Isaac Newton (1642-1727)

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Article summary

Isaac Newton is best known as a mathematician and physicist. He invented the calculus, discovered universal gravitation, and made significant advances in theoretical and experimental optics. His master-work on gravitation, the *Principia,* is often hailed as the crowning achievement of the scientific revolution. His significance for philosophers, however, extends beyond the philosophical implications of his scientific discoveries. Newton was an able and subtle philosopher, working at a time when science was not yet recognized as an activity distinct from philosophy. He engaged with the work of Rene Descartes **REP link** and G. W. Leibniz **REP link**, and showed sensitivity to the work of John Locke **REP link**, Francis Bacon **REP link**, Pierre Gassendi **REP link**, and Henry More **REP link**, to name just a few. In his time, Newton was not perceived as a scientific outsider, but as an active and knowledgeable participant in philosophical debates.

Nevertheless, Newton's work helped precipitate the separation of physics from philosophy. The *Principia* defined a program for physical research that persists to this day, but its early reception, particularly among Cartesians and Leibnizians, was difficult. To defend this program from criticism, Newton and his successors portrayed their work as essentially autonomous from the philosophical demands of their contemporaries, thus creating modern science.

Even without the *Principia*, Newton's place in history would have been guaranteed by his work in optics and mathematics. Newton discovered that white light was composed of rays from the entire visible spectrum and ingeniously measured a microscopic property of light he called "fits," a forerunner to our "wavelength." His work in pure mathematics was ground-breaking: he invented the calculus (independently of Leibniz **REP link**) and advanced both algebra and analytic geometry. His overall success in natural philosophy, which in his hands was applied mathematics, was largely due to his unparalleled skill as a mathematician.

Newton also engaged in activities that belong to neither modern science nor modern philosophy. His work on biblical chronology, interpretation of ancient prophecies, and alchemy took up much of his intellectual efforts, but this work was largely ignored in the century after his death by an Enlightenment **REP link** ideology occupied with painting its own past. Newton was partly responsible for this historiographical blindspot. He kept most of his 'esoteric' beliefs, such as his

rejection of the Trinity, hidden. He promoted a public image that placed him in the tradition of Galileo **REP LINK** and Huygens, figures more narrowly focused on physico-mathematics than he was.

1 Life and Primary Philosophical Texts

Isaac Newton was born on December 25, 1642 in Woolsthorpe, Linconshire. In 1654, he began his education at the King's School, Grantham. He was admitted to Cambridge in 1661 and began working on mathematics in 1664. Newton's earliest philosophical writings are his Cambridge student notes (*Certain Philosophical Questions* **Link to Newton, I. (1983)**, 1661–1664 and 'Waste Book' **Link to Newton, I. (1965)**, 1664/5). They are eclectic and span topics from the nature of imagination to "oyly bodies."

In the summer of 1665, after receiving his BA, Newton traveled to Woolsthorpe but was unable to return until the spring of 1667, due to an outbreak of the plague in Cambridge. In the academic solitude of Woolsthope, Newton established the fundamentals of the calculus, worked out basic problems concerning the moon's motion, and experimentally demonstrated the heterogeneity of white light. The year of 1665-6 is often called his "miracle year." He received his MA in 1668 and became Lucasian Professor of Mathematics in 1669.

Newton published his finding on the nature of light and colors in a series of papers in the *Philosophical Transactions of the Royal Society* **Link to Newton, I. (1958)** (1672–1676). In them he also articulated his conception of a natural philosophy established by means of mathematics and experiment, one that four decades later he would later call his "experimental philosophy" (see LINK TO SECTION 2). Sometime between 1668 and 1684, Newton also authored a work known as "De Gravitatione." **Link to Newton, (2004)** Although it was unpublished in his lifetime, it contains Newton's most nuanced critique of Cartesian philosophy and a nascent formulation of the principles on which the *Principia* was based.

Newton began work on the *Principia* in *1684*, after prompting from Edmond Halley*.* The *Principia* (1687) **Link to Newton, (1997)** used novel mathematical techniques and a novel theory of force to show that diverse phenomena such as free fall, planetary orbits, the tides, and cometary motion were all due to the action of a single force: universal gravity. The goal of the work was to finally settle a central question of early-modern natural philosophy: was the sun or the earth at the center of the

"System of the World"? With the theory of gravity at hand, Newton was able to answer that question: it was the sun – or more accurately, a point very close to it – that was truly at the center.

Although the *Principia* was immediately hailed as a mathematical success, many, particularly on the continent, were skeptical that it had properly established the existence of the gravitational force (See LINK TO SECTION 2). With an eye toward convincing his critics, Newton began revising the *Principia* in the 1690s. The revisions were ultimately abandoned and a second edition postponed until 1713, but Newton's extant drafts — particularly the "Classical Scholia" **Link to Newton, I. (2001)** and "Tempus et Locus" **Link to McGuire, J. E. (1978)** — provide unparalleled access to his views on the ontology of space, time, and force (see **LINK TO SECTION 4)**.

Newton hoped to convince his critics that his method in the *Principia* was sound by revising the causal and inductive principles to which the argument for universal gravitation appealed (see LINK TO SECTION 3). In the first edition of the *Principia* they were labeled as "Hypotheses," but in the second (1713) they were enshrined as "Rules of Philosophizing." **Link to Newton, I. (2004).** The rules were highly influential for scientific methodology in the 18th- and 19th-centuries, particularly in England and Scotland. Newton also added a "General Scholium" **Link to Newton, I. (2004).** to the second edition that articulated his views on God's relation to creation. The scholium exemplifies most profoundly Newton's devotion to arguments from design and his belief that the *Principia* was a work in natural theology. Similar sentiments were diffused throughout his work in alchemy and biblical interpretation. However, the alchemical work was known to only a few confidants, and the biblical work published only posthumously, as *Chronology of Ancient Kingdoms Amended* **Link to Newton, I. (1728)** (1728) and *Observations upon the Prophecies* **Link to Newton, I. (1733)** (1733).

Newton also engaged in correspondence that clarified his views for his contemporaries. Most notable are his exchanges with the theologian Richard Bentley **Link to Newton, I. (2004).** (1694) and Roger Cotes **Link to Newton, I. (1959–77)**, the editor of the second edition of the *Principia* (1712), on the nature of matter and the inductive and conceptual basis of the laws of motion.

The success of the *Principia* elevated Newton's social standing. He was elected to represent Cambridge in Parliament in 1689 and 1701, and became Warden of the Mint in 1696 and its Master in 1699. In 1703 he was elected President of the Royal Society and was knighted in 1705.

In the 1710s, Newton formulated a fourth "Rule of Philosophizing" and modified the existing three (see LINK TO SECTION 3). He authored, but chose not to publish, a set of definitions intended to precede those rules (the so-called "Body and Void" **Link to McGuire, J. E. (1966)** drafts, 1715–1716). In the third edition of the *Principia* (1726) all four rules strike a decidedly cautious, epistemic note. They foreswear uncritical realism about ontology and uncritical confidence in the results of physical inquiry. The position is also articulated in Newton's correspondence with Leibniz **Link to Koyré, A. and Cohen, I. B. (1962)** (through the mediation of Abbé Conti, 1715), the Leibniz-Clarke correspondence **Link to G. W. Leibniz and Clarke, Samuel (1980)** (1715–1716), and his drafts for Pierre Des Maizeuax's printing of the Leibniz-Clarke correspondence **link to Koyré, A. and Cohen, I. B. (1962)** (1719–1720). The Leibniz-Clarke correspondence is particularly noteworthy since it spells out the Leibnizian and Newtonian positions on the nature of space, time, God, matter, and physical action.

Newton's queries to the *Opticks* **Link to Newton, I. (1730)** are also philosophically rich, and were expanded with each edition of the work (1704, 1706, and particularly 1717). In them, Newton reiterated his commitment to natural theology and addressed most directly his belief that all gross matter was composed of insensibly minute, atomic particles. He sketched a broad vision for an inductively-based experimental philosophy. While the *Principia* set the framework for the development of terrestrial and celestial mechanics, the vision outlined in the queries set the framework for natural science more broadly. In no small measure because of the tremendous influence of the *work*, natural science became identified with the search for the forces of nature.

In the 1700s and 1710s, Newton was also embroiled in a priority dispute with Leibniz over the invention of the calculus. Although Newton made his mathematical breakthroughs in the 1660s, he reported on them only briefly in the *Principia* and did not publish them fully until 1704 (as addenda to the *Opticks*), a full twenty years after Leibniz's first calculus publication. Newton reviewed the dispute anonymously, but, of course, in his own favor in the anonymously published "An Account of the Book Entitled Commercium Epistolicum" **Link to Newton, I. (1715)** (1715).

2 Newtonian Mathematical and Experimental Method

When Newton entered Cambridge in 1661, the scholastic-Aristotelianism **REP Link: Aristotelianism in the 17th century** that had dominated intellectual life in Europe was already severely weakened. Although no doctrine emerged as a clear replacement, a group of approaches we now label as broadly 'mechanical' was gaining acceptance. Its advocates, among them Descartes **REP link** and Hobbes **REP link,** sought to explain all physical phenomena by appeal to only bodily motion and contact action, with bodies understood only through mathematically-tractable properties like size and shape.

At the same time, another more 'experimental' approach was also gaining acceptance, particularly in England. Rooted in the writing of Francis Bacon **REP link**, this approach eschewed any *a priori* commitments to the nature of matter and causation, and instead promoted broad and open-ended experimentation. It aimed at letting experiments themselves, not antecedent philosophical considerations, determine which features of the natural world were relevant for physical explanation.

Newton combined elements of both approaches. We see the combination in his 1672 paper on light and colors **Link to Newton, I. (1958)**. Newton argued that he had established *with certainty* that white light was composed of rays that refracted differentially when passed through a prism, and that to each degree of 'refrangibility' corresponded a different color. The claim to *certainty* jarred his contemporaries. Christiaan Huygens objected that Newton had not shown the true nature of colors, since he had not provided a mechanical 'hypothesis by motion' to explain them. For Huygens, no explanation was complete that did not appeal to the fundamental ontology of matter and motion. Robert Hooke objected that Newton's account improperly assumed a corpuscular theory of light. Hooke held that Newton's account of light could not be certain, since alternate accounts — particularly Hooke's own wave theory of light — could explain the phenomena just as well.

Newton responded that he did *not* intend to offer an account of the fundamental nature of light but that he nevertheless had *indubitably* established that light had certain "immutable qualities" that exemplified well-defined mathematical relationships. The juxtaposition of the two claims lies at the heart of his philosophy of science. Newton held that by bracketing off questions about underlying natures one could focus on higher-level, mathematically-tractable entities and properties (like 'ray' and 'refrangibility') whose characteristics experiments could establish with certainty. What could not be established with certainty was to be bracketed off. For him, it was better to make true claims about higher-level items than to make speculative claims about their lower-level bases. Moreover, experiments themselves showed both which entities and properties to focus on and which to bracket off.

Newton exemplified this attitude most famously in his defense of universal gravitation (the idea that any two bodies mutually attract with a force directly proportional to their masses and inversely proportional to the square of the distance between them). His adversaries claimed that he failed to establish the existence of universal gravitation because he did not explain its nature—particularly its ability to act at a distance—by appeal to fundamental mechanical properties and contact action. For Newton, however, universal gravitation stood independently of whatever its deeper explanation was (if there was one). The theory's inductive grounding in empirical evidence, not fundamental natures, was sufficient for establishing that it really existed and had the mathematically-tractable properties ascribed to it. Regarding a deeper explanation, Newton preferred to "feign no hypotheses."

In the case of gravity, the role of mathematics in establishing the inductive link between evidence and theory is particularly noteworthy. In Books I and II of the *Principia*, Newton articulated a general theory of motion that allowed given motions to measure the theoretical parameters of the force laws causing them, and theoretical parameters of force laws to entail the resulting motions. One of his innovations was to use inferences that held both *approximately* and *exactly*, with the exact inference being a special case of the approximate.

In Book III of the *Principia*, Newton used these general inferences, alongside data about actual motions, to determine which forces actually existed. He used an iterative process of increasingly accurate approximations to approach real-world motions piecemeal. In this process, a motion described by an initial approximation provided approximate information about the force law responsible for it. In essence, it "measured" the parameters of that force law. Then, by taking the approximately measured force law to hold *exactly*, each approximation provided a baseline for the next, iterative approximation. The next approximation was then used to measure, now even more finely, the parameters of the force law that could cause the more finely specified motion. The process was then repeated. Newton's argument for universal gravitation was not that these approximations were able to get increasingly closer to actually observed motions. Rather, it was that each step in the approximation sequence measured the very same force law: the inverse-square law of universal gravitation. The iterative process provided repeated confirmation that the same force was responsible for all celestial motion. In the *Principia,* Newton had only carried the approximation procedure so far, but the subsequent development of his theory confirmed his initial conclusions. This complex interplay of mathematics and observational data was lost on nearly all of his contemporaries. It constituted a truly new, mathematical and experimental, natural philosophy.

3 Universality, Certainty, and The Rules of Philosophizing

Newton's refusal to ground natural philosophical explanations in fundamental ontology was not without methodological problems. The "Rules of Philosophizing" address these problems.

Newton showed in the *Principia* that free fall on Earth and the motion of the moon were both due to an inverse-square force directed at the center of the earth. He also showed that the motions of the moons of Jupiter and Saturn were due to inverse-square forces directed at the centers of Jupiter and Saturn, and that the motions of the planets were due to inverse-square forces directed at the center of the sun. Since all these forces had the same mathematical form, and since we call the cause of falling bodies on Earth "gravity," Newton argued that they are *all* instances of "gravity." In addition, since *all* bodies on earth gravitate towards the Earth, the same must be true everywhere: *all* bodies must gravitate. More sophisticated considerations regarding cometary motion and the mutual perturbations of the planets further showed that the gravitational force extends to all distances, so it is *everywhere*. Since the gravitational force affects everything and is present everywhere, Newton concluded that it was truly *universal*. He also demonstrated that the gravitational force is proportional only to a body's mass, and no other property.

Is the inference to universality justified? First, how do we know that *the same* force affects all bodies? Perhaps the force that explains free-fall on Earth and the force that explains Saturn's motion around the Sun are mathematically similar, but physically different. Perhaps each planet has a force peculiar to itself. Second, how do we know that *all* bodies gravitate? Perhaps there are bodies that do not. Perhaps some bodies respond only to Jupiter's force, but not to Saturn's. Third, how can we know that this force is truly everywhere, to the farthest reaches of the universe?

Newton was clearly cognizant of these questions. He offered "Rules of Reasoning" (called "Hypotheses" in the first edition) that instruct us to discard the possibilities they raise. The rules delimit what inferences we can legitimately make in the course of natural inquiry (Newton, 1997, p. 794–6):

Rule 1 No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena.
Rule 2 Therefore, the causes assigned to natural effects of the same kind must be, so far as possible the same.

The first two rules recommend ontological minimalism and answer the first problem above. Given, for example, that the forces towards the Earth and Saturn have the same mathematical form and can account for observed motions around the two planets, the two rules entail that unless we have good reason to suppose that they are *not* of the same kind, we should discard the possibility. The third rule (added in the second edition), addresses the second and third problems:

Rule 3 Those qualities of bodies that cannot be increased and diminished and that belong to all bodies on which experiments can be made should be taken as qualities of all bodies universally.

The rule licenses inductive generalizations from a limited set of instances to *all* instances: since we can find no terrestrial or celestial body that fails to respond to the gravitational force in proportion to its mass, we can conclude that this is true for all bodies everywhere, even ones for which we have no evidence. Moreover, since bodies respond to the gravitational force at all distance we have encountered, we can conclude that they respond to the gravitational force at all distances. The "increased and diminished" criterion is meant to capture those qualities which no natural process can change, qualities that are therefore inseparably connected to bodies. Newton believed this rule was "the foundation of all natural philosophy."

Newton reiterated the idea that inherently risky inductive generalizations can nevertheless yield *certain* conclusions in the third edition. He made explicit there a tenet he had held for years:

Rule 4: In experimental philosophy, propositions gathered from phenomena by induction should be considered either exactly or very nearly true notwithstanding any contrary hypotheses, until yet other phenomena make such propositions either more exact or liable to exceptions.

The rule tells us that although philosophical claims are inherently open to revision in light of new experience, claims that have been established on the basis of induction can still be taken, at least for the time being, as certain or very nearly so. Newton's claims to certainty, even when they seem categorical, always contain the implicit caveat: until shown otherwise. His clear recognition of the reviseability and developmental nature of natural philosophy is striking in comparison to the claims of some of his seventeenth-century predecessors to have authored complete and definitive accounts of the natural world.

4 Space, Time, and God

Newton's conception of absolute space and time has been the subject of debate for centuries. The *Principia*'s "Axioms, or Law of Motions" and the definitions that precede them require a distinction between relative (or apparent) and absolute (or true) motion. Relative motion is the motion of a body with respect to another body, taken to be at rest. Absolute motion is the motion of a body with respect to the immobile, infinite container of all that exists, absolute space. Considerations concerning time mirror those concerning space.

"Relativists" from Leibniz to Mach argued that absolute space is ontologically gratuitous. They held that all motion is relative motion, and that the positive claims of Newtonian mechanics can be recovered with appropriately formulated relative quantities. Nevertheless, they often treated considerations regarding force as if there was a privileged, true state of motion associated with each body. In the scholium to the definition of the *Principia*, Newton argued this "true motion" cannot be defined by means of relative quantities. It *must* be understood as motion with respect to absolute space. The debate was not wholly clarified until the concept of "inertial frame" was introduced in the 19th century. We now know that Newtonian dynamics only requires a class of privileged inertial frames (or more minimally, spatial trajectories), which can be understood without positing an absolute space.

Newton himself was concerned with the ontological status of absolute space and time. He held that all existence was spatio-temporal existence, and thus that space and time were "necessary affections" of all beings, including God. But space and time were not necessary *per se*. Rather, *God*'s necessary and infinite being, since it was necessarily spatio-temporal, necessitated the existence of space and time. Whether the necessitating relation is causal, logical, or otherwise constitutive is a subject of interpretation. It is clear, however, that Newton thought God's presence in space allowed Him to be immediately aware of, and in command of, creation. In material related to the Classical Scholia, he approvingly cited Stoics who held that "a certain infinite spirit pervades all space into infinity, and contains and vivifies the entire world: and this spirit was… supreme divinity, according to the Poet cited by [Paul the Apostle], in him we live and move and have our being" (Newton 2001 **LINK**, p. 120).

Newton also believed God supported the frame of nature more specifically. For example, he held that God exercised his providence by using comets to distribute matter and motion throughout the universe. Thus stars that have been "exhausted bit by bit in the exhalation of light and vapors" could be "renewed by comets falling into them" and "kindled by their new nourishment" (Newton 1997 **LINK**, p. 937). Comets were also involved in human history and the continual destruction and renewal of the world. Newton speculated that the conflagration expected at the end of days could be caused by a comet falling into the sun and inflaming it, and the subsequent renewal by a comet drawing a moon of Jupiter or Saturn away from its orbit to create a new 'earth.' Gravity itself provided evidence for God's intervention. Given the attractive nature of the force, "a continual miracle is needed to prevent the Sun and fixed stars from rushing together" (reported by David Gregory in Newton 1959–77 **LINK**, Vol 3, p. 336).

The last point is most significant. Newton took the coherence and stability of the universe to be evidence of God's design. The task of natural philosophy, for him, was to reason "from particular Causes to more general ones, till the Argument end[s] in the most general," that is, God. Knowledge was not to be gathered for its own sake, but for the proof and celebration of the deity (Newton 1730 **LINK**, p. 404). This, he thought, was "a duty of the greatest moment" ("Untitled Treatise on Revelation," *The Newton Project*). There is no question that his life's work was directed to this end.

See Also:

Alchemy

Cosmology

Field theory, classical

Mechanics, classical

Natural Theology

Optics

Scientific method

Space

Theories, scientific

List of Works:

Manuscript sources at Cambridge University Library: http://cudl.lib.cam.ac.uk/collections/newton. (High quality scans of the majority of extant Newton manuscripts; Latin and Enligh.)

The Newton Project: http://www.newtonproject.sussex.ac.uk/. (The project provides transcriptions of many Newtonian works. The focus is on alchemical and religious works, but others are well represented. Many of the primary works listed below are available here.)

Newton, I. (1687). *Philosophiae naturalis principia mathematica*. London: Joseph Streater (for the Royal Society); 2nd edn, Cambridge, 1713; 3rd edn, London: Guil. & Joh. Innys (for the Royal Society), 1726. (Latin editions of Newton's master-work on the laws of motion, gravitation, and celestial mechanics.)

Newton, I. (1715). 'An Account of the Book Entitled *Commercium epistolicum*', *Philosophical Transactions* 29 (342): 173–224. Reprinted in Hall 1980 and partially in Newton (2004). (Newton's anonymous review of his priority dispute with Leibniz. Also contains an account of the methodological differences between the two thinkers, as Newton understood them.)

Newton, I. (1728). *Chronology of Ancients Kingdoms Amended*. London: J. Tonson in the Strand, and J. Osborn and T. Longman in Pater-noster Row. (A posthumously published text devoted to the dating of Greek, Persian, Jewish, and Assyrian historical and purportedly historical events. Newton's use of mathematically-based evidential reasoning here mirrors his use of it in celestial mechanics).

Newton, I. (1730). *Opticks, or a Treatise of the Reflections, Refractions, Inflections and Colours of Light*. 4th edn; New York: Dover, 1952. (Newton's groundbreaking work in optics. Apart from experiments and theoretical discussion of light and colors, it contains the famous "Queries" in which Newton speculates about the ultimate nature of matter, force, and future progress of natural philosophy.)

Newton, I. (1733). *Observations upon the Prophecies of Daniel, and the Apocalypse of St John*. London; repr. W. Whitla, *Sir Isaac Newton's Daniel and the Apocalypse with an Introductory Study… of Unbelief, of Miracles and Prophecy*. London: John Murray, 1922. (A posthumously published study in biblical interpretation. Although it was cleansed of Newton's heterodox opinions before publication, it provides clear insight into his theological priorities).

Koyré, A. and Cohen, I. B. (1962). "Newton and the Leibniz-Clarke Correspondence with Notes on Newton, Conti, and Des Maizeaux." Archives International d'Histoire des Sciences, 15:63–126. (A collection of primary texts related to Newton's involvement with the Leibniz-Clarke correspondence, as well as his personal correspondence with Leibniz).

Newton, I. (1958). *Isaac Newton's Papers and Letters on Natural Philosophy and Related Documents*. Ed. I.B. Cohen, assisted by R.E. Schofield, Cambridge, MA: Harvard University Press. Second revised edition 1978. (Contains the publications on light from 1672–1676) (Collected facsimiles of Newton's 1670s papers concerning light and colors, subsequent letters concerning them, and a variety of text concerning chemistry, atomism, and the aether. Includes Fontenelle's "Eloge" of Newton.)

Newton, I. (1959–77). *The Correspondence of Isaac Newton*. Eds H.W. Turnbull, A. Scott, A.R. Hall and L. Tilling, Cambridge: Cambridge University Press, 7 vols. (Full transcriptions of all extant correspondence by or to Newton.)

Newton, I. (1962). *Unpublished Scientific Papers of Isaac Newton*. Eds A.R. Hall and M.B. Hall, Cambridge: Cambridge University Press; repr. 2nd edn, 1978. (A variety of early papers in mechanics, the first full tract on the calculus, and 'De Gravitatione')

Newton, I. (1965). *The Background to Newton's Principia: A Study of Newton's Dynamical Researches in the Years 1664–84*. Ed. J.W. Herivel, Oxford: Clarendon Press. (Contains transcriptions of the *De motu* drafts leading up to the *Principia*, as well as a detailed study of their evolution.)

McGuire, J. E. (1966). "Body and Void and Newton's De Mundi Systemate: Some new sources." *Archive for the History of Exact Sciences*, 3:206–248. Reprinted in McGuire (1995), Ch. 3. (Newton's draft definitions intended for the third edition of the *Principia* (1726), as well as a detailed study of their significance for Newton's evolving thought.)

Newton, I. (1967–81). *The Mathematical Papers of Isaac Newton*. Ed. D.T. Whiteside, Cambridge: Cambridge University Press, 8 vols. (The authoritative presentation of Newton's extensive work on mathematics, with extensive historical and analytical commentary.)

Newton, I. (1972). *Isaac Newton's* Philosophiae naturalis principia mathematica*. The Third Edition (1726) with variant readings*. Eds A. Koyr and I.B. Cohen, with assistance of A. Whitman, Cambridge, MA: Harvard University Press, 2 vols. (A comparison of all three latin editions of the *Principia*, as well as Newton's manuscript sources.)

McGuire, J. E. (1978). "Newton on Place, Time, and God: An unpublished source." *British Journal for the History of Science*, 11:114–129. (Contains "Tempus et Locus," an important 1690s document in which Newton presents his ontology of space and time.)

Newton, I. (1983). *Certain Philosophical Questions: Newton's Trinity Notebook*. Eds J.E. McGuire and M. Tamny, Cambridge: Cambridge University Press. (Newton's notebook from his student days in Cambridge. It is eclectic and far-reaching, but decidedly *juvenilia*.)

Newton, I. (1984). *The Optical Papers of Isaac Newton*. vol. 1, ed. A.E. Shapiro, Cambridge: Cambridge University Press. (Authoritative presentation of Newton's early published and unpublished material on optics and optical experiments, alongside extensive historical and analytical commentary)

Newton, I. (1997). *Isaac Newton's Mathematical Principles of Natural Philosophy*, trans. I.B. Cohen and A. Whitman, Los Angeles: University of California Press. (The authoritative english translation of the *Principa*.)

Newton, I. (2001). "Newton's Scholia from David Gregory's Estate on the Propositions IV through IX Book III of his Principa," ed. and trans. Volkmar Schüller. In Lefevre, W., editor, *Between Leibniz, Newton, and Kant: Philosophy and Science in the Eighteenth Century*. Dordrecht: Kluwer Academic Publishers. See also McGuire, J. E. and Rattansi, P. M. (1966). "Newton and the 'Pipes of Pan' ". *Notes and Records of the Royal Society of London*, 21(2):108–143. (Contains the so-called "Classical Scholia," Newton's 1690s unpublished additions to Book III of the *Principia*. In them, Newton finds ancients precedents to the law of universal gravitation.)

Newton, I. (2004). *Isaac Newton: Philosophical Writings.* Ed. Andrew Janiak. Cambridge: Cambridge University Press. (Contains a newer translation of 'De Gravitatione,' and excerpts from other works, including the General Scholium to the *Principia*. The recommended starting point for a philosophical study of Newton.)

G. W. Leibniz and Clarke, Samuel (1980). *Leibniz and Clarke: Correspondence*. Edited, with Introduction, by Roger Ariew, Hackett Publishing Co. Inc. Indianapolis/Cambridge, 2000. (The famous correspondence between Leibniz and Clarke. It details the Leibnizian and Newtonian position on a variety of subjects, including space, time, matter, God, and the nature of physical action.)

Further Reading:

Janiak, A. and Schliesser, E., editors (2012). *Interpreting Newton: Critical Essays*. Cambridge University Press. (Collected recent essays on a variety of Newtonian topics, including metaphysics, method, historical influence, and relations with contemporaries.)

Cohen, I. B. and Smith, G. E., editors (2002). *The Cambridge Companion to Newton*. Cambridge University Press. (Collected essays that aim to cover the basics of Newtonian studies. A recommended introduction to the secondary literature.)

Biener, Z. and Schliesser, E., editors (2014). *Newton and Empiricism*. Oxford University Press. (Collected essays on Newton's reading of and reading by "empiricist" philosophers such as Bacon, Locke and Hume, as well as discussions of Newton's "empirical" methods in the 17th, 18th, and 19th centuries.)

McGuire, J. E. (1995). *Tradition and Innovation: Newton's Metaphysics of Nature*. Kluwer Academic Publishers, Boston. (Classic essays focusing on Newton's complex metaphysical beliefs as expressed in a variety of published and unpublished sources.)

Shapiro, A. E. (1993). *Fits, Passions, and Paroxysms: Physics, Method, and Chemistry and Newton's Theories of Colored Bodies and Fits of Easy Reflection*. Cambridge University Press, Cambridge [England]; New York, NY, USA. (An in-depth study of Newton's optics, by the leading authority on the matter. A great introduction to Newton's methods and thought outside of celestial mechanics.)

Janiak, A. (2008). *Newton as Philosopher*. Cambridge University Press, New York. (A study of Newton's metaphysics of nature and its relation to physical inquiry. Recommended for non-technical readers.)

Harper, W. (2011). *Isaac Newton's Scientific Method: Turning Data into Evidence about Gravity and Cosmology*. Oxford University Press, Oxford. (A careful reconstruction of Newton's argument for universal gravitation, as presented in the beginning propositions of Book III of the *Principia*. Requires some technical background knowledge.)

Ducheyne, S. (2011). *The Main Business of Natural Philosophy: Isaac Newton's Natural- Philosophical Methodology*. Archimedes. Springer, New York, 1st ed edition. (A thorough analysis of Newton's metaphysics and method, taking into account works in both mechanics and optics, as well as a variety of unpublished, religious, and alchemical sources.)

Rynasiewicz, R. (1995). "By Their Properties, Causes and Effects: Newton's Scholium On 'Time, Space, Place And Motion—I. The Text, Ii. The Context." *Studies in History and Philosophy of Science*, 26(1, 2):133–153, 295–321. (A classic study of Newton's "scholium on space and time." Required reading for those interested in Newton's metaphysics of space.)

DiSalle, R. (2006). *Understanding Space-Time: The Philosophical Development of Physics from Newton to Einstein*. Cambridge University Press, Cambridge, UK. (A historical-philosophical account of Newton's place in the broader trajectory of physical inquiry, from Newton to the 20th century. Particular emphasis is paid to Newton's relationship with Kant.)

Hall, A.R. (1980). *Philosophers at War: The Quarrel Between Newton and Leibniz*. Cambridge: Cambridge University Press. (A highly readable account of Newton's battles with Leibniz over the calculus and conceptual issues related to metaphysics and physics.)

Bertoloni Meli, D. (1993). *Equivalence and Priority: Newton Versus Leibniz*. Clarendon Press, Oxford. (A detailed study of Leibniz's hand-written notes on the first edition of Newton's *Principia.* Mandatory reading for understanding Newton's and Leibniz's relationship.)

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