Introduction

> Natural Philosophy consists in discovering the frame and operations of Nature, and reducing them, as far as may be, to general Rules or Laws – establishing these rules by observations and experiments, and thence deducing the causes and effects of things.
>
> – Isaac Newton[1]

Newton as natural philosopher

Newton's scientific influence permeates our culture. Forces are measured in newtons, we have "Newton's rings" and Newtonian fluids, we apply Newtonian mechanics in a remarkably wide range of cases, and the law of universal gravitation characterizes what is still considered to be a fundamental force. Indeed, the very idea that a force can be "fundamental," irreducible to any other force or phenomenon in nature, is largely due to Newton, and still has currency in the twenty-first century. Because of these achievements, Newton is regularly mentioned in the same breath with Copernicus and Galileo as a founder of modern science. Although Newton is rarely listed along with figures like Descartes or Spinoza as a founder of modern philosophy, and although he never wrote a treatise of the order of the *Meditations* or the *Ethics*, his influence on philosophy in

[1] Quoted by Richard Westfall, *Never at Rest* (Cambridge: Cambridge University Press, 1980), 632. This passage from Newton's "Scheme for establishing the Royal Society" represents a contribution to the debate between naturalists and mathematically minded philosophers in the Royal Society before Newton ascended to its Presidency. For a discussion, see Mordechai Feingold, "Mathematicians and Naturalists," in Jed Buchwald and I. Bernard Cohen (eds.), *Isaac Newton's Natural Philosophy* (Cambridge, MA: MIT Press, 2001).

the early modern period was nevertheless profound. Indeed, Newton was one of the great practitioners of what the early moderns called "natural philosophy."[2]

Fully understanding Newton means avoiding anachronistically substituting our conception of philosophy in the twenty-first century for what the early moderns understood by "natural philosophy." To be sure, the latter includes much that we now call "science," and yet it includes much else besides. Just as Newton painstakingly derived proposition after proposition concerning (say) the motion of bodies under certain conditions, he painstakingly went through draft after draft of his thoughts about (e.g.) the metaphysical status of space and time and God's relation to the "system of the world." This remains true despite the fact that his work on the former bequeathed to us a conception of science in which discussions of the latter play little if any role. Interpreting Newton solely as a "scientist" whose work spawned discussion by canonical philosophical figures ignores his contributions to the philosophical conversation in England and the Continent in his day. Newton was troubled by, and addressed, a range of issues that he considered to be philosophical in nature. These issues include the extent and underpinnings of our knowledge in physics; the ontological status of space and time; the relation between metaphysical and religious commitments on the one hand and empirical science on the other; and the proper characterization of God's creation of – and place within – the universe.

Thinking of Newton as a natural philosopher can also illuminate his intellectual influence on eighteenth-century philosophy, an influence that can hardly be overestimated and that spans the entire century, both in England and the Continent. The influence has at least two salient aspects. Newton's achievement in the *Opticks* and in the *Principia* was understood to be of such philosophical import that few philosophers in the eighteenth century remained silent on it. Most of the canonical philosophers in this period sought to interpret various of Newton's epistemic claims within the terms of their own systems, and many saw the coherence of their own views with those of Newton as a criterion of philosophical excellence.

[2] See Howard Stein, "Newton's Metaphysics," and Alan Gabbey, "Newton, Active Powers, and the Mechanical Philosophy," chs. 8 and 10, respectively, in I. Bernard Cohen and George Smith (eds.), *The Cambridge Companion to Newton* (Cambridge: Cambridge University Press, 2002), and Ernan McMullin, "The Impact of Newton's *Principia* on the Philosophy of Science," *Philosophy of Science* 68 (2001).

Early in the century, Berkeley grappled with Newton's work on the calculus in *The Analyst* and with his dynamics in *De Motu*, and he even discussed gravity, the paradigmatic Newtonian force, in his popular work *Three Dialogues between Hylas and Philonous* (1713). When Berkeley lists what philosophers take to be the so-called primary qualities of material bodies in the *Dialogues*, he remarkably adds "gravity" to the more familiar list of size, shape, motion, and solidity, thereby suggesting that the received view of material bodies had already changed before the second edition of the *Principia* had circulated widely. Hume interpreted Newtonian natural philosophy in an empiricist vein and noted some of its broader implications in his *Treatise of Human Nature* (1739) and *Enquiry Concerning Human Understanding* (1750). On the Continent, Kant attempted to forge a philosophically robust meditation between Leibnizian metaphysics and Newtonian natural philosophy, discussing Newtonian science at length in his *Metaphysical Foundations of Natural Science* (1786).

Newton's work also served as the impetus for the extremely influential correspondence between Leibniz and the Newtonian Samuel Clarke early in the century, a correspondence that proved significant even for thinkers writing toward the century's end. Unlike the *vis viva* controversy and other disputes between the Cartesians and the Leibnizians, which died out by the middle of the century, the debate between the Leibnizians and the Newtonians remained philosophically salient for decades, serving as the backdrop to Kant's treatment of space and time in the *Critique of Pure Reason* in 1781. Newton's work also spawned an immense commentarial literature in English, French, and Latin, including John Keill's *Introduction to Natural Philosophy* (1726), Henry Pemberton's *A View of Sir Isaac Newton's Philosophy* (1728), Voltaire's *Elements of the Philosophy of Newton* (1738), Emelie Du Châtelet's *Institutions of Physics* (1740), Willem s'Gravesande's *Mathematical Elements of Natural Philosophy* (1747), and Colin MacLaurin's *An Account of Sir Isaac Newton's Philosophical Discoveries* (1748). These and other commentaries were printed in various editions, were translated into various languages, and were often influential.

A second aspect of Newton's influence involves thinkers who attempted in one way or another to follow the Newtonian "method" in natural philosophy when treating issues and questions that Newton ignored. Euclidean geometry and its methods were seen as a fundamental epistemic model for much of seventeenth-century philosophy – Descartes' *Meditations* attempts to achieve a type of certainty he likens to that found in geometry, and Spinoza wrote his *Ethics* according to the "geometrical method." Propositions deduced from theorems in Euclidean geometry were seen as paradigm cases of knowledge. We might see Newton's work as providing eighteenth-century philosophy with one of its primary models, and with a series of epistemic exemplars as well. David Hume is perhaps clearest about this aspect of Newton's influence. His *Treatise* of 1739 has the subtitle: "An Attempt to Introduce the Experimental Method of Reasoning Into Moral Subjects," and there can be no doubt that he meant the method of the *Opticks* and the *Principia*. Indeed, as Hume's text makes abundantly clear, various eighteenth-century philosophers, including not only Hume in Scotland but Jean-Jacques Rousseau on the Continent, were taken to be, or attempted to become, "the Newton of the mind." For Hume, this meant following what he took to be Newton's empirical method by providing the proper description of the relevant natural phenomena and then finding the most general principles that account for them. This method would allow us to achieve the highest level of knowledge attainable in the realm of what Hume calls "matters of fact."[3]

Despite the influence of Newton's "method" on eighteenth-century philosophy, it is obvious that the *Principia*'s greater impact on the eighteenth century is to have effected a separation between technical physics on the one hand, and philosophy on the other. In the hands of figures like Laplace and Lagrange, Newton's work led to the progressive development of Newtonian mechanics, which remained the canonical expression of our understanding of many natural phenomena long after Newton's influence in philosophy proper had ceased to be felt. And yet to achieve an understanding of how Newton himself understood natural philosophy, we must carefully bracket such historical developments. To cite Kuhn's understanding of the development of a science, although Newton provided physics with its paradigm, he himself worked largely within its pre-paradigmatic context, and the pre-paradigmatic state, according to Kuhn, is typically characterized by extensive epistemological debates and controversies over the "foundations" or "first principles" of the science.[4] Newton himself engages in precisely these discussions both in

[3] A proposition expressing a matter of fact cannot be known to be true without appeal to experience because, unlike in the case of "relations of ideas," the negation of the proposition is not contradictory. This distinction lives on, somewhat altered, in Kant's distinction between analytic and synthetic judgments.

[4] Thomas Kuhn, *The Structure of Scientific Revolutions*, 3rd edn. (Chicago: University of Chicago Press, 1996), 88.

his optical work and in the *Principia* itself: his discussion of hypotheses, of space and time, and of the proper rules guiding research in natural philosophy are each intended to loosen what Newton took to be the pernicious grip of Cartesian notions within natural philosophy. So Newton's scientific achievement was in part to have vanquished both Cartesian and Leibnizian physics; in the eighteenth century, and indeed much of the nineteenth, physics was largely a Newtonian enterprise. But this achievement, from Newton's own perspective, involved an extensive, life-long series of philosophical debates. To ignore this is perhaps to ignore how Newton himself understood natural philosophy and its themes. I discuss several of those themes in what follows.

Newton's career and correspondence

Isaac Newton was born into a rural middle-class family in Woolsthorpe, Lincolnshire in 1642, the year of Galileo's death. Newton's philosophical training and work began early in his intellectual career while he was an undergraduate at Trinity College, Cambridge in the early 1660s. The notebooks that survive from that period[5] indicate his wide-ranging interests in topics philosophical, along with a reasonably serious acquaintance with the great "moderns" of the day, including Robert Boyle, Hobbes, Gassendi, and especially Descartes. Later in his life, Newton corresponded directly with a number of significant figures in natural philosophy, including Boyle, Huygens, and Leibniz. Newton's primary works, of course, are *Philosophiae Naturalis Principia Mathematica* – or *Mathematical Principles of Natural Philosophy* – and the *Opticks*. Each went through three successive editions during Newton's lifetime, which he oversaw under the editorship of various colleagues.[6]

[5] See J. E. McGuire and Martin Tamny (eds.), *Certain Philosophical Questions: Newton's Trinity Notebook* (Cambridge: Cambridge University Press, 1983).

[6] The *Principia* first appeared in 1687, ran into its third edition in 1726, just before Newton's death, and was translated into English by Andrew Motte in 1729; the Motte translation – as modified by Florian Cajori in a 1934 edition – remained the standard until I. Bernard Cohen and Anne Whitman published their entirely new version in 1999 (selections in this volume are from this edition; see the Note on Texts and Translations below). It also appeared in 1759 in an influential French translation by Emilie du Châtelet, the famous French Newtonian; remarkably, her translation remains the standard in French to this day. The *Opticks* first appeared in 1704, ran into its third edition in 1721, and was translated into Latin in 1706 by Samuel Clarke, Newton's famous defender in the correspondence with Leibniz; the Clarke translation ensured the text's accessibility on the Continent.

In addition to his published works and unpublished manuscripts, Newton's correspondence was extensive. It is important to remember that in Newton's day, intellectual correspondence was not seen solely, or perhaps even primarily, as a private affair between two individuals. It was viewed in much less constrained terms as a type of text that had an important public dimension, not least because it served as the primary vehicle of communication for writers separated by what were then considered to be great distances. As the thousands of letters sent to and from the Royal Society in Newton's day testify, science and philosophy would have ceased without this means of communicating ideas, results, and questions. It was therefore not at all unusual for letters between famous writers to be published essentially unedited. The Leibniz-Clarke correspondence was published almost immediately after Leibniz's death in 1716, Newton's correspondence with Richard Bentley was published in the mid-eighteenth century, and several of the letters reprinted in this volume were published in various journals and academic forums – including the Royal Society's *Philosophical Transactions* – in the late seventeenth and early eighteenth century.

Early work in optics

Although Newton's correspondence with the Royal Society and its members began reasonably early in his career, it is crucial for understanding his mature conception of natural philosophy and his life-long aversion to intellectual controversy. Newton's early optical work, which cannot be included in this volume, provides a significant example. In February of 1671/2, an article appeared in the *Philosophical Transactions* with the title: "A Letter of Mr. Isaac Newton."[7] In this discussion, Newton attempts to distinguish the presentation of an empirically based scientific theory from the presentation of what he would later term "hypotheses" concerning the nature of some phenomena described by a theory.

7 "A Letter of Mr. Isaac Newton, Professor of the Mathematics in the University of Cambridge; containing his New Theory about Light and Colors," *Philosophical Transactions of the Royal Society* 6 (Feb. 1671/2): 3075–87; reprinted in *Isaac Newton's Papers and Letters on Natural Philosophy*, ed. I. Bernard Cohen and Robert Schofield (Cambridge, MA: Harvard University Press, 1958). Newton's so-called second paper on light and colors, read at the Royal Society in 1675/6, is also reprinted in the edition by Cohen and Schofield. Cf. also *The Optical Papers of Isaac Newton*, vol. 1, ed. Alan Shapiro (Cambridge: Cambridge University Press, 1984).

Consider the structure of Newton's argument in this letter:[8]

(1) It is commonly assumed that the rays of sunlight are equally refrangible.
(2) A first experiment shows that when a beam of sunlight is allowed to enter a darkened room and to pass through a prism, the shape of the spectrum projected onto the opposite wall of the room is oblong.
(3) The assumption at (1) predicts that the shape of the spectrum should be circular.
(4) A possible explanation for this divergence is that the prism alters the sunlight by breaking it into smaller rays that bear differential refrangibility (hence an oblong rather than a circular spectrum results).
(5) A second experiment – the so-called *experimentum crucis* – involves the same experimental set-up as above, with a second prism placed so that the beam of sunlight, having passed through the first prism, then passes through the second. The spectrum remains oblong – that is, the second prism does not cancel the effect of the first prism.
(6) Since the second prism does not cancel the effect of the first prism, Newton concludes that the explanation at (4) should be rejected.
(7) Newton claims that since the explanation at (4) can be rejected because of the experiment at (5), and because the assumption at (1) predicts that the spectrum should be circular when in fact it is oblong, we should reject (1).
(8) Newton concludes from (7) that light rays are differentially refrangible.
(9) In the experiment involving the second prism noted at (5), the colors into which the sunlight is broken by the first prism retain their indexes of refraction after emerging from the second prism. So the differential refrangibility of the rays of light into which the sunlight is broken is correlated with the colors of those rays.
(10) Since we have concluded at (8) that rays of light are differentially refrangible "originally" – i.e. this is not due to the alteration of the light by a prism – we can conclude from (9) that sunlight is heterogeneous. That is, sunlight consists of constituent colored rays of light; colors do not result from modifications of sunlight.

[8] I follow the interpretation in A. I. Sabra, *Theories of Light from Descartes to Newton*, 2nd edn. (Cambridge: Cambridge University Press, 1981), 240ff.

The first problem Newton encountered in response to this argument is that what he calls his "theory" of light and colors was immediately misunderstood, at least from his point of view. Soon after Newton published his paper, Robert Hooke responded with a detailed letter to Henry Oldenburg, the Royal Society's secretary. From Hooke's perspective, Newton's "theory" or "hypothesis" does not principally concern the claims about differential refrangibility and heterogeneity; rather, the latter represent alleged properties of the phenomena that must be saved by a theory or hypothesis.[9] So Hooke searches Newton's paper for such a hypothesis and finds the notion, mentioned briefly by Newton, that light is a "body."[10] Hooke takes his debate with Newton to hinge on whether light consists of particles, as he thinks Newton maintains, or of waves, as Hooke alleges.

Hooke was not alone in his interpretation. In a letter to Huygens explaining Newton's theory of light, Leibniz writes that Newton takes light to be a "body" propelled from the sun to the earth which, according to Leibniz, Newton takes to explain both the differential refrangibility of rays of light and the phenomena of colors.[11]

So for Newton's interlocutors, a scientific theory or hypothesis is, broadly speaking, a conception of the nature of some phenomenon; it is a conception of what the phenomenon is. One accounts for the relevant empirical data – one saves the phenomena – precisely by describing this nature. This does not entail that Hooke or others took the saving of the phenomena in this sense to determine which hypothesis about the nature of light is correct; on the contrary, Hooke's principal point is that his theory

9 That Hooke does not think of these issues as forming an essential part of Newton's theory is clear for two reasons: (1) he is not concerned to reject the claim about differential refrangibility, but is concerned to reject Newton's theory; and (2) he takes his own hypothesis to be capable of accounting for both the fact about refrangibility and the fact, if it is a fact, about heterogeneity. See Hooke to Oldenburg, 15 Feb. 1671/2, in *The Correspondence of Isaac Newton*, ed. Herbert Turnbull, John Scott, A. R. Hall, and Laura Tilling (Cambridge: Cambridge University Press, 1959–77), vol. 1: 112 on the former point, and vol. 1: 113–14 on the latter.

10 See Hooke to Oldenburg, 15 Feb. 1671/2, in *Correspondence of Isaac Newton*, vol. 1: 113. In recounting Newton's theory, Hooke does mention the points about refrangibility and heterogeneity, but he thinks that Newton's "first proposition" is "that light is a body" and that differently colored rays of light are in fact "several sorts of bodies." I take this to represent Hooke's interpretation of how Newton can account for the data with the theory that light consists of particles.

11 In *Oeuvres complètes de Christiaan Huygens*, ed. Johan Adriaan Vollgraff (The Hague: Nijhoff, 1888–1950), vol. 10: 602. Ignatius Pardies, another of Newton's interlocutors, similarly found it difficult to differentiate the claim about the corporeal nature of light from Newton's ideas concerning refrangibility and heterogeneity. See his two letters to the Royal Society concerning Newton's work, both of which are reprinted in *Isaac Newton's Papers and Letters*, ed. Cohen and Schofield; cf. the discussion of Pardies in Sabra, *Theories of Light*, 264–7.

saves the phenomena as well as Newton's does. The point is that from the perspective of Newton's interlocutors, it makes little sense to suggest that Newton's presentation of empirical data concerning the properties of light based on experiments with prisms could constitute a scientific theory, independent of some hypothesis concerning the nature of light.

After the extensive correspondence, and controversy, generated in response to Newton's early optical views and experiments, Newton often threatened to avoid engaging in mathematical and philosophical disputes altogether. He insisted to friends and colleagues that he found intellectual controversy unbearable. Fortunately for us, he never followed through with his threat to disengage from discussions in natural philosophy, and sent many important letters in his later years. One of his more important pieces of correspondence after the optics controversy was with the natural philosopher Robert Boyle in 1679 (Newton's letter was published for the first time in the mid-eighteenth century).[12] In his lengthy letter to Boyle, Newton presents his speculations concerning various types of what we would now call chemical interactions; many of these speculations bear similarities to passages that appeared years later in the queries to the *Opticks*. The letter is also famous for presenting one of Newton's early speculations concerning how gravity might be physically explained; it presents, among other things, a picture of what Newton would countenance as a viable explanation of gravity in physical terms. This issue became of paramount importance once the *Principia* appeared.

Newton's relation to Descartes

Recent scholarship has emphasized that when Newton published the *Principia* in 1687, Cartesianism remained the reigning view in natural philosophy and served as the backdrop for much important research. We now recognize that Newton intended his *Mathematical Principles of Natural Philosophy* specifically to replace Descartes' own *Principles of Philosophy*, which was first published in Amsterdam in 1644.[13] As Cotes's famous and

[12] The letter to Boyle first appeared in *The Works of the Honourable Robert Boyle*, ed. Thomas Birch (London, 1744), vol. 1: 70–4.

[13] In his library, Newton had a 1656 Amsterdam edition of Descartes' *Principles*, along with a 1664 London edition of the *Meditations*. On Newton's relation to Descartes and to Cartesianism, see the extensive treatment in the chapter "Newton and Descartes" in Alexandre Koyré, *Newtonian Studies* (Cambridge, MA: Harvard University Press, 1965), and the discussion in Howard Stein, "Newton's Metaphysics," in *The Cambridge Companion to Newton*.

influential preface to the second edition of the *Principia* indicates, in 1713 the primary competitor to Newton's natural philosophy remained Cartesian in spirit if not in letter. Despite the astonishing impact that Newton's work had on various fields, including of course what we would call philosophy proper, it would be anachronistic to conclude that Newtonianism had replaced its primary competitor, for Cartesianism's influence did not dissipate until some time after Newton's death in 1727.

As his own unpublished manuscript *De Gravitatione* indicates, Newton not only read Descartes's *Principles* carefully, he patiently attempted to refute many of the central notions in that text. *De Gravitatione* raises a number of controversial interpretive issues, including first and foremost the provenance of the text itself. No consensus has emerged as to the dating of the manuscript – which remained unpublished until 1962 – and there is insufficient evidence for that question to be answered as of now,[14] but two things remain clear: first, the text is an extended series of criticisms of Cartesian natural philosophy; and, second, it is significant for understanding Newton's thought, not least because it represents his most sustained philosophical discussion.

De Gravitatione helps to dispel the easily informed impression that Newton sought, in the Scholium to the *Principia*, to undermine a so-called Leibnizian relationalist conception of space and time, just as his defender, Samuel Clarke, would attempt to do years later in the correspondence of 1715–16. Although Leibniz did eventually express what became the canonical early modern formulation of relationalism concerning space and time, and although Newton and Clarke were highly skeptical of such a view, it is especially misleading to read the *Principia* through the lens provided by the later controversy with the Leibnizians. Newton's extensive attempt in *De Gravitatione* to refute Descartes' broadly relationalist conception of space and time indicates that the Scholium should be read

[14] The text first appeared, in a transcription of the original Latin and an English translation, in *Unpublished Scientific Writings of Isaac Newton*, ed. A. R. Hall and Marie Boas Hall (Cambridge: Cambridge University Press, 1962). In the Halls' judgment, the text is juvenile and probably originates in the period from 1664 to 1668. Betty Jo Teeter Dobbs contends, in contrast, that the work is mature and was written in late 1684 or early 1685, while Newton was preparing the first edition of the *Principia*. See Dobbs, *The Janus Faces of Genius: The Role of Alchemy in Newton's Thought* (Cambridge: Cambridge University Press, 1991), 141–6, where she also reviews various alternative opinions on the matter. In a recent essay, Howard Stein raises several significant considerations concerning the question of dating – see "Newton's Metaphysics," 302 n. 39. Stein also discusses the broader significance of the text.

as providing a replacement for the Cartesian conception.[15] Newton had a Cartesian, and not a Leibnizian, opponent primarily in mind when he wrote his famous articulation of "absolutism" concerning space and time. It may be thought a measure of Newton's success against his Cartesian predecessors that history records a debate between the Leibnizians and the Newtonians as influencing every subsequent discussion of space and time in the eighteenth century.

Aspects of the *Principia*

Space and time

The discussion of space and time in the Scholium, and in the General Scholium, to the *Principia* provides the canonical formulation of so-called absolutism in the early modern period,[16] and the criticisms of Descartes in *De Gravitatione* illuminate this formulation. If one rejects a Cartesian view, defending in its place some type of "absolutism" concerning space and time – that is, if one contends that space and time exist independently of all objects and even of all possible relations among objects – there immediately arises at least one pressing question: what is the relation between God and space and time? Before God created the universe of objects and relations, did space and time nonetheless exist, and if so, what was God's relation to them?

As for the question of how to characterize God's relation to space and time – a question of considerable import in the early modern period – Newton presents, both in *De Gravitatione* and in the *Principia*, a complex and intriguing position. Roughly put, Newton's view has something like the following structure: (i) spatiality is a necessary affection of any being; (ii) God exists necessarily, so (iii) there is no time at which God fails to exist; and, therefore, (iv) space exists, and there is no time at which space fails to exist.[17] As we read in a now famous passage from *De Gravitatione*:

[15] This interpretation of Newton's *Principia* is presented by Howard Stein, "Newtonian Space-Time," in Robert Palter (ed.), *The Annus Mirabilis of Sir Isaac Newton 1666–1966* (Cambridge, MA: MIT Press, 1970).

[16] On Newton's absolutism, see Robert DiSalle, "Newton's Philosophical Analysis of Space and Time," ch. 1 in *The Cambridge Companion to Newton*.

[17] See the discussion in Stein, "Newton's Metaphysics." For further details concerning Newton's understanding of space, and for citations to relevant literature, see Andrew Janiak, "Space, Atoms, and Mathematical Divisibility in Newton," *Studies in History and Philosophy of Science* 31 (2000): 221–7.

> Space is an affection of a being just as a being. No being exists or can exist which is not related to space in some way. God is everywhere, created minds are somewhere, and body is in the space that it occupies; and whatever is neither everywhere nor anywhere does not exist. And hence it follows that space is an emanative effect of the first existing being, for if any being whatsoever is posited, space is posited . . . If ever space had not existed, God at that time would have been nowhere. (This volume pp. 25–6)

Notice that if Newton did not endorse the view that God created the universe, or if he were generally agnostic, his conception of space indicates that space would exist just in case any entity exists, for space is said to be an affection of any being whatever.

One intriguing implication of this view in *De Gravitatione* is that there is a sense in which God occupies space. In the *Principia*, Newton does not shy away from endorsing that implication explicitly, as a passage from the General Scholium indicates:

> He endures always and is present everywhere, and by existing always and everywhere he constitutes duration and space. Since each and every particle of space is *always*, and each and every indivisible moment of duration is *everywhere*, certainly the maker and lord of all things will not be *never* or *nowhere*. (This volume p. 91)

For Newton, space exists just in case God exists, and God is infinite both spatially and temporally speaking, so God exists everywhere throughout space at each moment of time. In this way, we can achieve a fuller understanding of Newton's view of space and time by reading *De Gravitatione* and the *Principia* in tandem.

Mathematical and physical treatments of force

Near the opening of the *Principia*, Newton contrasts what he calls the "mathematical" and the "physical" treatment of force.[18] In the definitions in Book I, after defining various sorts of motion and of force, and

[18] See the extensive discussion in I. Bernard Cohen's *The Newtonian Revolution* (Cambridge: Cambridge University Press, 1980), and the more recent interpretation in Andrew Janiak, "Newton and the Reality of Force," *Journal of the History of Philosophy* (forthcoming).

in particular after defining what he takes to be the various quantities of centripetal force, Newton writes of the concept of force as he employs it in general: “This concept is purely mathematical, for I am not now considering the physical causes and sites of these forces” [this volume p. 63]. Similarly, he describes his use of the term “impulse” by noting that he considers “not the species of forces and their physical qualities but their quantities and mathematical proportions, as I have explained in the definitions” [this volume p. 86]. So whereas a physical treatment of force describes, among other things, its “causes and qualities,” a mathematical treatment eschews such a description, providing instead a characterization of its “quantities.”

It is important to think of this Newtonian distinction as a technical one, that is, as a distinction that cannot be understood antecedent to its articulation in the text, despite the fact that it appears to be familiar. Newton’s contrast is subject to misunderstanding precisely because it is easily conflated with various familiar contrasts. For instance, if the physical is identified with the “real,” the mathematical might be identified with the “ideal,” and mathematical models might be thought of as mere idealizations. In fact, Newton’s mathematical account does involve certain idealizations. Consider, for instance, his caveat at the very end of the Definitions that open the *Principia*, just before he begins to discuss space and time in the Scholium:

> Further, it is in this same sense that I call attractions and impulses accelerative and motive. Moreover, I use interchangeably and indiscriminately words signifying attraction, impulse, or any sort of propensity toward a center, considering these forces not from a physical but only from a mathematical point of view. Therefore, let the reader beware of thinking that by words of this kind I am anywhere defining a species or mode of action or a physical cause or reason, or that I am attributing forces in a true and physical sense to centers (which are mathematical points) if I happen to say that centers attract or that centers have forces. (This volume p. 64)

This passage indicates an important idealization on Newton’s part: material bodies are perfectly real, but their “centers” as he considers them are merely mathematical points. Although gravity is very nearly as the inverse square of the distance between the centers of material bodies, where the center is an idealization,[19] bodies themselves are not geometrical objects and so their centers are not in fact mathematical points. The actual center of a body has some extension. The question, then, is whether gravity in its mathematical treatment should be understood on the model of a material body, as a real entity, or on the model of a "center" of a material body, as a mathematical idealization.

To see that the "mathematical" treatment of gravity characterizes a real entity, consider how Newton describes a force's "physical" treatment, which serves as the relevant contrast class. The latter involves at least the following two elements, as indicated in Definition 8:

(1) A characterization of the "seat" of the force. For instance, does it involve an aether? A vortex, or some type of fluid? Etc.
(2) A characterization of the force's relation to other phenomena and forces; e.g. does the cause of gravity also cause other forces, such as magnetism?

Thus Newton's contention that gravity is a $1/r^2$ force represents what we would ordinarily consider to be a physical claim – one concerning, for instance, ordinary physical quantities such as the distance between two material bodies. But this is not a physical claim in the technical sense because it does not concern (1) or (2). So the mathematical treatment deals with perfectly ordinary physical quantities and relations, such as distances and masses, and not merely with mathematical entities and idealizations, such as mathematical points.

There are two distinctions here. On the one hand, we can distinguish entities into those that are mathematical, such as numbers and points, and those that are physical, such as distances and masses. On the other, we can distinguish our treatments of entities into mathematical and physical varieties. Hence a physical entity like a body or a force can be treated in two different ways: the words 'mathematical' and 'physical' modify the treatment of a perfectly real entity, not the entity itself.

We should acknowledge that the mathematical treatment of force in the *Principia*, which culminates in the derivation of the law of universal

19 Newton, *The Principia: Mathematical Principles of Natural Philosophy*, ed. and trans. I. Bernard Cohen and Anne Whitman, with the assistance of Julia Budenz (Berkeley: University of California Press, 1999), 52. The work of George Smith indicates the significance of Newton's articulation of claims that are said to hold *quam proxime*: see especially "The Newtonian Style in Book II of the *Principia*," in Buchwald and Cohen (eds.), *Isaac Newton's Natural Philosophy*, and "The Methodology of the *Principia*," ch. 4 in *The Cambridge Companion to Newton*.

gravitation in Book III, also includes a startling unification of phenomena.[20] As part of his mathematical treatment, Newton contends, for instance, that the force that keeps the moon in its orbit, and that which accounts for the weight of bodies on earth, are the same force. Part of his reasoning is that two forces are identical in kind if their operation is governed by the same law; one might say that the applicability of the law serves as a criterion of identity. This unifies what were once called superlunary and sublunary phenomena, a unification that was obviously crucial for later research on gravitation.

Action at a distance

One of the most vexing issues raised by Newton's theory of gravity in the *Principia* is the question of action at a distance.[21] Any interpretation of Newton's own understanding of the import of his theory must acknowledge his discussion of the problem in a 1693 letter to Richard Bentley. The letter, reprinted in this volume, contains the following stark rejection of the notion:

> 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 . . . 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. (This volume p. 102)

It appears that if accepting Newton's theory of gravity commits one to accepting action at a distance, Newton's own sense of what is an intelligible cause of motion would be violated.

Newton connected his understanding of the notion that all material bodies – or all bodies with mass – bear "gravity" as a property with the

[20] The "deduction" of the law of universal gravitation is extremely complex, and certainly cannot be explicated here; see Howard Stein, "'From the Phenomena of Motions to the Forces of Nature': Hypothesis or Deduction?" *Proceedings of the Philosophy of Science Association 1990* 2 (1991): 209–22, and William Harper, "Newton's Argument for Universal Gravitation," ch. 5 in *The Cambridge Companion to Newton*.

[21] For a classic treatment, see Mary Hesse, *Forces and Fields: The Concept of Action at a Distance in the History of Physics* (London: Nelson, 1961).

question of how to avoid invoking distant action when characterizing gravitational attraction. In his letter to Bentley, in denying that one material body can act at a distance on another material body, Newton also denies that gravity is "innate" or "inherent" in matter, or that it is part of the "essence" of matter. He apparently thinks that to conceive of gravity as "innate" or "inherent" in matter is to think of it as due to no other physical process, entity, or medium between material bodies. Hence the claim about innateness or inherence amounts to the claim that there is action at a distance. Since Newton takes the latter to be simply unintelligible, it stands to reason that he rejects the claim concerning its inherence in matter. One way of avoiding the invocation of distant action, along with the claim about gravity's innateness or inherence in matter, is to leave open the possibility that gravity is due to an aetherial medium that acts on, and even penetrates, all matter. The aether's ubiquity throughout space might ensure that its action is only local in character.[22] And Newton attempts to account for the fact that the force of gravity is inversely proportional to the square of the distance between any two bodies by proposing that the density of the aether varies as one's distance from a given body increases. According to this hypothesis, the aether "impels" bodies to move toward one another; this action appears to earth-bound observers as that of an attractive force. The connection and import of these claims remains of continuing scholarly interest. The postulation of the aether also raises the question of how to understand Newton's considered attitude toward hypotheses.

Hypotheses

One of the recurring themes in Newton's discussions of his predecessors' and interlocutors' strategies in natural philosophy – especially those of Descartes and Leibniz – is the question of the proper role of "hypotheses" in systematic enquiries into nature.[23] Indeed, one of Newton's most famous pronouncements in the *Principia* is: "hypotheses non fingo," or

[22] Newton himself speculated about the characteristics an aether might have in query 21 to the *Opticks*; he did not think there was sufficient independent empirical evidence indicating the existence of an aether to place his speculation within the main text of the *Opticks*.

[23] For a discussion of the development in Newton's conception of hypotheses over time, see I. Bernard Cohen, "Hypotheses in Newton's Philosophy," *Physis: Rivista Internazionale di Storia della Scienza* 8 (1966): 163–84.

"I feign no hypotheses."[24] This phrase, which was added to the second edition of the text, is often taken to mean that Newton eschews all hypothetical reasoning in natural philosophy. In fact, Newton does not systematically avoid hypotheses; rather, he believes that within the boundaries of experimental philosophy – the *Principia* and the *Opticks* (excepting the queries) can be considered works in this area – one may not hypothesize, but it is not improper to propose hypotheses to prod future experimental research. Such hypothetical speculations are either reserved for the queries to the *Opticks*, or are more or less explicitly labeled as such in the optics papers from the 1670s and in the *Principia*. For instance, in the Scholium to Proposition 96 of Book I of the *Principia*, Newton discusses hypotheses concerning light rays. Similarly, in query 21 of the *Opticks*, he proposes that there might be an aether whose differential density accounts for the gravitational force acting between bodies, as we have just seen.

Why, then, is a given proposition characterized as a hypothesis? The case of the postulated aether in query 21 indicates an answer, for the most salient fact about the aether is that Newton lacks independent experimental evidence indicating its existence. This coheres with Cotes's rejection, in his preface to the *Principia's* second edition, of the common hypothesis that planetary motion can be explained via vortices on the grounds that their existence does not enjoy independent empirical confirmation [this volume, p. 52]. So hypotheses make essential reference to entities whose existence lacks independent empirical support. With such support, one's explanation would successfully shake off the mantle of "hypothesis." Newton's contention, then, is that both Descartes and Leibniz proceed in a "hypothetical" manner by attempting to explain phenomena through invoking the existence of entities for which there is no independent empirical evidence.[25]

Newton's attitude toward hypotheses is connected in another way to his skepticism concerning Cartesian and Leibnizian natural philosophy. In the General Scholium, he contends: "For whatever is not deduced from

[24] We owe this translation of the phrase to Alexandre Koyré, who first noted that Newton uses the word "feign" in a parallel discussion in English: *From the Closed World to the Infinite Universe* (Baltimore, MD: Johns Hopkins University Press, 1957), 229 and 299 n. 12.

[25] In order to account for the motions of the planetary bodies in his *Tentamen*, for instance, Leibniz introduces *ex hypothesi* the premise that some kind of fluid surrounds, and is contiguous to, the various planetary bodies, and then argues that this fluid must be in motion. See the *Tentamen* in Gottfried Wilhelm Leibniz, *Mathematische Schriften*, ed. C. Gerhardt (Berlin, 1849), vol. 6: 149, and Domenico Bertoloni Meli, *Equivalence and Priority: Newton vs. Leibniz* (Oxford: Oxford University Press, 1993), 128–9.

the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy" (p. 92 in this volume). It therefore appears that hypotheses may be generated from various sorts of metaphysical principle or view, and so the exclusion of hypotheses may also represent a way of distinguishing "experimental philosophy" from metaphysics. Indeed, one of Newton's primary complaints against both the Cartesians and Leibniz is that they mix metaphysical with experimental concerns, that they infuse metaphysical views, which he thinks are always questionable and highly disputable, into their experimental philosophy, thereby preventing the latter from proceeding on a secure empirical footing. His discussion of hypotheses is one of several ways in which Newton raises this concern about his predecessors' methods.

But how does this interpretation of Newton's attitude toward hypotheses illuminate his conception of the cause of gravity? After all, in the General Scholium, "hypotheses non fingo" concerns the postulation of a cause for gravity. It is sometimes claimed that Newton took any "physical" characterization of gravity – any characterization of its cause – to involve hypotheses, the very type of assumption he strove so stridently to expunge from physics. However, Newton does not rule out causal explanations of gravity because they necessarily involve hypotheses. Rather, when Newton wrote the General Scholium there was no independent empirical evidence to support the relevant causal explanations of gravity, so they remained merely hypothetical. Hence "hypotheses non fingo" means that we have insufficient data to characterize gravity physically; it means neither that we have grounds for ending the search for such data, nor that attempts to use new data to produce a physical characterization would involve a sullying of physics by hypotheses. The "physical" treatment of force Newton eschews in the *Principia* must await sufficient empirical findings.

The queries to the *Opticks*

There are many salient differences between Newton's two great works, the *Principia* and the *Opticks*, despite the tremendous influence each had on subsequent research in their respective scientific fields in the eighteenth century and beyond. As I. Bernard Cohen has astutely shown, Newton's choice of the vernacular rather than Latin for the presentation of his optical views may reflect his opinion that English was more appropriate for a field like optics, which had not yet achieved the same status as the science of the *Principia*, in part because it had not yet been sufficiently mathematized.[26] Although Newton did include certain important – and influential – speculative remarks in the *Principia*, most notably in the famous General Scholium, the *Opticks* ends, in its later editions, with a series of thirty-one "queries" in which Newton presents speculations on an extremely wide range of natural phenomena, including some in what we would now call biology, chemistry, and physics. These queries indicate Newton's avowed willingness to consider all manner of hypotheses: he argues in the "Account," which I discuss below, that he explicitly separates these questions from the rest of the text of the *Opticks* and labels them as such to avoid the charge that he has "feigned" the hypotheses.

This highlights again the subtlety of Newton's attitude toward hypotheses, which is easily missed. As we have seen, some proposition – for instance, "The motion of the planets in elliptical orbits around the sun is caused by the action of an aether with differential density at distinct points in space" – will be labeled a hypothesis if there is no, or at any rate obviously insufficient, independent empirical evidence indicating the existence of the postulated entity, in this case the aether. But that same proposition can be considered as a prod to further empirical research; it is not "feigned" unless one adopts an unwarranted epistemic attitude toward it, for instance, if one asserts it to be the correct explanation of some documented natural phenomenon. The queries, then, press us to distinguish the epistemic status of a proposition vis-à-vis a relevant body of empirical data, and the proper epistemic attitude toward such a proposition, given all the relevant empirical data. Newton does not feign hypotheses in the General Scholium to the *Principia* in order to present a causal explanation of gravity – for instance, he does not contend that gravity must be due to the operation of an aether – but he is certainly

[26] Just as intriguingly, Cohen has emphasized that Newton left his name off the title page of the *Opticks*, perhaps another indication of the less than fully systematic and scientific character of the work in that field. See I. Bernard Cohen, "The Case of the Missing Author: The Title Page of Newton's *Opticks* (1704), with Notes on the Title Page of Huygens's *Traité de la Lumière*," in Buchwald and Cohen (eds.), *Isaac Newton's Natural Philosophy*.

willing to speculate about the possible properties of an aether in query 21 to the *Opticks*, as he had already done at the end of his 1679 letter to Boyle. Beginning already with his work in optics in the early 1670s, Newton consistently felt that his interlocutors were insufficiently careful regarding such epistemic matters, a fact nicely highlighted by Newton's own speculations in the queries.

Newton's relation to Leibniz

The most influential philosophical correspondence of the eighteenth century, that between Leibniz and Newton's stalwart defender, the theologian Samuel Clarke, was preceded by a little-known, reasonably brief, but also quite significant exchange in 1693 between Leibniz and Newton himself (they had previously corresponded nearly twenty years earlier on other matters). After praising Newton for his tremendous accomplishment in the *Principia*, Leibniz contends that Newton's theory of gravity fails to indicate not only the cause of gravity, as was acknowledged explicitly by Newton himself, but also the cause of the phenomena treated by Newton's theory, especially the planetary orbits. As indicated by Leibniz's own account of celestial phenomena, the *Essay on the Causes of Celestial Motions* (or *Tentamen*) of 1689, he thought that the phenomena in question must be understood as following from some cause that meets what he took to be the strictures of the mechanical philosophy: they must follow from bits of matter in motion that transfer motion only through impact on other bits of matter. Newton had famously failed to uncover any such cause, or mechanism.

Newton's own response to this well-known charge, one unfortunately not taken up by Clarke in his later correspondence with Leibniz, was that although he had indeed failed to uncover the cause of gravity, he nonetheless had established that gravity itself is causal. That is, from Newton's point of view, gravity had been successfully identified as the cause of the celestial phenomena in question, particularly the planetary orbits. This claim is crucial because it brings us to the heart of Newton's understanding of gravity in particular, and of force in general, especially as it is articulated in the sections of the *Principia* reproduced in this volume. As the Definitions make explicit, Newton thinks of gravity as one type of centripetal force, and the latter is defined at the outset as a cause of changes in states of motion.[27] Hence it should come as no surprise to find Newton warning Leibniz against inferring that gravity itself is not a cause from the fact that Newton had failed to uncover gravity's cause. For Newton had defined gravity from the outset as one type of cause, as one sort of force that alters the states of motion of material bodies. Precisely how Newton can conceive of gravity itself as a cause without invoking action at a distance, if that is possible at all, is a topic of continuing interest.

Newton's correspondence with Leibniz in 1693, albeit brief, is of considerable significance because it highlights Newton's attempt to convince Leibniz that the theory of gravity in the *Principia* is sufficient to undermine the vortex theory favored by Leibniz. It is also significant because it represents an interaction between them that was not tainted by the controversy over the calculus; the latter did not seriously flare up until the English Newtonian John Keill claimed in 1708 that Leibniz had stolen the calculus from Newton. This controversy, with all its nationalist undertones and hyperbolic rhetoric, would taint much of the more famous correspondence between Leibniz and Clarke, and would eventually see Newton write and publish a supposedly anonymous response to a supposedly impartial review of the calculus affair by a committee convened under the auspices of the Royal Society (the "Account").

Nearly twenty years after their illuminating exchange in 1693, Leibniz and Newton narrowly missed a second opportunity to discuss their philosophical differences. In May of 1712, Leibniz wrote a letter to Nicholas Hartsoeker that was highly critical of the Newtonians; it was later published in the *Memoirs of Literature*, a journal to which Roger Cotes, the editor of the *Principia's* second edition, held a subscription. After Cotes brought Leibniz's criticisms to Newton's attention – especially the claim that the *Principia* renders gravitation a "perpetual miracle" because it does not specify the physical mechanism underlying it – Newton wrote an intriguing, but only posthumously published, rebuttal. Here is part of Newton's paraphrase of Leibniz's original letter: "But he [i.e. Leibniz] goes on and tells us that God could not create planets that should

[27] See pp. 60–1 in this volume. It is widely believed that Newton named the type of force that "tends to a centre as to a point" *centripetal* in honor of Huygens, who dubbed the force with the opposite tendency *centrifugal*.

move round of themselves without any cause that should prevent their removing through the tangent. For a miracle at least must keep the planet in" (see this volume p. 117). Newton's response to this Leibnizian charge, I believe, is illuminating: "But certainly God could create planets that should move round of themselves without any other cause than gravity that should prevent their removing through the tangent. For gravity without a miracle may keep the planets in" (ibid.). The crux of the retort, then, is that gravity causes the planets to follow their orbital paths rather than their inertial trajectories along the tangents to those orbits. Newton apparently held this conception of gravity throughout much of his life.

By the time Newton wrote his "Account" of the Royal Society report concerning the calculus affair, the controversy between Newton and Leibniz had effected a significant rift between their followers in England and on the Continent. Not surprisingly, therefore, Newton's "Account" is highly polemical and includes many incendiary remarks, but it also includes several intriguing comparisons between what he takes to be the Newtonian "experimental philosophy" and the "metaphysics" promoted by Leibniz; we reproduce those remarks in this volume. The text indicates, among other things, that Newton was acquainted not just with Leibniz's contributions to mathematics and dynamics, but with at least some of his more narrowly metaphysical work, including his view of the pre-established harmony. It reworks familiar themes from the 1693 correspondence with Leibniz, and from Leibniz's exchange with Clarke, such as their differing attitudes toward the so-called mechanical philosophy, but it also highlights Newton's own conception of the important philosophical elements of the *Principia* and of the *Opticks* through extensive quotation from those texts. Each of the passages Newton singles out as salient is reprinted in this volume.

One should not overemphasize Newton's philosophical interests or achievements: to the extent that they are distinct from his results in mathematics, mechanics, and optics, they certainly pale in comparison to the latter. One should also not overlook Newton's skepticism concerning the practice of philosophy in his day, a time when the influence of late scholasticism was still felt, and when a prodigious quantity of speculation accompanied the rise of what we call modern philosophy and modern science. Newton was keenly aware of the limits of the knowledge of nature achieved in this period, limits that he thought of his interlocutors and critics as trespassing by proposing hypotheses. As he wrote to Robert Boyle in 1679, in "natural philosophy" there is "no end of fancying." Happily for us, this did not prevent Newton from contributing substantially to the development of early modern philosophy.

Chronology

1642	Birth of Isaac Newton in January; death of Galileo Galilei
1646	Birth of Gottfried Wilhelm Leibniz in July
1650	Death of René Descartes
1654	Newton is enrolled at King's School in Grantham
1661	Newton matriculates at Trinity College, Cambridge University
1662	The Royal Society is chartered by an edict of Charles II
1665	Newton graduates from Trinity College with a B.A.
1664–6	The so-called *anni mirabiles*, or miraculous years; Newton's invention of the fluxional calculus
1667	Newton is made a fellow of Trinity College
1668	Newton is awarded an M.A. from Trinity College
1669	Newton becomes the second Lucasian Professor of Mathematics at Cambridge, following his former teacher Isaac Barrow in the position
1672	Newton sends his "Theory about Light and Colors" to the Royal Society; elected fellow of the Society
1673	Leibniz is elected fellow of the Royal Society
1675	Newton's "An Hypothesis Explaining the Properties of Light" is read to the Royal Society in London
1676	Leibniz visits London in October
1678/9	Newton corresponds with Robert Boyle
1684	Edmond Halley visits Newton in Cambridge, spurring Newton on to write what would eventually become the *Principia*
1687	First edition of *Philosophiae Naturalis Principia Mathematica* is published in London at Halley's urging

1689	Leibniz's *Tentamen* appears in *Acta Eruditorum*
1690	Newton corresponds with Locke; publication of Locke's *Essay Concerning Human Understanding* in London
1691/2	Death of Boyle; Boyle's will endows the Royal Society's Boyle Lectures in defense of religion
1692/3	Richard Bentley and Newton correspond extensively; Bentley delivers the first Boyle Lectures in London
1693	Leibniz and Newton correspond
1696	Newton appointed Warden of the Mint in London
1703	Newton elected President of the Royal Society (a position he retained until his death in 1727)
1704	First edition of the *Opticks* is published in London (with sixteen queries) by the printers to the Royal Society
1704/5	Samuel Clarke delivers the Boyle Lectures in London
1705	Newton is knighted by Queen Anne at a grand ceremony in Cambridge
1706	First edition of the Latin translation of the *Opticks*, prepared by Samuel Clarke, is published in London (with the original sixteen, plus seven new, queries)
1713	Second edition of the *Principia*, edited by Roger Cotes, is published in Cambridge
1713	The *Commercium Epistolicum*, a partisan account of the calculus controversy overseen by Newton, appears in the Royal Society's *Philosophical Transactions*
1715	Newton anonymously publishes "Account of the *Commercium Epistolicum*" in the *Philosophical Transactions*
1715–16	Clarke and Leibniz correspond extensively via Princess Caroline of Wales
1716	Death of Leibniz in November
1717	Clarke has his correspondence with Leibniz published in London
1718	Second edition of the *Opticks* is published in London (with thirty-one queries)
1721	Third edition of the *Opticks* is published in London (virtually unchanged from the second edition)
1726	Third edition of *Principia* published in London
1727	Death of Newton in March

Further reading

Classic works on Newton and his influence include Ferdinand Rosenberger's *Isaac Newton und seine physikalischen Principien* (Leipzig: J. A. Barth, 1895), Léon Bloch's *La Philosophie de Newton* (Paris: Libraires Félix Alcan, 1903), Alexandre Koyré's *Newtonian Studies* (Cambridge, MA: Harvard University Press, 1965), and I. Bernard Cohen's *The Newtonian Revolution* (Cambridge: Cambridge University Press, 1980). Influential treatments of somewhat more specialized topics include Mary Hesse, *Forces and Fields: The Concept of Action at a Distance in the History of Physics* (London: Thomas Nelson and Sons, 1961), Richard Westfall, *Force in Newton's Physics: The Science of Dynamics in the Seventeenth Century* (London: Macdonald, 1971), Ernan McMullin, *Newton on Matter and Activity* (Notre Dame, IN: University of Notre Dame Press, 1978), and A. I. Sabra, *Theories of Light from Descartes to Newton* (Cambridge: Cambridge University Press, 1981, second edition), which is philosophically astute.

Because the field of Newtonian studies is flourishing, the relevant literature is vast. For excellent selections of papers and articles on diverse topics, see the classic collection *The Annus Mirabilis of Sir Isaac Newton 1666–1966*, edited by Robert Palter (Cambridge, MA: MIT Press, 1970), and the more recent collections, *Philosophical Perspectives on Newtonian Science*, edited by Philip Bricker and R. I. G. Hughes (Cambridge, MA: MIT Press, 1990), *Isaac Newton's Natural Philosophy*, edited by Jed Buchwald and I. Bernard Cohen (Cambridge, MA: MIT Press, 2001), and *The Cambridge Companion to Newton*, edited by I. Bernard Cohen and George Smith (Cambridge: Cambridge University Press, 2002); the last work contains an extensive bibliography of works by and about Newton.

Important studies of the *Principia* and its background include John Herivel, *The Background to Newton's "Principia": A Study of Newton's Dynamical Researches in the Years 1664–1684* (Oxford: Clarendon Press, 1965), I. Bernard Cohen, *Introduction to Newton's "Principia"* (Cambridge, MA: Harvard University Press, 1971), Bruce Brakenridge, *The Key to Newton's Dynamics: The Kepler Problem and the "Principia,"* with translations by Mary Ann Rossi (Berkeley: University of California Press, 1995), Dana Densmore, *Newton's "Principia": The Central Argument*, with translations and illustrations by William Donahue (Santa Fe, NM: Green Lion Press, 1995), François DeGandt, *Force and Geometry in Newton's "Principia"*, translated by Curtis Wilson (Princeton: Princeton University Press, 1995), S. Chandrasekhar, *Newton's "Principia" for the Common Reader* (Oxford: Oxford University Press, 1995), and Nicholas Guicciardini, *Reading the "Principia": The Debate on Newton's Mathematical Methods for Natural Philosophy from 1687 to 1736* (Cambridge: Cambridge University Press, 1999). On Newton's optics, see Sabra's *Theories of Light from Descartes to Newton*, A. R. Hall's *And All Was Light: An Introduction to Newton's "Opticks"* (Oxford: Clarendon Press, 1993), and Alan Shapiro's *Fits, Passions, and Paroxysms: Physics, Method, and Chemistry and Newton's Theories of Colored Bodies and Fits of Easy Reflection* (Cambridge: Cambridge University Press, 1993).

The standard biography of Newton remains Richard Westfall's magisterial *Never at Rest* (Cambridge: Cambridge University Press, 1980), which is available in a condensed version as *The Life of Isaac Newton* (Cambridge: Cambridge University Press, 1993). For early biographical views of Newton, see *Isaac Newton*, *Eighteenth-Century Perspectives*, edited by A. Rupert Hall (Oxford: Oxford University Press, 1999). For a shorter discussion, see I. Bernard Cohen's entry on Newton in the *Dictionary of Scientific Biography*, volume 10 (New York: Scribner's, 1974). The best account of Newton's intellectual disputes with Leibniz is Domenico Bertoloni Meli's *Equivalence and Priority: Newton vs. Leibniz* (Oxford: Oxford University Press, 1993). The broader cultural and historical context of Newton's work is explored in Betty Jo Teeter Dobbs and Margaret Jacobs, *Newton and the Culture of Newtonianism* (Atlantic Highlands, NJ: Humanities Press, 1995).

The principal sources for the scholarly study of Newton's oeuvre include: *Isaac Newton's "Philosophiae Naturalis Principia Mathematica," the Third Edition with Variant Readings*, edited by Alexandre Koyré and I.

Bernard Cohen, with Anne Whitman (Cambridge, MA: Harvard University Press, 1972), along with the new standard translation, *The "Principia": Mathematical Principles of Natural Philosophy, a New Translation*, translated by I. Bernard Cohen and Anne Whitman, with Julia Budenz (Berkeley: University of California Press, 1999), and *Opticks: or, A Treatise of the Reflections, Refractions, Inflections and Colours of Light* (New York: Dover, 1952), which is based on the fourth edition of 1730. Some of the more important articles and papers written by Newton are available in these collections: *Isaac Newton's Theological Manuscripts*, edited by Herbert McLachlan (Liverpool: Liverpool University Press, 1950), *Isaac Newton's Papers and Letters on Natural Philosophy*, edited by I. Bernard Cohen and Robert Schofield (Cambridge, MA: Harvard University Press, 1978, revised edition), *Unpublished Scientific Papers of Isaac Newton*, edited by A. R. Hall and Marie Boas Hall (Cambridge: Cambridge University Press, 1962), *The Mathematical Papers of Isaac Newton*, edited by D. T. Whiteside (Cambridge: Cambridge University Press, 1967–81), and *The Optical Papers of Isaac Newton*, volume 1: *The Optical Lectures of 1670–1672*, edited by Alan Shapiro (Cambridge: Cambridge University Press, 1984). Newton's undergraduate notebooks from Trinity College are available as *Certain Philosophical Questions: Newton's Trinity Notebook*, edited by J. E. McGuire and Martin Tamny (Cambridge: Cambridge University Press, 1983). For a complete reproduction of Newton's letters, see *The Correspondence of Isaac Newton*, edited by Herbert Turnbull, John Scott, A. R. Hall, and Laura Tilling (Cambridge: Cambridge University Press, 1959–77). The Newton Project at Imperial College, London is an ongoing program to make all of Newton's works, including extensive unpublished manuscript materials, available to the public via the Internet: <http://www.newtonproject.ic.ac.uk>.

Note on texts and translations

I Correspondence with Robert Boyle [1679]. Newton's letter to Boyle of 28 February 1678/9 is taken from the version in *Correspondence of Isaac Newton*, edited by H. W. Turnbull et al. (Cambridge: Cambridge University Press, 1959–), volume 2: 288–96.

II De Gravitatione [date unknown; likely before 1685]. With my assistance, Christian Johnson (University of Notre Dame) revised and corrected the translation of *De Gravitatione* in *Unpublished Scientific Writings of Isaac Newton*, edited by A. R. Hall and Marie Boas Hall (Cambridge: Cambridge University Press, 1962), which also includes a transcription of the original Latin text. Johnson and I have attempted to follow Newton's own English usage in other texts when translating the Latin of *De Gravitatione*. We have consulted two other editions: *De La Gravitation, ou, les Fondements de la Méchanique Classique*, edited by Marie-Françoise Biarnais (Paris: Les Belles Lettres, 1985); and, *Über die Gravitation . . . Texts zu den philosophischen Grundlagen der klassischen Mechanik*, edited and translated by Gernot Böhme (Frankfurt am Main: Vittorio Klostermann, 1988); the latter includes a facsimile of the original Latin manuscript. We also consulted Howard Stein's (partial) translation of the text; we are grateful to Stein for sharing his unpublished work with us.

III Philosophiae Naturalis Principia Mathematica [1687, first edition]. The excerpts are from *The "Principia": Mathematical Principles of Natural Philosophy*, translated by I. Bernard Cohen and Anne Whitman, with the assistance of Julia Budenz (Berkeley: University of

California Press, 1999); this is based on the third edition of 1726, the last in Newton's lifetime. The excerpts are reprinted here with the kind permission of the University of California Press.

IV Correspondence with Richard Bentley [1692–3]. The four letters to Bentley, written between 10 December 1692 and 25 February 1693, are from the version in *Correspondence of Isaac Newton*, volume 3: 233–6, 238–40, 244, 253–6.

V Correspondence with G. W. Leibniz [1693/1712].

(a) Leibniz's letter to Newton on 7 March 1693 and Newton's reply on 16 October 1693 are taken from the translation in *Correspondence of Isaac Newton*, volume 3: 258–9 and 286–7, respectively.
(b) Leibniz's letter to Hartsoeker on 10 February 1711 is from the English translation in *Memoirs of Literature*, volume 3: 453–460 (London, second edition, 1722, a reprint of the first edition of 1712); this is the version Cotes and Newton read. The letter is also available in *Die Philosophischen Schriften von Gottfried Wilhelm Leibniz*, edited by C. J. Gerhardt (Leipzig: Alfred Lorenz, 1931), volume 3: 516–21.
(c) Newton's posthumously published response to (b), written to the editor of the *Memoirs of Literature* sometime after 5 May 1712, is from the version in *Correspondence of Isaac Newton*, volume 5: 298–300.

VI Correspondence with Roger Cotes [1713]. Newton's letter to Cotes of 28 March 1713, along with a draft of that letter, are taken from the versions in *Correspondence of Isaac Newton*, volume 5: 396–7 and 398–9, respectively.

VII An Account of the Book Entitled *Commercium Epistolicum* [1715]. Newton's anonymously published review of the *Commercium Epistolicum*, the Royal Society's report concerning the calculus dispute with Leibniz, is taken from the version in *Philosophical Transactions*, volume 29 (1714–16): 222–4.

VIII Opticks [1721]. The excerpts from the queries are from the last edition published in Newton's lifetime, *Opticks, or, A Treatise of the Reflections, Refractions, Inflections, and Colours of Light* (London, 1721, 3rd edn.), with the exception of the numbers provided on p. 128, which have been altered to match those of the fourth edition (London, 1730).