

## Crosscutting Concepts: Strengthening Science and Engineering Learning

Newton originally applied the idea of attractions and repulsions solely to the range of terrestrial phenomena mentioned in the preceding paragraph. But late in 1679, not long after he had embraced the concept, another application was suggested in a letter from Hooke, who was seeking to renew correspondence. Hooke mentioned his analysis of planetary motion—"in effect, the continuous diversion of a rectilinear motion by a central attraction. Newton bluntly refused to correspond but, nevertheless, went on to mention an experiment to demonstrate the rotation of Earth : let a body be dropped from a tower; because the tangential velocity at the top of the tower is greater than that at the foot, the body should fall slightly to the east. He sketched the path of fall as part of a spiral ending at the centre of Earth. This was a mistake, as Hooke pointed out; according to Hooke's theory of planetary motion, the path should be elliptical , so that if Earth were split and separated to allow the body to fall, it would rise again to its original location. Newton did not like being corrected, least of all by Hooke, but he had to accept the basic point; he corrected Hooke's figure, however, using the assumption that gravity is constant. Hooke then countered by replying that, although Newton's figure was correct for constant gravity, his own assumption was that gravity decreases as the square of the distance. Several years later, this letter became the basis for Hooke's charge of plagiarism . He was mistaken in the charge. His knowledge of the inverse square relation rested only on intuitive grounds; he did not derive it properly from the quantitative statement of centripetal force and Kepler's third law, which relates the periods of planets to the radii of their orbits . Moreover, unknown to him, Newton had so derived the relation more than 10 years earlier. Nevertheless, Newton later confessed that the correspondence with Hooke led him to demonstrate that an elliptical orbit entails an inverse square attraction to one focus—one of the two crucial propositions on which the law of universal gravitation would ultimately rest. What is more, Hooke's definition of orbital motion—"in which the constant action of an attracting body continuously pulls a planet away from its inertial path"—suggested a cosmic application for Newton's concept of force and an explanation of planetary paths employing it. In 1679 and 1680, Newton dealt only with orbital dynamics; he had not yet arrived at the concept of universal gravitation.

### Universal gravitation

Nearly five years later, in August 1684, Newton was visited by the British astronomer Edmond Halley, who was also troubled by the problem of orbital dynamics. Upon learning that Newton had solved the problem, he extracted Newton's promise to send the demonstration. Three months later he received a short tract entitled *De Motu* ("On Motion"). Already Newton was at work improving and expanding it. In two and a half years, the tract *De Motu* grew into *Philosophiae Naturalis Principia Mathematica*, which is not only Newton's masterpiece but also the fundamental work for the whole of modern science.

Significantly, *De Motu* did not state the law of universal gravitation. For that matter, even though it was a treatise on planetary dynamics, it did not contain any of the three Newtonian laws of motion. Only when revising *De Motu* did Newton

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embrace the principle of inertia (the first law) and arrive at the second law of motion. The second law, the force law, proved to be a precise quantitative statement of the action of the forces between bodies that had become the central members of his system of nature. By quantifying the concept of force, the second law completed the exact quantitative mechanics that has been the paradigm of natural science ever since.

The quantitative mechanics of the Principia is not to be confused with the mechanical philosophy. The latter was a philosophy of nature that attempted to explain natural phenomena by means of imagined mechanisms among invisible particles of matter. The mechanics of the Principia was an exact quantitative description of the motions of visible bodies. It rested on Newton's three laws of motion: (1) that a body remains in its state of rest unless it is compelled to change that state by a force impressed on it; (2) that the change of motion (the change of velocity times the mass of the body) is proportional to the force impressed; (3) that to every action there is an equal and opposite reaction. The analysis of circular motion in terms of these laws yielded a formula of the quantitative measure, in terms of a body's velocity and mass, of the centripetal force necessary to divert a body from its rectilinear path into a given circle. When Newton substituted this formula into Kepler's third law, he found that the centripetal force holding the planets in their given orbits about the Sun must decrease with the square of the planets' distances from the Sun. Because the satellites of Jupiter also obey Kepler's third law, an inverse square centripetal force must also attract them to the centre of their orbits. Newton was able to show that a similar relation holds between Earth and its Moon. The distance of the Moon is approximately 60 times the radius of Earth. Newton compared the distance by which the Moon, in its orbit of known size, is diverted from a tangential path in one second with the distance that a body at the surface of Earth falls from rest in one second. When the latter distance proved to be 3,600 (60<sup>2</sup>) times as great as the former, he concluded that one and the same force, governed by a single quantitative law, is operative in all three cases, and from the correlation of the Moon's orbit with the measured acceleration of gravity on the surface of Earth, he applied the ancient Latin word *gravitas* (literally, "heaviness" or "weight") to it. The law of universal gravitation, which he also confirmed from such further phenomena as the tides and the orbits of comets, states that every particle of matter in the universe attracts every other particle with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between their centres.

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When the Royal Society received the completed manuscript of Book I in 1686, Hooke raised the cry of plagiarism, a charge that cannot be sustained in any meaningful sense. On the other hand, Newton's response to it reveals much about him. Hooke would have been satisfied with a generous acknowledgment; it would have been a graceful gesture to a sick man already well into his decline, and it would have cost Newton nothing. Newton, instead, went through his manuscript and eliminated nearly every reference to Hooke. Such was his fury that he refused either to publish his *Opticks* or to accept the presidency of the Royal Society until Hooke was dead.

## Reference

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