Cambridge University Press
978-1-107-01546-3 - The Cambridge Companion to Newton: Second Edition
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Introduction

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Isaac Newton was *the* giant of science in the seventeenth and eighteenth centuries, just as James Clerk Maxwell was *the* giant of science during the latter nineteenth century. By providing a completely novel cosmology, in which a taxonomy of interactive forces among particles of matter was fundamental, his *Principia Mathematica* of 1687 constituted an exemplary scientific revolution. This supplanted not only the Aristotelian system, but also that of the so-called "mechanical philosophy" espoused by moderns such as Descartes. Conceptions such as "mass" and "force" were quickly recognized by Newton's contemporaries as powerful concepts for representing aspects of bodies that allowed them to be measured and their dynamical interactions calculated. Newton's claim that almost all of the cosmos (including the internal structure of bodies) was entirely empty of matter, however, was deeply unpalatable to those committed to plenist and vortical accounts. Worst of all, many found Newton's great doctrine of universal gravitation, and the notion of "attraction" that underlay it, wholly unacceptable. It was easy for his most adept commentators to reject the idea of objects attracting each other immediately over vast distances as a return to the objectionable occult qualities of the scholastics.

The problems with accepting the reality of universal gravitation were linked to criticisms of the new conception of theory that Newton offered. The standard view, accepted both by scholastic natural philosophy and the mechanical philosophy, was that such phenomena were to be explicated in terms of known physical causes. Newton launched repeated attacks on the way that many of his contemporaries explained natural phenomena by means of what he called "hypothetical" metaphysical or physical entities such as "corpuscles" or the "aether," many of which formed central parts of great (but, to Newton, fictitious) cosmological systems. It should be said that this remained Newton's official public position only, for in private, and over more than six decades, he had a firm conviction about the existence of corpuscles and aethers. Occasionally these views became more widely known, notably in the "Hypothesis" read out to the Royal Society in the winter of 1675–6 and in the "Queries" added to his *Optice* of 1706 and to the second edition of *Opticks* in 1717.

Most importantly, however, Newton brought together an empiricist, inductivist and anti-hypotheticalist sensibility from his immersion in the writings of Hooke and Boyle with a commitment to a mathematical approach to nature inspired by writers such as Galileo and Christiaan Huygens. Propositions were to be inferred from phenomena, Newton proclaimed, and made more general by induction until one arrived at the most general laws of nature. These laws, which were mathematical, could then be used to explain phenomena in the relevant domain of their application. This was enough to count as explanation within natural philosophy, with no need to have recourse to as yet unconfirmed underlying entities. Newton left open the possibility, however, that future empirical research would confirm the existence of entities that were currently undetectable.

Nothing about Newton is better known than the story that he came upon his theory of gravity while contemplating the fall of an apple in his mother's garden when away from Cambridge during the plague. Newton definitely did give careful thought at some point during the late 1660s to the possibility that terrestrial gravity extends, in an inverse-square proportion, to the Moon. From his papers and correspondence, however, we can clearly see that the earliest date that can be assigned to his theory of universal gravity is late 1684 or early 1685, during the course of his revision of the tract "De motu." As I. B. Cohen shows in his chapter, a necessary precondition for his conception of universal gravitation was his creation of the new concepts of *mass* and *force*, which were also required for his laws of motion, a topic examined in Bruce Pourciau's chapter as well as Cohen's. The theory of gravity did not arise as a "eureka" moment in a Lincolnshire garden, but was a product of thoughts about orbital motion extending over many years.

From the point of view of his contemporaries, Newton's theory consisted of a sequence of progressively more controversial claims: from the inverse-square centripetal acceleration of orbiting bodies to interactive forces not merely between orbiting and central bodies, but among the different orbiting bodies as well; then, to the law of gravity according to which the forces on orbiting bodies are proportional to the masses of the distant bodies toward which these forces are directed; and finally to the sweeping claim that there are gravitational forces between every two particles of matter in the universe. William Harper's chapter on Newton's "deduction" of his theory of gravity examines how Newton put this sequence forward, invoking specific evidence for each claim in turn. Even the most outspoken critics of universal gravitation thought Newton had established some of the claims in the sequence. Though they balked at different points, the common feature was where they thought concession of a claim was tantamount to conceding action at a distance. Newton himself was troubled by action at a distance – so much so that it seems to have driven him into thinking through and then laying out a new, elaborate approach to how empirical science ought to be done, an approach that the *Principia* was expressly intended to illustrate.

Curtis Wilson's chapter shows that Newton's important achievement in celestial mechanics involved two seemingly incompatible points. On the one hand, the *Principia* raised Kepler's rules, especially the area rule, from the status of one among several competing approaches to calculating orbits, to the status where they came to be thought of as laws, *the* laws of planetary motion. On the other hand, the *Principia* concluded that none of Kepler's "laws" is in fact exactly true of the actual system of planets or their satellites, and this in turn shifted the focus of orbital mechanics to deviations from Keplerian motion. With the exception of a few results on the lunar orbit, the *Principia* made no attempt to derive these deviations, and even in the case of the lunar orbit it left one major loose end that became a celebrated issue during the 1740s. The difficult task of reconciling Newtonian theory with observation occupied the remainder of the eighteenth century following Newton's death. This effort culminated with Laplace's *Celestial Mechanics*, the first volumes of which appeared in the last years of the century. It was in these volumes that what physicists now speak of as Newtonian physics first appeared comprehensively in print, more than a hundred years after the first edition of the *Principia*.

Robert DiSalle's chapter shows that the relationship between Einstein's theories of special and general relativity and Newton's theories of motion and gravity is an intricate one. Still, one point that is certain is that Einstein did not show that Leibniz had been correct in his claims about the relativity of space. For Leibniz denied that there can be any fact of the matter about whether the Earth is orbiting the Sun, or the Sun the Earth, and Einstein's theories do not show this. Newtonian gravity holds in the static, weak-field limit of Einsteinian gravity, so that the former bears the same sort of relationship to the latter that Galilean uniform gravity bears to Newtonian gravity, allowing the evidence for the earlier theory in each case to carry over, with suitable qualifications about levels of accuracy, to the later theory. Moreover, as Euler showed in the late 1740s, and as Kant learned from Euler,[1] Newton's approach to space and time is inextricably tied to his laws of motion, in particular to the law of inertia. Abandoning Newtonian space and time in the manner Leibniz called for would entail abandoning the law of inertia as formulated in the seventeenth century, a law at the heart of Leibniz's dynamics. In gaining ascendancy over Leibniz's objections, Newton did not set physics down a dead-end path from which it was finally rescued by Einstein; rather, Einstein's theories of relativity represent a further major step along the path initiated by Newton.

A BRIEF BIOGRAPHICAL SKETCH

Newton's pre-Cambridge youth spans the period from the start of the Civil War to the Restoration of Charles II. He was born in Woolsthorpe, a tiny village near Grantham, on Christmas Day 1642, a little short of twelve months after Galileo had died.[2] Newton's father, who had died the previous October, was a farmer. Three years after Newton's birth, his mother Hannah married a well-to-do clergyman, 63-year-old Barnabas Smith, rector of the neighboring village of North Witham. She moved to her new husband's residence, leaving young Isaac behind, to be raised in the family home, Woolsthorpe Manor, by his maternal grandparents.[3] When Smith died in 1653, Hannah returned to the family farm with three new children in tow. Less than two years later Newton was sent to the Grantham Free School, returning to Woolsthorpe in the winter of 1659–60. The family expected that he would manage his father's farm, but it soon became evident that – to put it mildly – he was not cut out for the job. Henry Stokes, the headmaster of Newton's school, and Hannah's brother William Aiscough, who had received an M.A. from Cambridge, persuaded her that her son's destiny lay elsewhere and he returned to Grantham to prepare for a university education. In the summer of 1661 he entered Trinity, his uncle's Cambridge college, as an undergraduate.

Newton's years at Trinity College, as a student and Fellow and then as a professor, were spent predominantly in solitary intellectual pursuits. As an undergraduate he read the works of Aristotle and later commentators and some scientific works such as Kepler on optics. At some point towards the end of his third year as a student, he began reading widely on his own. In early 1664 he appears to have abruptly ended his interest in scholastic texts and ideas, and turned to the contemporary writings of such figures as René Descartes, Henry More, Robert Boyle, and Robert Hooke. His undergraduate notebook, which contains his scholastic notes on natural philosophy, his notes on modern natural philosophers, and his very first scientific experiments, reveals how Newton very quickly spotted serious problems with the views of such authors. The research program that led to his discovery of the heterogeneity of white light and the construction of the reflecting telescope emerged from a number of different ideas and approaches. These included theoretical speculations about the speed of globules constituting different colored lights, the anatomical dissection of the optic nerve of a sheep, the examination of variously colored threads through a prism, and the insertion of a bodkin and a brass plate underneath his eyeball to test the power of his imagination. His notes show how he repeatedly turned questions into research projects by devising innovative empirical tests.[4]

Restoration Cambridge also boasted one of the leading British mathematicians, Isaac Barrow, whose lectures he attended. Barrow happened to be at Newton's college, and the two men communicated with each other on various topics in mathematics and optics over the next few years. It is highly likely that Newton's first forays into mathematics and natural philosophy were guided by Barrow but the evidence from Newton's two student mathematical notebooks shows that, early on, he engaged in entirely independent and path-breaking research in a series of areas in mathematics. This was carried out through extensive reading of recent publications, most notably the second edition of van Schooten's Latin translation, with added commentary, of Descartes's *Géometrie*.[5]

Within an incredibly short period of less than two years, Newton had mastered the subject of mathematics, becoming de facto the leading mathematician in the world. He reached this status during the inaccurately styled "annus mirabilis" of 1664–6, when the university was closed because of the great plague and he returned to the family farm in Woolsthorpe. It was during this period that Newton developed the basic results of the differential and integral calculus, including the fundamental theorem relating the two. At the same time, he also made experiments on refraction and color that similarly put him at the forefront in optics. His notebooks from the mid 1660s show him working out answers to questions about motion, most notably uniform circular motion, that were undoubtedly provoked by his engagement with the ideas of Galileo and especially Descartes (from whom, among much else, he learned the law of inertia). It was also during this early period that Newton independently discovered the v^2/r rule for uniform circular motion, a few years before Christiaan

Huygens, who had discovered it in 1659, published it in his renowned *Horologium Oscillatorium*.

On his return to Cambridge following the plague years, Newton was elected a Fellow of Trinity College, receiving his M.A. in 1668. During these years, he continued his work in mathematics and optics, and he became immersed in chemical and alchemical research. At some point in the summer of 1669 he wrote a tract, "De Analysi," or "On Analysis by Infinite Series," in which he presented his key discoveries in the calculus. This work was circulated among British mathematicians and, notably, a copy was sent to the 'intelligencer' John Collins in London. It was undoubtedly because of this tract that Barrow recommended the youthful Newton to succeed him as Lucasian Professor of Mathematics. Newton occupied this chair from 1669 until he formally resigned in 1701, five years after moving to London.

Newton's publications before the *Principia* amounted to the series of letters on the theory of light and colors, including the invention of a reflecting telescope, published in the *Philosophical Transactions of the Royal Society* from 1672 to 1676. He was so embittered by the controversies that were engendered by these publications that he vowed to publish no further results from his research in natural philosophy. The statutes of his Lucasian chair did require him to deposit annually a copy of his lectures in the University Library. Among these are his Optical Lectures of 1670–2, which present an enormous range of experiments bolstering and complementing those described in his publications, and a series of Lectures on Algebra given from 1673 to 1683. The technical proficiency reached in these lectures makes it plain that – on the assumption that the surviving texts represent something similar to what was delivered in class – very few students could have handled the material.

In late 1679, in an effort to reinvigorate the activities of the Royal Society, Robert Hooke wrote to Newton concerning his "hypothesis" that curved or orbital motion could be analyzed by supposing two components: an inertial tangential motion and an accelerated motion directed toward a center of force. He also raised the question of the precise trajectory described by a body under an inverse-square force directed toward a central point in space. During the course of this brief correspondence, Newton discovered the relation between inverse-square centripetal forces and Keplerian motion that comprises the initial stepping-stone of the *Principia*. Yet whatever further conclusions he reached at the time, universal gravity was not one of them. This is clear from his correspondence with the Astronomer Royal John Flamsteed, following the appearance of the "Great Comet" at the end of 1680. Flamsteed initially suggested that two objects seen in December 1680 and January 1681 were the same celestial object, first attracted and then repelled in front of the Sun by a magnetic force. In response, Newton argued that if it had really been one object then it had inexplicably slowed down during the phase where its direction was reversed. Moreover, no magnet-type mechanism could explain this sudden cometary *volte face*. Putting both of these insights together, Newton suggested that if it was really the same comet then it must have gone around the back of the Sun, and he also noted that the Sun must have continually exercised an attractive force during the whole episode. It is clear from his remarks that, although he had effectively demolished the idea that the force was magnetic, he had as yet no alternative to put in its place.[6]

In the summer of 1684 Edmond Halley visited Newton in Cambridge in order to ask him a question that the London savants could not answer: what curved path results from an inverse-square force directed toward a center? Newton is reported to have replied without any hesitation: the curve is an ellipse. Although he could not lay his hands on a demonstration he had allegedly already written out, he promised Halley that he would send the proof on to London. In November, Halley duly received the proof as part of a longer (though still short) tract entitled "De motu corporum in gyrum." He was so impressed by the magnitude of Newton's achievement that he hastened to Cambridge for a second visit. On arrival, he learned that the reclusive professor was continuing research on orbital motion, and having ascertained that the tract was going to be expanded into a book, Halley agreed to supervise its publication on behalf of the Royal Society. The manuscript of Book 1 of the *Principia* arrived in London in spring of 1686, prompting a bitter dispute with Hooke, who claimed priority for the concept of an inverse-square solar force. Halley managed to keep Newton working in spite of the controversy, finally receiving Book 2 in March and Book 3 in April 1687.[7]

Publication of the *Principia* in 1687, which ended Newton's life of comparative isolation, led to adulation in Britain and intense opposition to his theory of gravity elsewhere. Other events also impinged on his life of donnish retirement. As early as February 1687, before he had even sent Halley Book 2, Newton became embroiled in efforts to defend the University of Cambridge from having to obey an order issued by the Roman Catholic King James II compelling them to award degrees to Catholics. He was one of eight dons who appeared before Judge Jeffreys to argue the university's case a few months later, and it was because of this, as much as his acknowledged intellectual and personal merits, that in the immediate wake of the Glorious Revolution he was elected to the Convention Parliament as a representative of the university. During his time as an MP, Newton did a great deal of committee work on business relating to religious toleration and the statutes of the two English universities, but he decided not to seek immediate re-election after the Parliamentary session was ended by William III in January 1690.

Newton now threw himself into a wide range of intellectual projects with a degree of intensity that matched that of the plague years. Freed from the demands of political life, he initiated work on a radically restructured second edition of the *Principia* and a never-finished comprehensive treatise on geometry, and he undertook sustained research projects on theological topics. In 1691 he did some remarkable work on integration in a paper entitled "De Quadratura Curvarum," although this was only published in 1704 (in order to assert his priority in the area) as an addition to the first edition of *Opticks*.

He also continued experimental research in alchemy and performed novel experiments on diffraction phenomena, laying out the basic structure of what would become *Opticks*. His best scientific work in this period was on the theory of the Moon's motion, carried out in the middle of the 1690s. This was the last piece of innovative work in the natural sciences that he undertook, though it ultimately ended in failure. It also triggered over two decades of hostilities with John Flamsteed, who would write a searing and by no means inaccurate account of Newton's morals and behavior in a private reminiscence.

Chronic overwork, coupled with the emergence of an ever-simmering paranoia that was fueled by his failure to land a plum job in London, both contributed to the catastrophic breakdown that he experienced in late summer 1693. These troubles soon abated, however, and with the support of his patron and erstwhile Trinity colleague Charles Montagu, he was appointed Warden of the Mint in 1696, and Master of the Mint three years later. By the first decade of the eighteenth century he was renowned in the Republic of Letters as a man of the highest intellectual abilities, as well as being a politician and a senior government administrator. He was elected President of the Royal Society in 1703, a post he held until his death, and he was knighted for his services to the government in 1705. Catherine Barton, the vivacious teenage daughter of his half-sister, moved in with him not long after he became Warden of the Mint, gaining great prominence in London social circles. She continued to reside with him until he died, even after she married John Conduitt (who succeeded Newton as Master of the Mint) in 1717.

The first decade of the new century witnessed the publication of the first edition of his *Opticks*, a work written in English rather than in Latin. In addition to "De Quadratura Curvarum" (which exhibited Newton's dot-notation for differentials), the appendix contained "Enumeratio Linearum Tertii Ordinis." In quick succession he published *Optice* (1706), translated from English by his confidant Samuel Clarke, and he authorized the publication of his lectures on algebra.