Cambridge University Press
978-0-521-27435-7 - Never at Rest: A Biography of Isaac Newton
Richard S. Westfall
Excerpt

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The discovery of a new world

Convictus primus.	Secundus.	Quadrantarij.
M^r. Johes Smith.	Ric: Smith	Johes Bigge.
	Ed: Lowrey.	Isaac Newton.
Coll: Trin:	Johes Nowell	Josua Scargell.
	Tho: Ferrar.	Georg: Crosland.
	Barhamus Olyver.	Hen: Wright.
	Johes Doud.	Johes Tenant
	Johes Hawkins.	Eras: Sturton.[1]
	Johes Rowland.	
	Ed: Jolly.	

NEWTON'S name in the matriculation book of Cambridge University on 8 July 1661, together with those of sixteen other students recently admitted to Trinity College, bears witness to an event so obviously significant in his life (as it must have been for the other sixteen, and as similiar events have been for countless young men through eight centuries of Western history) that one flirts with banality even to mention it. He had left his home in the hamlet of Woolsthorpe in Lincolnshire some five weeks earlier, a raw provincial youth venturing more than ten miles from the place of his birth probably for the first time. He had been admitted to Trinity College on 5 June. As it turned out, the change in scene involved much more than the inevitable shattering of rural provincialism. In Cambridge, Newton discovered a new world. In one sense, of course, every youth who truly enters a university discovers a new world; such is the process of education, the opening of fresh horizons. Newton discovered a new world in a more concrete sense of the phrase, however. By 1661, the radical restructuring of natural philosophy that is called the scientific revolution was well advanced. Behind the familiar facade of nature, philosophers – we would call them scientists – had indeed discovered a new world, a quantitative world instead of the qualitative world of daily experience, mechanistic instead of organic, indefinite in extent instead of finite, an alien world frightening to many but in its challenge thrilling to some. In Cambridge, Newton discovered this discovery. It was by no means inevitable or even probable that he do so, for Cambridge University did not thrust the new world of scientific thought before its students. In all likelihood, the other sixteen young men who matriculated from Trinity that day in July never suspected

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[1] Cambridge University Library, *Matriculations 1613–1702,* 8 July 1661.

its existence. The obscurity of their youth passed imperceptibly into the obscurity of their manhood, and no one today writes their biographies. Cambridge was a place where books were sold, however, and where libraries collected them. One who chose could encounter learning which the university itself did not foster; Newton chose, and with the choice determined his place in history. There were many facets to Newton's life that were not concerned with natural science, and a biography worthy of the name must present them. Nevertheless, the sole reason one undertakes to write a biography of Newton is the relation in which he stood to the new world of the scientific revolution.

As the heavens embrace our globe, so astronomy surrounded the scientific revolution. To date the beginning of an intellectual movement is always an arbitrary choice, but the succession of developments that followed the publication of Nicholas Copernicus's *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*) in 1543 has led historians almost unanimously to assign the birth of modern science to that year. Copernicus proposed a new solution to the central problem that had occupied astronomy for two thousand years, to account for the irregular motions of the planets against the unchanging background of the fixed stars.[2] Previous astronomy had started from the assumption, dictated by common sense and daily experience, that the earth is at rest. All the phenomena observed in the heavens, then, are real motions. Copernicus proposed instead that heavenly phenomena are in part mere appearances which arise from the motion of the earth.

To the earth Copernicus assigned two motions, a daily rotation on its axis and an annual revolution about the sun.[3] The daily rotation from west to east accounted of course for the apparent daily rotation of the heavens from east to west. More than four hundred years after Copernicus, we still find it convenient to speak of the rising and setting of the sun and moon; before Copernicus, they were held to do so literally. More important for astronomy, Copernicus boldly wrenched the earth from its moorings in the center of the universe, labeled it as one planet among others, and set it in motion with the others around the sun. He promoted the sun from the rank of planet and placed it at the center of the system. The annual orbit of the earth explained the most dramatic of the planetary phenomena, their periodic retrogressions in their normal progression from west to east among the fixed stars. To explain

[2] I use the phrase "new solution" in contrast to the prevailing astronomy. It is well known that Copernicus was not the first to propose a heliocentric system.

[3] Copernicus himself assigned a third motion to the earth, an annual conical motion of its axis. Kepler later pointed out that it was illusory.

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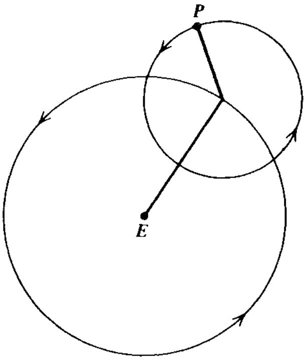

Figure 1.1. A major deferent on an epicycle whereby Ptolemaic astronomy accounted for the apparent retrogressions of the planets.

these phenomena, Greek astronomers had developed the device of the epicycle (Figure 1.1). The planets did not travel in circles about the earth; rather they traveled in circles (epicycles) the centers of which traveled in circles (deferents) about the earth. From our point of view, this solution to the major problem of planetary orbits had the effect of projecting the earth's annual orbit onto each planet's motion – as epicycle in the cases of the superior planets (Mars, Jupiter, and Saturn), as deferent in the cases of the inferior planets (Mercury and Venus). The essence of Copernicus's revision of astronomy lay in his inauguration of our point of view and in his demonstration that planetary retrogressions may be not real motions, but apparent motions deriving from the real motion of earth.

Unfortunately, the matter could not rest on this plane of simplicity. As ancient astronomers had established, one uniform circular motion centered in the earth was unable to account for the positions of the sun during a year, and two uniform circular motions, deferent and epicycle, were unable to account for the positions of the planets. In all cases there were small deviations from the positions predicted by the circles, to account for which astronomers had resorted to other devices such as tiny epicycles and eccentric circles (Figure 1.2). So also Copernicus found that a single circle could not account for the motion of the earth or of any planet around the sun. With the ancients he shared the conviction that the immutability and perfection of the heavens require astronomy to confine itself to combinations of the perfect figure, the circle. Hence he too had recourse to tiny epicycles and eccentrics to account for the same small deviations.

More than half a century later, Copernicus's greatest disciple, Johannes Kepler, completed the structure of heliocentric astronomy

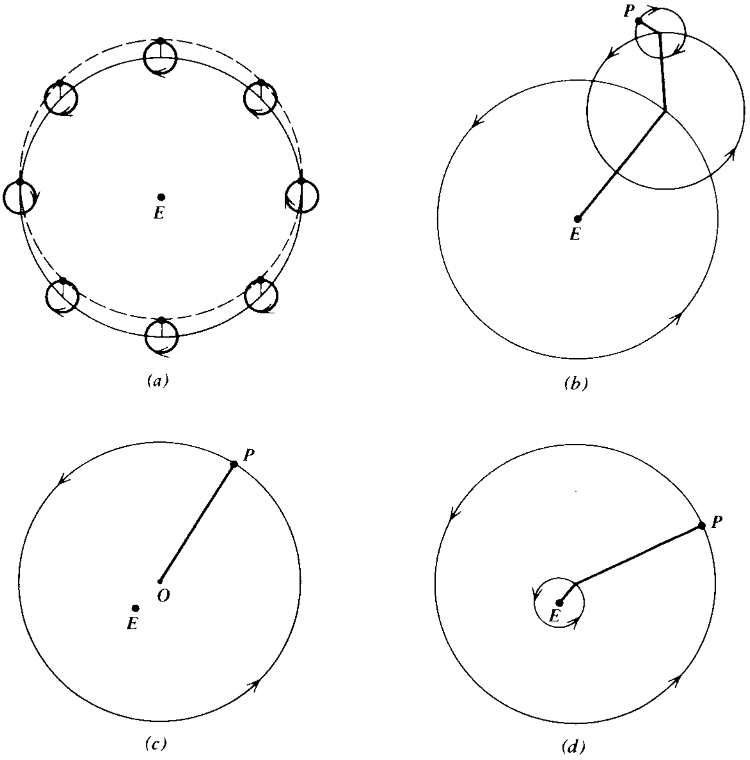

Figure 1.2. Various devices in Ptolemaic astronomy. *A* shows the effect of a minor epicycle with the same period as the deferent; *B*, an epicycle on a major epicycle; *C*, an eccentric; and *D*, an eccentric on a deferent. The size of the minor epicycles and the amount of eccentricity in relation to the size of the deferent circle are exaggerated considerably.

by abandoning the feature closest to Copernicus's heart, the perfect circle. Employing the immense body of observations compiled by the Danish astronomer, Tycho Brahe, Kepler concluded that Mars travels about the sun in an ellipse, and he promptly generalized the conclusion to all the planets. Published in his *Astronomia nova (A New Astronomy*, 1609*)*, the elliptical shape of the orbits is known as Kepler's first law. In one stroke he swept away all the machinery of epicycles and eccentrics. The minor deviations that had given rise to them merged in the elegance of a single curved line. To the first law he added a second, that the area of the ellipse swept out by the radius vector of the moving planet is proportional to the time (Figure 1.3). With the second law he fulfilled a necessary demand of every working astronomer in supplying a means by which to compute the location of a planet at any time. Ten years later, in the *Harmonices mundi (Harmonies of the World)*, Kepler added a third law

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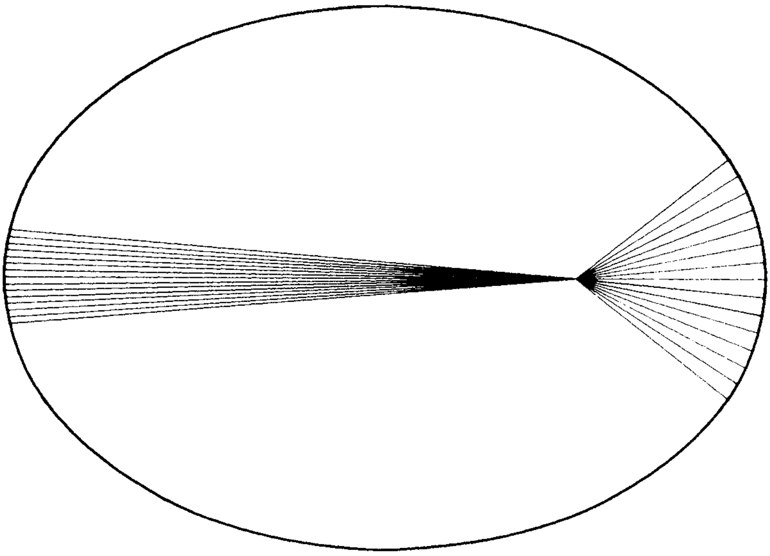

Figure 1.3. Kepler's second law, that the area swept out by the radius vector is proportional to time. The eccentricity of the ellipse is greatly exaggerated.

which tied the planets together into an organized system by relating the mean radii and periods of their orbits: $T^2 \propto R^3$.

The same year that saw the publication of Kepler's *Astronomia nova* also witnessed the entry into astronomy of the instrument destined to become its principal tool. In 1609 Galileo Galilei first turned a telescope on the heavens, and the following year he began to publish his observations. Galileo was an ardent Copernican and attempted to turn his observations to the support of the Copernican system. He observed the rugged surface of the moon, which contradicted earlier notions of the crystalline perfection of the heavens. So did the spots on the sun, which formed and dissolved in relatively short periods of time, and which moved across its face, indicating that the sun turned on its axis. He discovered satellites of Jupiter, so that the earth ceased to be unique in its accompanying satellite. He observed the phases of Venus, which were incompatible with the geocentric system since they demonstrated that Venus circles the sun. All of this and especially the last lent support to heliocentric astronomy, though there was no way in which Galileo or anyone else could observe the motion of the earth or the centrality of the sun through a telescope.[4]

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[4] The literature on the development of heliocentric astronomy is immense. A brief account can be found in Thomas Kuhn, *The Copernican Revolution* (Cambridge, Mass., 1957), a longer account in Alexandre Koyré, *The Astronomical Revolution*, trans. R. E. W. Maddison (London, 1973).

When Newton arrived in Cambridge, the learned world had had a further half century to digest the work of Copernicus, Kepler, and Galileo. From the point of view of evidence, little had changed. Not until the nineteenth century did the Foucault pendulum furnish something like a direct demonstration that the earth turns on its axis, and the observation of stellar parallax directly confirm the annual motion. Nevertheless, by 1661 the debate on the heliocentric universe had been settled; those who mattered had surrendered to the irresistible elegance of Kepler's unencumbered ellipses, supported by the striking testimony of the telescope, whatever its ambiguities might be. For Newton, the heliocentric universe was never a matter in question.

But the heliocentric universe, especially in Kepler's formulation, offered as many challenges as conclusions. There had always been a tension within the geocentric system between physical and mathematical accounts. For cosmological purposes, Aristotle's homocentric spheres, which had solidified over the years into crystalline spheres, provided the physical picture of the universe. Working astronomers had meanwhile constructed planetary theory out of the various devices of deferents, epicycles, eccentrics, and equants. A final reconciliation between the two had been impossible, but astronomers had learned simply to tolerate the disparity. Heliocentric astronomy quickly abolished the crystalline spheres. In Kepler's view, Tycho's observations of comets had shattered the spheres; Kepler's own ellipses confirmed their demise. With the spheres went the very structure of the heavens, so that the new astronomy offered the improbable assertion that planets, without any means of support or guidance, whether visible or imagined, trace and retrace precisely defined ellipses in the immensity of space.

To this unavoidable problem Kepler offered a solution in terms of forces centered in the sun, one pushing the planets along in their paths, another controlling their distances from the sun. This celestial dynamics furnished the thread of Ariadne that Kepler's investigation successfully followed. Mathematically, it was consistent with his laws. It is one of the anomalies of seventeenth-century science, however, that a new science of mechanics rendered Kepler's dynamics obsolete within a generation, although we continue to accept as valid the laws that originally emerged from the dynamics. Descartes proposed a different physical theory of the cosmos. His vortex explained the gross phenomena of a heliocentric system; it carried all the planets in the same plane in the same direction around the sun. What the vortex could not produce were the exact mathematical relations of Kepler's laws – indeed not any one of the three.

Hence the old tension between the physical structure of the cosmos and the mathematical theory of astronomy reappeared in a new setting. One difference rendered the new version of the tension impossible to tolerate. In the ancient world, physics took precedence over astronomy. Astronomers might save the phenomena with ingenious constructions, but no one asserted their physical reality. Kepler did assert the reality of his ellipses as paths that planets follow through space; and in the end, the seventeenth century believed him. One way or another, the disparity between the mathematics of the heavens and their physics would have to be resolved; until it was, a gaping hole leered at natural philosophers from the very heart of their new science. Newton was one of those who quickly perceived this fact.

Astronomy, the science of the heavens, supplied the cosmic setting of the scientific revolution. The most important skirmishes of the revolution took place on earth. Early in the seventeenth century, Galileo laid the foundations of a new science of mechanics. It was impossible for there to be a radical restructuring of natural philosophy in which mechanics, the science of motion, would remain unmoved, for motion plays a central role in every conception of nature. Like astronomy, mechanics had a tradition stretching back to the ancient world; unlike astronomy, it had been a topic of extensive and productive discussion during the Middle Ages. In addition, it was inextricably entwined in the new astronomy. On the one hand, the received mechanics of Aristotle, even with its medieval modifications, refused to be reconciled to the assertion that the earth is in motion. On the other hand, in the climate of scientific thought as it existed in 1661, only the science of mechanics could resolve the cosmic problem posed by the new astronomy. If astronomy provided the setting of the scientific revolution, mechanics supplied its solid core.

More than any other man, Galileo created the new mechanics. A convinced Copernican, he devoted his energy not to the sort of technical details whereby Kepler brought astronomical theory into agreement with the observed positions of planets, but to the question of credence raised by the affront to common sense inherent in the proposition of a moving earth. The central argument in Galileo's *Dialogo sopra i due massimi sistemi del mondo (Dialogue on the Two Chief World Systems)* hinged on this point. As astronomy, the *Dialogue* was a fraud. It expounded a heliocentric system based on circular orbits which could not even approximate observed planetary positions. As mechanics, however, it showed that a moving earth can be compatible both with untutored daily experience and with carefully observed phenomena of motion on the earth. Central to Galileo's argument was the principle of inertia. Galileo did not in fact use the word "inertia"; for that matter, he did not enunciate the

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principle in the form we accept today. Nevertheless, he redefined the concept of motion in such a manner that we recognize in it the essential aspect of our principle of inertia.

To Aristotle, to move was to be moved. The motion of any body required a moving agent. Motion implied ontological change as well. The growth of an acorn, whereby it realizes its potential to be an oak, was motion. The education of a youth, whereby he realizes his potential to be a man of reason, was motion. Manifestly, both processes require a cause, that is, an agent or mover. Equally the motion of a heavy body falling, whereby it realizes its potential as a heavy body to be as close to the center of the universe as possible, appeared to require a moving agent. In the case of the heavy body, its fall was a natural motion caused by its nature as a heavy body once impediments to fall were removed. Bodies were also subject to violent motions in which external agents forced them to go where they had no inclination of their own; the moving agents were obvious enough in violent motions. Galileo set mechanics on a new course by redefining motion to eliminate most of its Aristotelian connotations. From the discussion of motion he cut away sprouting acorns and youths alearning. Local motion, which had been for Aristotle the simplest case and hence the example most suited to analysis, became for Galileo the sum total of the meaning of motion. And to motion in this sense, he insisted, a body is indifferent. A heavy body does not realize any potential when it falls; nothing it in changes. So also no violence is done to its nature when it is flung upward. Although he frequently used the phrase "natural motion," any real distinction between natural and violent motions disappeared from his mechanics. All motion is one and the same. It is not a process whereby potential is brought into realization. Motion is simply a state in which a body finds itself, a state to which it is indifferent.

Projectile motion had furnished the classic difficulty to Aristotelian mechanics, for a projectile continues to move after it has separated from its overt mover. Aristotle had solved the difficulty by arguing that the medium through which a projectile moves functions as mover and sustains the motion. Medieval philosophers had transferred the mover from the medium to the body itself. When it is placed in motion, they argued, a body acquires an impetus, an internal motive force, which sustains the motion. Galileo reduced projectile motion to its simplest case, a ball set rolling on a horizontal plane, and in his mind's eye he observed its motion. Since he required the frictionless plane of rational mechanics and a perfectly round ball, he had to observe it in his mind's eye. He concluded that under such ideal conditions a ball will continue to roll forever, as far as the plane continues. On real planes, of course, real balls come to rest, but the smoother the plane and the rounder the ball the longer it will roll. Motion is a state to which a body is indiffer-

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ent. A ball on a horizontal plane can neither set itself in motion nor bring itself to rest. As Descartes, who shared this conception of motion, stated the case, philosophers had been asking the wrong question. They had asked what keeps a body in motion; one ought to ask instead what ever stops it.

With the new conception of motion, the principle of inertia, if I may speak loosely, the difficulties imagined to follow from the earth's motion dissolved away. Cannons fired east and west would carry equal ranges; cannons fired north and south would strike targets (or to speak more exactly perhaps of seventeenth-century gunnery, would miss them with normal facility). Objects dropped from towers would appear to observers to fall straight down since the observers are, of necessity, passengers on the same moving earth who participate in the common diurnal rotation. Galileo had more in mind than the question posed by astronomy, however. He proposed nothing less than a complete reconstruction of the science of motion – into a new science, as he proudly labeled it in his final book – and to reconstruct the science of motion completely was, in his view, to make it mathematical. Perhaps astronomy, which had always been a mathematical science of celestial motion, suggested the model. Galileo was accustomed to say that in the Copernican system the earth became a heavenly body. If the immutable heavens alone offer a subject proper to mathematics, the earth had been promoted into that class. One aspect of mechanics also offered a model of mathematical science. The balance, the lever, the inclined plane, the science of statics (as we would summarize them all), had invited mathematical treatment both in the ancient world and in medieval Europe. Archimedes especially, "divine Archimedes" as Galileo called him, had shown how the rigor of geometry could be applied even to a mundane science. Not the least of Galileo's self-esteem swelled from the realization that he had done what even divine Archimedes had not: To the mathematical science of bodies in equilibrium he had added a mathematical science of bodies in motion.

Galileo's new conception of motion supplied the cornerstone for the new structure. Defined mathematically, the motion of a perfect ball rolling on a frictionless horizontal plane is uniform motion. In equal periods of time it traverses equal distances. Bodies also move vertically, of course, and it had long been observed that when they fall, they move with increasing velocity. Medieval philosophers had even defined "uniformly difform motion," but they had analyzed it in the abstract without applying the definition to real motions. Changing the name to "uniformly accelerated motion," Galileo identified it with the motion of heavy bodies falling.[5] A body in

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[5] As in the case of Copernicus, Galileo had a predecessor. Domingo de Soto, a Spanish scholastic of the mid-sixteenth century, had identified free fall as uniformly difform motion. He had not elaborated a full system of kinematics on the basis of his insight, however.

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uniformly accelerated motion gains (or loses) equal increments of velocity in equal increments of time. Since he held, again in opposition to Aristotle, that all bodies are composed of the same matter, which is always heavy, he reasoned that bodies everywhere on the earth, whatever their size and whatever their substance, fall with a rate of acceleration common to them all. As in the case of uniform motion, the assertion supposed ideal conditions analogous to his frictionless planes. Since a medium such as air is always present, actual fall never realizes uniformly accelerated motion. As with horizontal motions again, the more one approximates ideal conditions, the more one approaches the defined motion.

The speed with which ordinary bodies fall, combined with the crudity of the instruments available to measure time, made it impossible to check this theory directly. Galileo recognized, however, that he could observe the identical phenomenon, slowed down to a measurable rate, on inclined planes. The established analysis of inclined planes even permitted him to calculate how much it is slowed down. Using a water clock to measure time, he corroborated the fact of uniformly accelerated motion in nature.

From the definition of uniformly accelerated motion Galileo proceeded to deduce the basic relations of kinematics that students still learn on their first introduction to mechanics, that a body falling from rest traverses distances proportional to the square of the time of the fall, that its velocity is proportional to the time of the fall and to the square root of the distance fallen. As a final tour de force, he demonstrated that a projectile, which (again under ideal conditions) moves with a motion compounded of uniform horizontal and uniformly accelerated vertical elements, must follow a parabolic trajectory.[6]

By 1661, the science of mechanics had assumed an anomalous stance. Though Galileo had not written in the Latin of the learned world but in Italian, a number of publicists had made his results available to the European scientific community. His relations of acceleration, velocity, distance and time both in uniform and in uniformly accelerated motion had become the common property of the science, accepted by all and questioned by none. Nevertheless,

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[6] The literature on Galileo is at least as immense as that on the new astronomy. The most influential work has been Alexandre Koyré, *Etudes galiléennes* (Paris, 1939). Maurice Clavelin, *La Philosophie naturelle de Galilée* (Paris 1968), offers a more recent, excellent account. Stillman Drake has treated Galileo's mechanics in a series of articles too numerous to quote entirely here; among the most important are "The Concept of Inertia," *Saggi su Galileo Galilei* (Florence, 1967), pp. 3–14; "Galileo and the Law of Inertia," *American Journal of Physics*, *32* (1964), 601–8; "Uniform Acceleration, Space, and Time," *British Journal for the History of Science*, *5* (1970), 21–43. He has recently summarized his work on Galileo in *Galileo at Work: His Scientific Biography* (Chicago, 1978). *Galileo, Man of Science*, ed. Ernan McMullin (New York, 1967), contains articles which deal with every aspect and the majo interpretations of Galileo's science.