Society, who procured money for its printing, partly from his own pocket. In 1687 the work appeared under the title *Philosophiae naturalis principia mathematica* ('Mathematical Principles of Natural Philosophy').

The title of the book expresses how it could lay down new foundations for astronomy. 'Natural philosophy' was in England the name for scientific research; why mathematical principles were needed he explained in Book III, which bears the special title 'The System of the World'. There he said: 'Upon this subject I had, indeed, composed the third book in a popular method, that it might be read by many; but afterwards, considering that such as had not sufficiently entered into the principles could not easily discern the strength of the consequences, nor lay aside the prejudices to which they had been many years accustomed, therefore, to prevent the disputes which might be raised upon such accounts, I chose to reduce the substance of this book into the form of propositions (in the mathematical way), which should be read by those only who had first made themselves masters of the principles established in the preceding books.'[134] This is understandable when we consider that Newton was extremely sensitive to criticism, which, often based on shaky foundations, was set against results on which he had pondered carefully and profoundly; often he postponed publication of his results to avoid unpleasant polemics. The mathematical demonstration convinced the well-instructed and deterred the ignorant. It was at the same time that Spinoza expounded his philosophy in the mathematical form of propositions and demonstrations.

The contents of the first two Books, indeed, consist of mathematics; it is geometry applied to the motion of bodies, i.e. what we call 'theoretical mechanics'. In his preface Newton said: 'Therefore geometry is founded in mechanical practice, and is nothing but that part of universal mechanics which accurately proposes and demonstrates the art of measuring. But since the manual arts are chiefly employed in the moving of bodies, it happens that geometry is commonly referred to their magnitude and mechanics to their motion. In this sense rational mechanics will be the science of motions resulting from any forces whatsoever, and of the forces required to produce any motions, accurately proposed and demonstrated.'[135] Rational mechanics was the discipline needed to unite earthly and celestial motions into one system. Earthly motions were ruled by Galileo's laws of falling and gravity; celestial motions were ruled by Kepler's laws of planetary orbits. To connect them, Newton, as the founder of the new science, completing the work of Galileo and Huygens, began by stating its principles in the form of 'Definitions' and 'Axioms, or Laws of Motion'.

(1) Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it. (2) The change of motion is proportional to the motive force impressed; and is made in the direction of the line in which that force is impressed. (3) To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.[136] The concept of mass was introduced as 'the quantity of matter arising from its density and bulk conjointly'; 'the quantity of motion arises from the celerity multiplied by the quantity of matter; and the motive force arises from the accelerative force multiplied by the same quantity of matter.' Mass and weight were sharply distinguished. Hence it is that, near the surface of the earth, where the accelerative gravity, or force productive of gravity, in all bodies is the same, the motive gravity or the weight is as the body; but if we should ascend to higher regions, where the accelerative gravity is less, the weight would be equally diminished, and would always be as the product of the body, by the accelerative gravity.[137]

Because the chief aim is the treatment of the freely moving heavenly bodies, centripetal forces were introduced directly under the definitions. 'A centripetal force is that by which bodies are drawn or impelled, or any way tend, towards a point as to a centre. . . . Of this sort is gravity . . . and that force, whatever it is, by which the planets are continually drawn aside from the rectilinear motions, which otherwise they would pursue, and made to revolve in curvilinear orbits. . . . They all endeavour to recede from the centres of their orbits; and were it not for the opposition of a contrary force which restrains them to, and detains them in their orbits, which I therefore call centripetal, would fly off in right lines, with a uniform motion.' Then, after mentioning a projectile shot from a mountain horizontally with sufficient velocity, which would go round the earth in an orbit, he proceeded: '. . . the moon also, either by the force of gravity, if it is endued with gravity, or by any other force, that impels it towards the earth, may be continually drawn aside towards the earth, out of the rectilinear way which by its innate force it would pursue; and would be made to revolve in the orbit which it now describes: nor could the moon without some such force be retained in its orbit.'[138]

Then, through rigid mathematical demonstrations, Newton derived from Kepler's laws the forces determining the motion of the planets. His Proposition I (Cajori ed., p. 40) deals with the law of areas: if a revolving body is subject to a centripetal force directed to a fixed point, the areas described by radii drawn to that point will be proportional to the times in which they are described. For the demonstration, reproduced in Appendix C, Newton made use of equal finite time intervals in which the radius describes a triangle and after each of which the force gives a finite impulse to the body towards the centre. Then he proceeded: 'Now let the number of those triangles be augmented, and their breadth diminished in infinitum; and their ultimate perimeter will be a curved line: and therefore the centripetal force, by which the body is continually drawn back from the tangent of this curve, will act continually.'[139]

In these words we see that behind the geometrical form stands the spirit of his method of fluxions which pervades his geometry; it is the idea of considering quantities and motions not as definite abrupt values but as in process of originating, changing, or disappearing. Newton could be a renovator of astronomy because at the same time he was a renovator of mathematics. In his demonstrations he made use of geometrical figures of straight lines and triangles of finite size; but then he let the number of such parts be augmented and their size diminished *ad infinitum*, to fit a curved orbit and a continually working force; and he showed that the demonstrations then rigidly hold.

By means of the same figure, the reverse was demonstrated: when the succeeding areas are equal for equal time intervals, the working force is always directed to the same point. Thus Kepler's second law of the areas proportional to the time intervals proved that the planets are moved by a force directed towards, hence emanating from, the sun. For the case of a circular motion Newton showed that his method leads to the same formula for the centrifugal force as had been derived by Huygens.

Thereupon, Newton in Proposition XI derived in a general way the law of the centripetal force toward the sun from Kepler's first law that the orbit of a planet is an ellipse with the sun in a focus. By making use of the well-known geometrical properties of the ellipse, he found that the force was as the inverse square of the distance to the sun. Considering the fundamental importance of this demonstration for the history of astronomy, we have reproduced it in Appendix D (p. 500). The same rate of variation with distance—as shown above—was found by comparing two different planets (supposed, for simplicity's sake, to have circular orbits) and applying Kepler's third law. This meant that different planets at the same distance from the sun have the same acceleration and that hence the attraction exerted upon them by the sun was independent of their substance. These conclusions gave a new significance to Kepler's laws; simple empirical regularities before, they now acquired unassailable certainty as consequences of a universal law of attraction. The attempts made in the seventeenth century to find other orbits or laws of motion for the planets now lost all sense.

The mathematical propositions found their application in the third Book. From observations of the Jupiter satellites it had been derived that Kepler's laws also held for them; hence the forces that kept them in their orbits were directed to the centre of Jupiter and were inversely as the squares of the distances from that centre. The same held for the satellites of Saturn. The planets were attracted in the same way by the sun, and the moon by the earth. The acceleration of falling bodies on the surface of the earth was computed from the orbital motion of the moon to be $15\frac{1}{2}$ Paris feet, 'or, more accurately, 15 feet 1 inch $1\frac{4}{9}$ line'; whereas the same acceleration derived by Huygens from the length of a pendulum oscillating seconds amounts to 15 feet 1 inch $1\frac{7}{9}$ line. 'And therefore the force by which the moon is retained in its orbit becomes, at the very surface of the earth, equal to the force of gravity which we observe in heavy bodies there. And therefore (by Rules 1 and 2) the force by which the moon is retained in its orbit is that very same force which we commonly call gravity; for, were gravity another force different from that, then bodies descending to the earth with the joint impulse of both forces would fall with a double velocity.'[140] By Rules 1 and 2 he means the first of the 'Rules of Reasoning in Philosophy' (*Regulae philosophandi*) at the start of Book III: (1) We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances; (2) Therefore to the same natural effects we must, as far as possible, assign the same causes. These rules in modern times may look superfluous and artificial; but, in a century in which so many fantasies were offered as science, this admonition of intellectual discipline was not superfluous. And he concluded: 'The force which retains the celestial bodies in their orbits has been hitherto called centripetal force; but it being now made plain that it can be no other than a gravitating force, we shall hereafter call it gravity. For the cause of that centripetal force which retains the moon in its orbit will extend itself to all the planets.'[141]

The moons of Jupiter gravitate towards Jupiter, the planets towards the sun. There is a power of gravity tending to all the planets; Jupiter also gravitates towards its satellites, the earth towards the moon; all the planets gravitate towards one another. All bodies are mutually attracted by a force between them that moves the greater body a little, the small body much. The weights of bodies towards different planets, hence the quantities of matter in the several planets, can be computed from the distances and periodic times of bodies revolving about them; they are found, if one is put for the sun, to be $\frac{1}{1067}$ for Jupiter, $\frac{1}{3021}$ for Saturn, $\frac{1}{169282}$ for the earth. The force exerted by a celestial body is composed of the attractions of its parts, i.e. of the smallest particles of matter. This universal gravity or attraction, afterwards called 'gravitation', is a general property of all matter; all particles attract one another in accordance with Newton's law of the inverse squares of their distances. Newton demonstrated that the total attraction of a spherical body is exactly the same as though all its mass were concentrated in the centre; Kepler's laws can hold for the planets because they, as well as the sun, are spherical bodies.

The theory of gravitation was not only a more universal formula than the empirical laws from which it had been derived, for it gave in addition explanations for a number of other phenomena. Newton demonstrated that, besides elliptic orbits, parabolic and hyperbolic orbits also led to the same law of attraction, so that by this law each of these conic sections was a possible orbit, with the sun always in the focus. This result could at once be applied to the comets; their mysterious sudden appearance and disappearance were in exact accord with the infinite branches of a parabola or a hyperbola. Kepler had supposed that comets ran through space and passed the sun along straight lines. Cassini had tried, without result, to represent the observations by oblique circular orbits. Borelli, however, in 1664 suspected that the orbits were parabolas. In 1680 a great comet appeared which came close to the sun and, having rapidly made a half-turn around it, went away in the same direction whence it had come. Dörffel, a minister at Plauen in Saxony, explained its course by means of a narrow parabola with a small focal distance.

Newton gave a theoretical basis to these suspicions by stating that the orbits of the comets must be conic sections; he assumed them to be widely extended ellipses of large eccentricity, which at their tops were so nearly parabolas that parabolas could be substituted for them. He indicated a method of deriving the true orbit in space from the observed course between the stars, and he applied it to the comet of 1680. By this method Halley computed parabolic orbits of 24 comets of which two had appeared in 1337, and in 1472, and the others in the sixteenth and seventeenth centuries. In his publication of the results in 1705, he drew attention to the fact that three among them—the comets that had appeared in 1531, in 1607, and in 1682—had nearly identical orbits in space. Since both intervals were 76 or 75 years, he concluded that they were three successive appearances of the same comet, which in a good 75 years describes a strongly elongated ellipse about the sun. In a memoir of 1716 he returned to the question and pointed to comets that had been seen in the years 1456 and 1378 as possible appearances of the same body, and predicted its next return in 1758.

In his *Principia* Newton also derived the oblateness of a rotating sphere, especially of the earth. In this he had been preceded by Huygens, who, though his first computations in his diary were much earlier, about 1683 wrote a supplement to his discourse on the cause of gravity, sent it to the secretary of the Paris Academy in 1687, and himself in 1690 published both the discourse and the supplement, together with his treatise on light. In this supplement he put forward that, in consequence of the earth's rotation, a plumb line is not directed towards the centre of the earth, but is (in medium latitudes) by $\frac{1}{10}°=6'$ inclined to the south. 'This deviation is contrary to what has always been supposed to be a very certain truth, namely, that the cord stretched by the plumb is directed straight toward the centre of the earth. . . . Therefore, looking northward, should not the level line visibly descend below the horizon? This, however, has never been perceived and surely does not take place. And the reason for this, which is another paradox, is that the earth is not a sphere at all but is flattened at the two poles, nearly as an ellipse turning about its smaller axis would produce. This is due to the daily motion of the earth and is a necessary consequence of the deviation of the plumb line mentioned above. Because bodies by their weight descend parallel to the direction of this line, the surface of a fluid must put itself perpendicular to the plumb line, since else it would stream farther downward.'[142]

In an Addendum written in 1690 Huygens computed an oblateness of $\frac{1}{578}$; this value was based on the assumption that gravity as proceeding from the vortices as its cause was constant throughout the body of the earth. Newton, however, now had a better theory; proceeding from gravity as the result of the attraction of all the separate particles, he found it to decrease regularly from the surface to the centre, where it vanishes. So he derived the ratio of the polar axis to the equatorial diameter to be 229 : 230, i.e. an oblateness of $\frac{1}{230}$. These theoretical derivations were strongly opposed by the French astronomers, who put their trust in their geodetical measurements. Careful determinations of the length of one degree of the meridian to the south of Paris had given a somewhat larger value (57,098 toises) than had been derived from the arc of Paris–Dunkirk (56,970 toises). Cassini and his colleagues concluded that the degrees became smaller when going north and that hence the earth must be elongated at the poles. This contradiction between theory and practice made the French astronomers sceptical toward the theory as a whole.

Newton dealt with other astronomical phenomena that now found their explanation in the theory of gravitation. First he pointed out that the attraction of the moon by the sun worked as a disturbing influence upon the moon's orbit and was the cause of the irregularities in the moon's course discovered by Ptolemy and by Tycho Brahe. He gave a first theoretical computation of the regression of the lunar nodes and found that it is strongest in the quarter-moons and zero at full and new moon. Then he showed how the tides are caused by the different ways in which the solid earth and the movable oceanic waters are attracted by the moon and the sun. The precession, that regular slow increase in the longitudes of the stars by a change in the position of the earth's axis of rotation, could also be explained by the attraction of sun and moon upon the flattened earth. By making a comparison with the nodes of imagined moons revolving along the earth's equator, he could even compute the right value 50″ per year (9.12″ by the sun, 40.88″ by the moon).

That the planets by their mutual attraction must disturb their motion he understood, of course, as a consequence of his theory: 'But the actions of the planets one upon another are so very small, that they may be neglected. . . . It is true that the action of Jupiter upon Saturn is not to be neglected . . . the gravity of Saturn towards Jupiter will be to the gravity of Saturn towards the sun as 1 to about 211. And hence arises a perturbation of the orbit of Saturn in every conjunction of this planet with Jupiter, so sensible, that astronomers are puzzled with it.'[143] All the other mutual influences are so slight that he assumed the aphelion and the nodes of the planets to be fixed, or at least nearly so, and he even concluded: 'The fixed stars are immovable, seeing they keep the same position to the aphelia and the nodes of the planets.'[144]

Newton, by his theory of universal gravitation, gave to the knowledge of the motions of the heavenly bodies so solid a basis as never could have been suspected. In this great scientific achievement the two formally opposite principles of Bacon and Descartes are unified: he proceeded from practical experience, from rules deduced from observations by precise computation, and out of them constructed a general theoretical principle which permitted him to derive all the separate phenomena. And all these deductions were demonstrated by the most exact and acute mathematics. No wonder that, after traditions had been vanquished and the difficulties of the new mode of thinking overcome, his

compatriots exalted him as an almost superhuman genius. Honours were bestowed upon him; from 1703 until 1727, the year of his death, he was President of the Royal Society. His appointment in 1696 as 'Warden of the Mint' (in 1699 promoted to 'Master of the Mint') was not simply a post of honour or a lucrative sinecure. He and his colleague, the philosopher John Locke, together with the ministers Somers and Montague, by their energetic measures in minting good silver coin, repaired Britain's deplorable monetary system, a necessary basis for the expansion of its commerce which ensued.[145]

Newton in his *Principia* did not restrict himself to an exposition of his new theory, which for us is the essential thing. For his contemporaries, criticism of the older dominant theory was equally needed. So the entire Book II is devoted to the motion of fluids and to the resistance which moving bodies experience in fluids: the first foundations for a scientific treatment of these phenomena. Here the vortices had to stand the test of science; the progress of half a century was the progress from vague philosophical talk to exact mathematical computation. The conclusion was, in Newton's words: 'Hence it is manifest that the planets are not carried round in corporeal vortices'; and in a verdict still more severe: 'so that the hypothesis of vortices is utterly irreconcilable with astronomical phenomena, and rather serves to perplex than explain the heavenly motions'.[146]

Notwithstanding this crushing criticism of the vortex theory, most Continental scientists remained sceptical towards the doctrine of gravitation. This appears most clearly in what Huygens wrote in 1690 in the above-mentioned Addendum to his Discourse on the cause of gravity. In comparing their different results on the oblateness of the earth, he said: 'I cannot agree with the Principle which he supposes in this computation and elsewhere, viz. that all the small particles, which we can imagine in two or many different bodies, attract and try to approach one another. This I cannot admit because I think I see clearly that the cause of such an attraction cannot be explained by any principle of mechanics or by the rules of motion.'[147] Of course; for in his opinion the weight of heavy bodies was caused by their being pressed down by the whirling ether outside and not through influences from inside the earth, so that the celestial bodies themselves did not act upon one another. He had nothing against Newton's centripetal force, by which the planets were heavy toward the sun, because he himself had shown that such gravity could be understood from mechanical causes. Long ago he also had imagined that the spherical figure of the sun, as well as that of the earth, could be explained by this gravity; but he had not extended its action as far as to the planets, 'because the vortices of Descartes that formerly appeared to me very probable and which occupied my mind, were opposed to it. Nor had I thought of that regular decrease of gravity, namely, as the inverse square of the distance; that is a new and very remarkable property of gravity, for which it would certainly be worth while to seek the reason.'[148]

Here it appears that what to Newton was a solution, to Huygens was a new problem. Perceiving now by Newton's demonstrations that this gravity counterbalanced the centrifugal forces of the planets and exactly produced their elliptical motion, Huygens had no doubt that Newton's hypotheses on gravity were true, as also Newton's system founded thereon. It must appear all the more probable, since it solved many difficulties that gave trouble in the vortices of Descartes; for instance, as to why the eccentricities and inclinations of the planetary orbits always remained constant and their planes passed through the sun, and their motions accelerated and retarded, as we observe, which could hardly happen if they were swimming in a vortex about the sun. And now we see also how the comets can traverse our system; it was difficult to conceive how they could have a movement opposite to the vortex which was strong enough to drag the planets along. But by Newton's theory this scruple has been removed, since nothing prevents the comets from travelling in widely extended ellipses about the sun.

'There is only this difficulty,' Huygens continued, 'that Newton . . . will have celestial space to contain only very rare matter, in order that the planets and comets meet with less impediment in their course. This rarity accepted, it seems to be impossible to explain the action either of gravity or of light, at least in the way I always used.'[149] In 1678 Huygens had already expounded, and in 1690 printed, a theory of light as a vibration, a wave motion propagating through the world ether, and in this way he had explained the phenomena of reflection and refraction. Newton had developed the entirely different theory—which was not published until 1704—that light consists in ejected particles passing through space with great velocity. Refraction of a ray obliquely falling upon a glass surface—which in Huygens's theory was due to slower propagation of the waves—in Newton's theory was easily explained by the consideration that the light corpuscles were bent toward the normal by the attraction of the denser glass matter. There was thus a profound difference in the supposed underlying world structure. For Newton, space was empty or nearly so; the light corpuscles, as well as the planets, run their course unimpeded, and gravity works through empty space from one body to another. Huygens could not agree with Newton's attraction because his theory of light required that space be filled with ether.

So in his 'Addendum' he returned to discussions of the nature, the fineness, and the tenuity of the whirling particles surrounding the earth. Newton, he said, argued to prove the extreme rarity of the ether in order that the motions due to gravity be not hampered by its resistance; but this substance, instead of hampering the motion, causes gravity. 'It would be different if we should suppose gravity to be an inherent quality of bodily matter. But I do not believe that this is what Newton accepts, because such an hypothesis would remove us far from the mathematical and mechanical principles.'[150] In the same trend of thought, Leibniz, after reading the *Principia*, wrote to Huygens (October 1690): 'I do not understand how he conceives gravity or attraction; it seems that to him it is only a certain immaterial and inexplicable virtue, whereas you explain it very plausibly through the laws of mechanics.'[151]

Here the profound basis of the controversy comes to light. Huygens admitted the exactness of Newton's computations and formulae; but they offered him no explanation. They gave no answer to the questions posed by him and his French colleagues: what is the origin of attraction? why is it that two bodies without any contact are driven toward one another? If space is filled with matter, this matter, by its contact, by pressure and attraction, transfers the motion; we see how streaming water and blowing wind drag objects with them; these are mechanical forces, easily understandable. An attraction from afar, over empty space, is entirely foreign to mechanical action.

Did Newton and his partners not see this difficulty? Certainly they did; but it did not worry them. Fundamentally, Newton, according to the general trends of thought at that time, agreed with Huygens. That he felt the same need of explanation as his contemporaries appears from a letter written in 1678 to Robert Boyle, the master of chemistry and discoverer of the law of the 'spring' of gases. Here he tried to give gravity a cause in the ether pervading all gross bodies and consisting of particles of different degrees of fineness; but his notions about things of this kind, he said, were so undigested that he was not well satisfied with them; 'you will easily discern whether in these conjectures there be any degree of probability.'[152] That he considered attraction at a distance no sufficient explanation may be seen from the letters he wrote (1692–93) to Richard Bentley, who was in correspondence with Newton on account of a series of lectures, in which he (Bentley) demonstrated the existence of God and refuted atheism by means of the law of gravitation. Newton, who was deeply occupied with theological questions and had often written on biblical subjects, in his first letter showed his agreement with this trend of thought: 'Why there is one body in our system qualified to give light and heat to all the rest, I know no reason, but because the author of the system thought it convenient. . . . To your second query I answer that the motions, which the planets now have, could not spring from any natural cause alone, but were impressed by an intelligent Agent. . . . To make this system, therefore, with all its motions, required a cause which understood, and compared together, the quantities of matter in the several bodies of the sun and planets and the gravitating powers resulting from thence . . . and to compare and adjust all these things together in so great a variety of bodies, argues that cause to be not blind and fortuitous, but very well skilled in mechanics and geometry' (letter of December 10, 1692).[153] And in his third letter of February 25th he wrote on the attraction: 'It is inconceivable that inanimate brute matter should, without the mediation of something else, which is not material, operate upon, and affect other matter without mutual contact; as it must do, if gravitation, in the sense of Epicurus, be essential and inherent to it. And this is one reason why I desired you would not ascribe innate gravity to me. That gravity should be innate, inherent and essential to matter, so that one body may act upon another at a distance through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it. Gravity must be caused by an agent acting constantly according to certain laws; but whether this agent be material or immaterial, I have left to the consideration of my readers.'[154]

In the second edition of his *Principia* (1713), in a 'General Scholium' added to the end of the third Book, to refute the criticisms that he had introduced occult qualities into natural philosophy, the same opinions were expressed in a more reticent way: 'Hitherto we have explained the phenomena of the heavens and of our sea by the power of gravity, but have not yet assigned the cause of this power. This is certain, that it must proceed from a cause that penetrates to the very centres of the sun and the planets, without suffering the least diminution of its force; that operates not according to the quantity of the surfaces of the particles upon which it acts (as mechanical causes used to do), but according to the quantity of the solid matter which they contain. . . . But hitherto I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called an hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy . . . and to us it is enough that gravity does really exist and act according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and of our sea.'[155]

That this was not the last word of his Natural Philosophy appears in

the way he then continued: 'And now we might add something concerning a certain most subtle spirit which pervades and lies hid in all gross bodies; by the force and action of which spirit the particles of bodies attract one another at near distances' and electric bodies operate and light is emitted, 'and the members of animal bodies move at the command of the will, namely, by the vibrations of this spirit, mutually propagated along the solid filaments of the nerves. . . . But these are things that cannot be explained in few words, nor are we furnished with that sufficiency of experiments which is required to an accurate determination and demonstration of the laws by which this electric and elastic spirit operates.'[156] With these words the books of the *Principia Mathematica* close.

These sentences show that his mind was also capable of imaginative flights. But his theory remained entirely free from them. In his theory, only those relations appear which are demonstrable by exact mathematics; this is its essential characteristic. By means of the laws of gravitation, the phenomena can be derived and predicted by computation; this is the purpose of science. We meet here again with the contrast between the practical mind of the English and the theoretical mind of the Continental scientists. The latter racked their brains about the question concerning from what fundamental truths their theories followed. The former did not care and were content if they could work with the theories and derive practical results. Doubtless this was, as already pointed out, a consequence of the general mode of thinking of these peoples, rooted in their living conditions. The same personal liberty and daring energy which in the centuries that followed drove the English middle class towards commercial and industrial world power made the English scholars in their 'experimental philosophy' the pioneers of science.

Pioneers of scientific method, indeed. What in Newton's work presented itself as resignation, not asking for deeper causes but boldly applying it to further results, became the principle of modern science; a law of nature is not an explanation of the phenomena from established primary 'causes'.