Chapter 1

Physics, Metaphysics, and Method in Newton's Dynamics

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Newton's masterful scientific achievement was constructed under the influence of much previous philosophical discussion and controversy that went beyond the limits of scientific debate narrowly construed. Much that Newton says in the *Principia* also ranges beyond the confines of experimental or even theoretical science and into the realm of what we usually think of as philosophy. And Newton's work gave rise, possibly more than any other work of science before or since (excepting just possibly the work of Darwin and Einstein) to vigorous philosophical as well as scientific discussion. Let us look at some of the philosophical issues behind, within, and ensuing from Newton's work.

It is convenient to group the discussions into three broad categories. First, there is the "metaphysical" debate over the nature of space, time, and motion. Next there is the debate over what can be properly construed as a scientific explanation of some phenomenon. Lastly, there is the controversy over what the appropriate rules are by which scientific hypotheses are to be credited with having reasonable warrant for our belief. We will discuss these three broad topics in turn.

The Metaphysics of Space, Time, and Motion

There are passages in Aristotle that some read as an anticipation of the doctrine about space and time called "relationism," as when he speaks of the place of an object in terms of the matter surrounding it or talks of time as the "measure of motion." But the full-fledged doctrine of relationism is a product of the scientific revolution. The doctrine is first explicitly stated by Descartes in his later work, is accepted by Huyghens, and is worked out in great detail by Leibniz. In one of the most curious episodes in the history of scientific and philosophical thought, Newton, who all along was philosophically predisposed against relationism, changes the whole character of the metaphysical debate about the nature of space and time by offering a scientific, almost an "experimental," refutation of the relationist's claims.

In the ancient tradition there is a sense in which there is no real debate going on about the absolute or relational notion of motion. Motion is taken to be a property of an object that is not a merely relative property. An object is either at rest or in motion, and one need not supplement assertions about the state of the object by noting that the rest or motion is being posited with respect to some reference object that one has in mind. On the other hand, given the belief that the earth is at rest in the center of the universe, the earth itself, with its cosmic position, provides the standard of rest relative to which objects are adjudged to be at rest or in motion.

The strong impetus toward relationism arose out of the desire, beginning with Copernicus himself, to make the earth's rotational motion creditable. In defending his views against his critics, Copernicus speaks of earthly things as sharing in the earth's natural motion. In trying to back up Copernicanism Galileo points out how physical experiments fail to distinguish smooth motions in a straight line on the earth's surface. After all, a ball dropped from the mast of a ship, although in motion with respect to the pier, is at rest with respect to the ship itself. No wonder, then, that it drops to the foot of the mast.

Descartes generalized this to the claim that it was nonsensical to speak of an object being at rest or being in motion *simpliciter*. An object could be at rest or in motion only with respect to some other object taken as the reference relative to which rest or motion, and kind of motion, was to be specified. Descartes used the doctrine of the relativity of motion, combined with the suggestion that we usually speak of things as moving when they are in motion with respect to the things continuous with them, to claim that his theory of the earth driven in a vortex of the plenum about the sun could be properly said to be at rest. Descartes' relationism is plainly also motivated by the new anti-Aristotelian view of the space of the cosmos. Instead of a finite realm marked out by an earth at the center and the starry sphere at the boundary, the cosmos is, for Descartes, as for Giordano Bruno, an infinite Euclidean three-dimensional space. In such a space, alike at every point and in every direction, nothing in the nature of "space itself" provides a reference frame for position or for motion.

Leibniz gives a worked out account of a metaphysics of space and time that is relationist through and through. A nice presentation of his views can be found in a series of letters he exchanged with Samuel Clarke, a disciple of Newton and defender of Newton's absolutism. Leibniz's views of space and time are actually a portion of a deeper metaphysics on his part about which we can only make the briefest remarks. Partly as a response to the difficulty of imagining a causal relationship between mind and matter, and partly motivated by thoughts about perception and its relation to the world that drove later philosophers to varieties of idealism and phenomenalism, Leibniz posits a world composed solely of spiritual beings and their properties, the monads. These basic constituents have no causal relations to one another. But they experience coherent lives due to a "preestablished harmony" instilled in them by God at their creation, which leads each of them to a programmed existence corresponding to the evolution of each other monad.

But we can understand much of Leibniz's space–time relationism by working in a scheme in which material events occur and material things exist. Events bear temporal relations to one another, they occur before or after one another, and different amounts of time separate their occurrences. Objects existing together at one time bear spatial relations to one another. They are above or below one another, one object can be between two others, they have certain specifiable distances between them. There are, then, two "families" of relations, the temporal relations among events and the spatial relations among things.

But what there is not, according to Leibniz, is "time itself" or "space itself." To imagine such "entities" is as foolish as to imagine that in a family of people who bear familial relations to one another, there is something that exists as an entity in its own right above and beyond the existing people. No, only the people exist, although they do bear many familial relations to one another. Similarly, events occur, and they bear temporal relations to one another. Material objects exist (in the misleading version of Leibniz we are dealing with) and they bear spatial relations to one another. But there is no time itself and no space itself that would exist even if no material events occurred and no material objects existed.

Leibniz offers a series of arguments designed to show that the opposite view, say that space exists as a substance in its own right, is manifestly absurd. All of the arguments rest upon the idea that if time and space existed in their own right, then to ask when things happened in time and where things happened in space would be meaningful. But, Leibniz argues, such questions are absurd.

Suppose substantival space exists. Then God could have created the entire material world somewhere other in space than where he put it. But in doing so he would have had to act without a "sufficient reason" for putting the material world in one place rather than another. But, according to a fundamental metaphysical principle of Leibniz, nothing happens without sufficient reason. So substantival space cannot exist.

Suppose substantival space exists. Now imagine two possible worlds, alike save that the entire material world occupies different places in space itself in the two worlds. These worlds would be, according to the substantivalist, distinct possible worlds. But they would be alike in every qualitative respect. Here Leibniz is operating under the assumption, of course, that every point in space itself is like every other, and every direction in space itself is like every other, that is that space is homogeneous and isotropic. But another Leibnizian fundamental principle is that if *A* and *B* have all qualitative properties alike, then *A* is the same thing as *B* (the Identity of Indiscernibles). So the two worlds must be, contrary to substantivalism about space, the same possible world. So substantivalism is wrong.

Finally, were the material world somewhere else in substantival space, this would make no difference whatever in any of our possible empirical experiences of things. But it is nonsense to speak of differences in the world that are totally immune from any observational consequences whatever. So substantival space doesn't exist.

What is time? Time is an order of occurrences, that is a set of relations among material happenings. What is space? Space is an order of relations holding among material things considered as existing at the same time. Actually it isn't quite that simple, for time and space are orders of *possibilities.* Let us just deal with space. There is empty space in the world (if, that is, you don't agree with Descartes that all space is filled with matter). But how can we speak of empty space, say between here and the sun, if there is no such thing as space? Well although nothing material is between the sun and the earth (let us suppose), something *could* be there. To speak of the empty space of the world, even of its geometric properties, is to speak of what the family of spatial relations would be like were there material objects occupying the places of space that are in fact empty. It is these "relations in possibility" that constitute what we are talking about when we talk of empty space, and not some mysterious space substance waiting to have material stuff coincide in position with it.

But not everyone before Newton or contemporaneous with him is a relationist. Indeed, two clear influences on Newton's thought were Henry More and Isaac Barrow. Both taught at Cambridge and it was Barrow, Newton's direct teacher, who ceded his professorial chair to his more brilliant student.

More, called the "Cambridge Platonist," was an ardent exponent of the doctrine that space existed in its own right. "It is infinite, incorporeal and endowed only with extension." Space, according to More, is "one, simple, immobile, eternal, perfect, independent, existing by itself, incorruptible, necessary, immense, uncreated, uncircumscribed, incomprehensible, omnipresent, incorporeal, permeating and embracing all things, essential being, actual being, pure actuality." Indeed, God is always and everywhere present in space itself. Space is a substance in that it exists in its own right. Even if there were no matter in it, space would still have its same being. And this being is an actuality, not a mere mode of possible relations among material things. The echo of More can be clearly heard again and again in Newton's own philosophical remarks about the nature of space.

There are interesting purely philosophical arguments that can be adduced to support such a substantivalist position against Cartesian–Leibnizian relationism. For example, if there were no such thing as space itself with its own existing actual structure, what would provide the ground for the law-like behavior of the possible spatial relations among things, made so much of by Leibniz? If there were no actual space obeying the laws of geometry, why would it be the case that whatever material things existed, with whatever spatial relations they had to one another, those relations would have to conform with the laws of geometry? Arguments in this style are the stock in trade of the substantivalist objections to relationism. We shall not pursue them, focusing instead on Newton's novel "scientific" refutation of relationism.

Barrow also believes in an infinite, eternal space that exists before the material world and beyond it. And, he insists, "so before the world and together with the world (perhaps beyond the world) time was and is . . ." Sometimes his language takes on a "modal" cast not unlike that of Leibniz, as when he says that time "does not denote an actual existence, but simply a capacity or possibility of permanent existence; just as space indicates the possibility of an intervening magnitude . . ." But, he is insistent, time is not a mere abstraction from motion or change. There is a "flow" of time which is uniform and unchanging. Even if all motion and change in the universe ceased, time would continue to elapse at its steady rate. We can measure the lapse of time with clocks that are more or less adequate, but no material clock is a perfect measurer of the lapse of time. He is a little vague on how we know the real rate at which time elapses, but suggests that it is through a kind of "congruence" among our various measures that we infer the real rate at which time is elapsing. Barrow's very words are often discernible in Newton's remarks.

Newton had many things to say about the metaphysics of space and time. In the unpublished work "*De Gravitatione*" he speaks of absolute place and motion in terms familiar from More. He often has theological things to say about space and time as well, taking the Deity to be eternal and ubiquitous, existing at all time in all places. In one notorious passage he speculates about space being the "sensorium" of the Deity, God's visual field, as it were. In other places he puzzles over the metaphysical nature of space, sometimes saying it is like a substance, sometimes thinking of it as an attribute (of the Deity), and in other places saying that it has a nature of its own unlike ordinary substance or accident. But it is not in espousing any such "absolutist" doctrines about space and time, nor for rehearsing the usual philosophical arguments for them, that Newton draws our attention. For Newton provides a wholly novel argument in favor of the existence of space as an independent entity over and above material things, and for an absolute measure of the "rate of flow" of time. His argument rests upon bringing to the surface a blatant contradiction latent in Descartes.

Descartes' one fully correct contribution to dynamics was in his version of what became Newton's First Law of Motion. Objects not acted upon by external forces persist in uniform motions in a straight line. But the truth of that law, indeed, the very comprehensibility of what the assertion of the law means, requires that we be able to say what it is to move with constant speed and what it is to move in a straight line. But if we can choose measures of the lapse of time as we wish, any motion can be regarded as at constant speed or at variable speed as we wish. Constant speed means the same distance covered in the same time, and that implies, if constant speed is not to be arbitrarily asserted or denied of an object, that our measure of the sameness of time intervals be absolute, or at least invariant up to a linear transformation (that is, a choice of zero point and choice of scale for time intervals). And to say that something moves in a straight line also implies some standard of reference relative to which motion is genuinely straight. Be allowed to choose any reference frame that is fixed in a material object that moves however you like, and any motion can be construed, relative to some selected frame, as straight-line or not straight-line as one chooses. To make the first law of motion meaningful requires an absolute standard of lapse of time and an absolute reference frame relative to which uniform straight-line motion is to be counted as genuine uniform straight-line motion.

As Newton argues in the "Scholium to the Definitions" of the *Principia*, we can easily detect deviation from inertial motion experimentally. He chooses his examples from rotation (the non-flatness of the surface of the spinning water in the bucket, the tension on the rope holding together the spheres in rotation about the center of the rope), but examples from linear acceleration would suffice as well. Deviations from uniform, straight-line motion show up by the presence of inertial forces. Therefore uniform straight-line motion is not arbitrarily chosen but fixed by nature and empirically discernible. It is that motion which continues unabated when no forces act on the moving object and it is that motion which generates no inertial forces.

One could put an object into relative acceleration by leaving it alone and applying forces to the reference object relative to which the motion of the test object is to be judged. But such relative acceleration is not absolute acceleration. For an object to be truly accelerated, absolutely accelerated, forces must be applied to the object itself. But if acceleration is absolute, there must be, Newton believes, absolute place and absolute change of place. For only then could absolute acceleration even be defined.

Finally, absolute motion as revealed by its dynamical effects must be attributed to the earth along with all the other planets. Only by considering the earth in truly accelerated motion in its elliptical orbit about the sun can we understand the need for the mutual attractive force sun and earth exert on each other, which serves as the "tether" keeping the earth from following its otherwise natural, inertial, straight-line motion. So much the worse for Descartes' attempt at keeping on good terms with the Inquisition by using relationism to defend a claim of the earth being at rest.

Newton's "experimental proof" of the existence of substantival space becomes the subject of several centuries of ongoing controversy. It is the core critical element a relationist such as Ernst Mach must deal with in the nineteenth century, and it is central to twentieth-century attempts at characterizing an appropriate metaphysics for space–time. Suffice it to say here, though, that Newton is certainly right that any espousal of a dynamical theory that places inertial motion at the very center of its theoretical apparatus cannot be compatible with the kind of spatial and temporal relationism espoused by Descartes and Leibniz. Flat-out relationism as they intended it is not easily reconcilable with the existence of special states of motion that reveal themselves as dynamically distinguished in nature.

Leibniz tried to respond to the Newtonian argument, as it was presented to him by Clarke in their correspondence, but his final response to the Newtonian arguments is quite weak. Leibniz says, "I grant there is a difference between an absolute true motion of a body, and a mere relative change in its situation with respect to another body. For when the immediate cause of change is in the body, that body is truly in motion; and then the situation of other bodies, with respect to it, will be changed consequently, though the cause of that change not be in them." But consider a wheel spinning for all eternity in an otherwise empty universe. There is no relative motion of the wheel with respect to other bodies at all. And there is a sense in which there is no "cause" that sets the wheel in motion. Yet, if Newton's science is right (and Leibniz is not disagreeing with it), the wheel's rotation will show up in its internal stresses. To be sure, each point of the wheel suffers internal forces from the other points of the wheel. These are the forces that simultaneously deviate each point from its inertial motion and hold the wheel together. But Newton will insist that the need for such forces to keep the points of the wheel on their circular orbits must be accounted for in terms of something special about the motion of those points, something kinematically and not dynamically characterized. Otherwise the need for the forces could only receive a circular explanation: "The forces are needed because the points of the wheel are in the kind of motion for which forces are needed." And to characterize what is special about the motion of the points in terms that do not themselves invoke the needed forces can only be to assert that the motion of the points requires those forces because the points of the wheel are deviating from uniform motion in a straight line. And that deviation implies the existence of space as the reference frame relative to which such deviation is real, true, absolute deviation.

It is fascinating to see how Huyghens responds to the Newtonian arguments. Huyghens once said that straight-line motions were all merely relative, but that circular motions had a criterion that identified them – the tension in the rope needed to keep the object in its circular orbit, for example. He later tries to give a relationist account of circular motion in terms of points on a wheel on opposite sides of the axle moving in opposite directions relative to one another. But this won't do, for in a reference frame fixed in the wheel, all the points on the wheel are simply at rest. Huyghens is just assuming the description of the system from the point of view of an inertial reference frame. Furthermore, linear accelerations show up dynamically as well. When the emergency brake is pulled and the train screeches to a halt at a station, it is the coffee in the cups held by the passengers on the train that sloshes out of the cups, not the coffee in the cups held by people on the station platform. Yet relationistically speaking, the platform is just as much accelerated relative to the train as the train is to the station.

There are, of course, deeply problematic aspects to Newton's account. Although absolute acceleration reveals itself dynamically, absolute place and absolute uniform motion do not. If we accept Leibniz's claim, anticipating later positivism, that it is nonsensical to speak of features of the universe that have no observational consequences whatsoever, how can we tolerate a theory that posits the existence of both absolute place and absolute uniform motion, but which, on its own terms, declares them as having no empirical import whatever? Newton was clearly aware of the problem of the empirical irrelevance of states of absolute uniform motion. He himself points the important facts out in Corollary V to the Laws of Motion in the *Principia*. The best he can do to repair this gap in his theory is to propose the peculiar Hypothesis I of Part III of the *Principia*, which rests on what “all agree to,” that the center of the solar universe is at rest, and to use that hypothesis to then fix the center of mass of the solar system as being at rest. Corollary VI to the Laws shows that there is an even deeper problem in the Newtonian system, in that even some accelerated motions may have no dynamical effects. Both corollaries rest upon implicit assumptions that go beyond Newton’s Laws of Motions, the assumptions to the effect that the motions will not change the interactive forces among the particles of the moving systems. Both results will play deep roles in later dynamics. The equivalence of all inertial frames will later be fundamental in special relativity and in the reconstruction of Newtonian theory from a space–time point of view (Galilean or neo-Newtonian space–time), and the empirical irrelevance of uniform universal acceleration will play its role in the foundations of general relativity and in the space–time reconstruction of the Newtonian theory of gravity.

Issues Concerning Explanation

Philosophers try to characterize the general notion of the nature of a scientific explanation. Usually it is assumed that we can say what it is for something to count as having the right character to be a scientific explanation without paying much attention to what the actual contents of some particular science are in which the explanations are being offered. That is, it is often assumed that we can make sense of unpacking the *form* of what an explanation must be like in indifference to the particular *contents* of particular explanations offered in particular scientific theories.

But is that really so? Or is it the case, rather, that our very idea of what sorts of things are to count as explanatory is conditioned by the particular contents of what we take to be our best available explanatory theories? This issue can be nicely illustrated by looking at some of the debates about the nature of scientific explanation that arose out of the Newtonian synthesis in dynamics. But to understand these we must first look at the account of explanation most popular among knowledgeable scientists immediately prior to Newton’s great work.

The ideals of scientific explanation arising out of Newton’s work are best understood in contrast to the explanation ideals promulgated by Descartes and his followers, where the model of scientific explanation offered was proposed as an alternative to what were taken to be, rightly or wrongly, the ideals of explanation of Descartes’ predecessors. The Cartesians are constantly contrasting their “modern” notion of scientific explanation with the outworn and foolish ideas, they think, of their Aristotelian or “Peripatetic” opponents.

The Aristotelians believed in species of natural motions as well as forced motions. Natural motions consisted in the attempt of objects to return to their natural places in the universe, such as the motion of falling earthly things, and the perfect, eternal circular motions of the heavenly bodies. All other motions are forced. For Cartesians natural motions are motions at constant speed in a straight line – inertial motions. All other motions are forced.

For Aristotelians, the world is a place of substance and properties. There are many kinds of properties of things, and properties can inhere in things both in actuality and in mere potentiality. For Cartesians there are only two substances, mind and matter. And only two kinds of general properties, thought and extension. For Aristotelians there are many kinds of changes, comings into being and passings out of being, as properties come and go in actuality. Motion, properly so-called, is only one kind of change. These changes are to be accounted for in terms of the four causes: the formal, material, efficient and final causes of the change. For Cartesians there is only one kind of change in the realm of matter, that is change describable in terms of the basic notions of time and space alone. For the Cartesians, that is, all material change is motion in the narrower sense of change of spatial place in time.

For Aristotelians, at least in the version of them favored by their Cartesian critics, explanation is often in terms of properties of things that are hidden from our direct observational awareness. Peripatetic physics, the Cartesians say, is incessantly resorting to the attribution of "occult," hidden, qualities to things to explain their behavior. But Cartesian physics denies the reality of such hidden causes, or even the meaningfulness of attributing them to objects. For Cartesians all explanatory features must be "manifest," directly open to our observational awareness.

For the Cartesians all explanation of all change, that is of all motion, must take one of two forms. The motion may be natural motion, that is inertial motion, in which case no further explanation of it is needed. If the motion is not inertial, it must deviate from uniform motion in a straight line only because some other motion has directly impinged upon the moved object. A ball is accelerated when another moving ball collides with it. A planet moves in an orbit only because it is dragged along by the vortex of the medium in which it resides. Non-inertial motion is always the result of other, contiguous motion. And the fundamental rule governing this causation of one motion by another is that motion is conserved. The accelerated ball has its motion changed only to the degree that its gain or loss of motion is compensated by the gain or loss of motion of the ball impacting it.

Any explanatory account of the world that deviates from the Cartesian pattern must not only fail to be scientifically correct, it must fail to meet the conditions necessary for something to be a genuine scientific explanation at all. The account Newton gives of the motion of the planets fails in many ways to meet the proper standards for explanation as the Cartesians see it. Their response is twofold, even though, curiously, their two objections are often quite at odds with one another. On the one hand, Newton is often accused by the Cartesians of a kind of reactionary resort to justly condemned, outmoded forms of explanation. He invokes, say the Cartesians, the infamous occult properties of the Aristotelians. Worse yet, he allows explanations of motion that do not themselves invoke previous motion as the explanatory element, and he tolerates mysterious influences of objects on one another even when the objects are not contiguous to one another. On the other hand, Newton is often accused by the Cartesians of merely describing the motions of things, and not offering an explanation of their motions at all!

Consider some contrasts between the Newtonian and the Cartesian explanatory schemes. The one element they clearly have in common is the postulation of uniform speed in a straight line as the natural state of motion of things, although as we have seen, Newton takes the posit of such natural motions to be blatantly inconsistent with Descartes' relationist theory of space and time.

Newton invokes both quantity of matter, mass, and force as fundamental concepts in his descriptive scheme. In fact he believes in other primitive qualities of matter as well, such as hardness and impenetrability. There is no obvious way that Newtonian physics can be characterized solely in terms of the kinematic notions of place, time and motion, to which the Cartesian is conceptually restricted. Whether these apparent primitive concepts are really needed in the Newtonian theory is something much debated in Machian and later reconstructions of Newtonian theory. Neither mass nor force are obviously "manifest" properties, as Cartesians take relative place and motion to be. Furthermore, Newton invokes the notions of absolute place and absolute time interval. Here the basic concepts are purely kinematic in nature, but they are, once again, not manifest as relative place and clock-measured time would be.

For Newton the fundamental explanation of change of motion is force, the force an object exerts upon another, be it a force of contact impulse or the action, at a distance, of gravitational attraction. Motion need not be accounted for in terms of antecedent motion. Indeed, Newton expresses grave reservations about the correctness of any comprehensive posit of the conservation of all motion, remarking how motion can be generated where none was before and how, by means of friction and like effects, it can disappear from the world. This is so even though Newton was quite aware of how the conservation of linear momentum for point particles acting on each other by forces followed from his Third Law; and even though, as we shall discuss later, other "conservation of motion" results either follow from Newton's original theory or become deeply integrated into its later formalisms.

This invocation of the notion of force in the Newtonian sense traces back to Galileo. It was in his work that the notion of force invoked in statics, primarily in the form of weight that impinged on some static framework, was invoked as the originator or generator of motion in dynamics.

And of course, motion need not require, at least in the first instance, an explanatory account in which all causes are taken as acting contiguously in space. We will note below, Newton's own preference for explanatory accounts that eschew any genuine action at a distance, but at least on the surface the actions of the heavenly bodies on each other, of gravitational attraction – the actions that govern the whole motion of the cosmos – seem plainly to violate Cartesian precepts that all causes are immediately next to their effects.

Newton is very sensitive to the charges laid against him by the Cartesians. On the one hand he is adamant that his account of motion does not resort to "occult qualities." He sometimes argues that when he speaks of the gravitational attraction one object exerts upon another, he is not positing some hypothetical cause of the motions or changes of motions of objects. He is, rather, merely noting the observable deviations from inertial motions that are induced when objects are in one another's proximity. That deviation is, for both objects, proportional to the product of their inertial masses and inversely proportional to the square of the distance between them. And it is directed along the line connecting the objects. From that, the law of gravitational "force" follows, and that is all the law is committed to. If anyone is dealing in the "hidden," Newton says, it is those who propose particular "mechanisms" to account for this mutual gravitational influence bodies have on one another (such as the not-directly observable vortices in the plenum that account for the cosmic motions, in Descartes' theory).

There is no simple way to characterize Newton's methodology. On the one hand his restriction, within the main body of the work, to the mathematical description of the motions of things summarized in general laws, with its eschewal of the search for hidden mechanisms, makes Newton seem quite the positivist. On the other hand nothing more infuriates the positivistically minded philosophers of his day, or of later eras, than his postulation of absolute space and absolute time.

Anxious to avoid what he takes to be the pointless and endless controversies that rage between scientists and philosophers, Newton, famously, asserts in the *Principia* that he does not "frame hypotheses" about the nature of the mechanism of gravitational attraction. As we shall see, he claims that all of the assertions he has made in the Laws of Motion and the Law of Universal Gravitation rest on far firmer grounds than any mere "hypothesis."

Nonetheless, Newton does frame hypotheses – about gravity and about many other things as well. In the "General Scholium" that forms the last section of the *Principia*, in the "Queries" section to his famous work *Opticks*, and elsewhere, Newton makes many proposals about the possible mechanisms that might result in gravitational attraction, that might account for light showing the properties that it displays (many experimentally determined for the first time by Newton himself), and that might explain the various structural and behavioral features of matter of various kinds. His hypotheses about gravity, for example, often have a very Cartesian flavor to them, as they postulate "ethers" that fill the universe with various fluid properties of pressure and resistance, and whose relation to matter (perhaps of lower pressure where matter is present, resulting in a "push" that moves matter toward matter) might, possibly, explain the law-like behavior of gravitational attraction. Such "mechanisms" might also remove from gravity the taint of action at a distance. It is worth noting here that the elements that later function to suggest the replacement of "action at a distance" theories by theories that propose an ontology of "fields" intermediate between the interacting objects, that is to say the time lapse in inter-particle actions and the violation in conservation of energy that results if one is not very careful in framing an "action at a distance" theory, play no role in the controversies embroiling Cartesians and Newtonians in Newton's time.

Some of Newton's hypotheses remain only curiosities in the history of science. Others, such as his particle theory of light, remain, if not really correct, important contributions to the development of later science. Still others, such as his hypothesis expressed in the "Queries" to the *Opticks* that there might be other forces along with that of gravity by which matter influences matter, and that these other forces might account for such things as the structure and behavior of materials, are prophetic insights into what became large components of the future growth of scientific understanding.

In any case, though, Newton is always careful to distinguish what he is guessing at or speculating at, that is, what he is "hypothesizing," from that which he thinks he has established by experiment, observation, and the kind of legitimate inferences from these upon which he thinks the core law-like assertions of the *Principia* are based.

Philosophically the most important thing to notice about this whole debate is the way in which scientists and philosophers become committed to a doctrine about the very nature of what a scientific explanation is, depending on which particular theories about that nature they hold at the time. For Cartesians, what they called "mechanical" explanations were constitutive of what any scientific explanation had to be. Any "explanation" that violated their precepts of being framed solely in manifest kinematic terms, of relying on motion only to generate motion, and of demanding contiguity of cause and effect, was not explanatory at all. It was either "mere description" without explanatory force, or it was pseudo-explanation resorting to rejected Peripatetic mumbo-jumbo. As we have seen in the case of Newton's account of motion under the influence of gravity, both accusations were made simultaneously.

With the triumph of the Newtonian dynamical scheme, however, came a wholly new idea of what any putative explanation must be like in order that it be a genuine scientific explanation. If an account of a phenomenon did not resort to natural motions being changed by interactive mutual forces among particles, it could not be a genuinely scientific, or sometimes, "causal," or sometimes, "mechanical" explanation of what was going on.

Just as Newton's science, in not fitting the Cartesian pattern of appropriate explanation by triumphing scientifically, cast grave doubt upon the very Cartesian demands for the structure of explanation in general, later science, in not easily fitting into a Newtonian pattern, led methodologists to become skeptical of what had become the Newtonian standard of the necessary conditions to be met by any scientific explanation. This becomes crucial in the critiques of generalized Newtonianism in science, put forward by Mach and others in the nineteenth century, and in later positivism.

It is worthwhile noting here that the Cartesian criteria of legitimacy in explanation suffered an additional blow from ongoing developments in dynamics that was not the result of the Newtonian synthesis. Along with occult qualities, Cartesians demanded the total rejection of the notion of "final cause" applied to the physical world. For Aristotelians each event was explicable both in terms of its immediate, driving predecessors – its efficient causes – and in terms of the obtainment of some goal or end, a final cause; for Cartesians, in the physical realm at least, only efficient causes were to be tolerable as legitimate explainers.

But the reintroduction into optics of a least time principle by Fermat seemed to provide a place for final causes in that branch of physics. Such principles, originally explored by Hero of Alexandria in the case of reflection and invoked by Fermat to account for the Descartes–Snell law of refraction, seemed to the Cartesians to smack badly of the forbidden Aristotelian idea of nature acting for an end or purpose. When Maupertuis discovered that a principle of least action could serve as a general foundational principle for dynamics, and when that principle was given decisive rigorous form by Euler, the reappearance of final causes threatened to be one more "reactionary" blow delivered to the failing body of Cartesian "progressive" dogma about the restrictions to be applied to the domain of legitimate explanatory methods in physics.

Newton's "Rules of Reasoning in Philosophy"

Newton had framed dynamics in terms of his three fundamental laws of motion and had applied dynamics to a theory of the heavenly motions by supplementing the dynamical laws with a law of universal gravitation. But why should we believe in the truth of the Newtonian account?

Newton himself was highly sensitive to criticism and deeply concerned to anticipate what he expected to be angry and vituperative attacks on his masterwork, the *Principia*. First there were the perpetual battles over precedence in discovery endemic to the science of Newton's day and of our own as well. Newton is careful to give generous credit where he thinks it is due, to Galileo on inertia, on the fact that constant force generates equal changes of motion in equal times, and on the fact that the acceleration due to gravity is independent of the size and constitution of the falling object; to Huyghens, Wallis and Wren on the conservation of momentum in collisions; to Huyghens on the magnitude of centrifugal force; and to Bouilleau, Wren and others on the inverse square diminution of the force holding planets to the sun. Sometimes, though, he is less than generous, failing to note Descartes' first fully correct statement of the inertia law and Descartes' first statement of a principle of the conservation of motion (even if Descartes got the principle wrong); and also failing to give Hooke enough credit for being, perhaps, the first person to state correctly that the motion of the heavenly bodies required only inertia and centripetal force alone. Since much of the *Principia* can be considered a sound refutation of everything Descartes said about the structure of the universe the less than generous stance toward Descartes can, perhaps, be understood. Since Hooke falsely claimed credit not only for getting elliptical orbits out of an inverse-square law, but for anticipating Newton's invention of the reflecting telescope as well, Newton's stinginess in granting him credit can also be understood. Hooke's nasty controversy with Newton over the nature of light also played a role, as we shall see, in Newton's framing of his methodological remarks in Book III of the *Principia*.

But it is not quarrels over precedence that most concern Newton. In 1671 Newton presented to the Royal Society the results of his wonderful experiments on the refraction and dispersion of light. These were published along with some of Newton's speculations about the corpuscular composition of light. Hooke responded immediately with a critical attack, offering his own "hypotheses" about the nature of light to contend with those of Newton. The resulting quarrelsomeness so upset Newton that he withdrew from publishing virtually any of his work until finally persuaded to come out with the *Principia* by Halley. Newton was well aware that his views in the *Principia* were likely to start another round of even greater controversy, especially at the hands of defenders of the Cartesian scheme of explanation.

As we have seen, Newton did not cease "hypothesizing," even within the *Principia* itself, where, in the "General Scholium" speculative thoughts about the mechanism of gravity receive their due. But he is careful throughout the work to isolate such "hypotheses" from the far more important work of developing his mathematically formulated laws of dynamics and of gravity, and using them to ground the laws governing the motions of the heavenly bodies. He also takes pains in several places to let the reader know that his grounds for believing in the truth of his laws are not the guesswork of hypothesis, but something that he thinks provides a far more secure basis for scientific belief. If the reader accepts these claims, then the core developments of the work will remain immunized from squabbles of the sort that arise when one bit of speculative scientific guesswork is confronted by other "hypotheses" of the same nature.

One thing Newton does not try to do is to show that his laws can be established by some kind of purely rational thought, that is by *a priori* reasoning or by Descartes' "clear and distinct ideas." He affirms the role of pure mathematics in his work and the soundness of his reasoning that follows from its use. But he is well aware of the fact that the soundness of the system as a whole is only as sure as the soundness of its "first principles." These, he insists, are derived not by any mode of pure thought, but by inference from the facts nature presents to our observation and experiment.

In the "Scholium to the Laws," Newton says, "Hitherto I have laid down such principles as have been received by mathematicians, and are confirmed by abundance of experiments." Galileo had, Newton suggests, discovered the Law of Inertia and the Second Law in his experiments on gravity and motion and had derived from them the famous results on the paths of projectiles. Wren, Wallis and Huyghens, Newton goes on, had discovered the truth of the Third Law in their work on collisions. Here Newton realizes that his generalization of that principle beyond collisions and into the realm of attractions is on more dubious experimental ground, and so he offers both deductive reasons why the law must extend to such phenomena and a confirming experimental test using floating magnets.

The laws, then, are supposed by Newton to be established by observation and experiment, which is then generalized from particular experiences to all phenomena by what is commonly called inductive reasoning. To be sure, the philosopher, especially one coming after David Hume and Nelson Goodman, will realize how many pitfalls stand in the way of someone who wants to underpin their beliefs on the grounds of the sole combination of observation and induction. But Newton is surely right in contrasting the support his laws of dynamics receive from quite direct experience projected by universalization, with the more tenuous kind of support an hypothesis that involves the widespread positing of "hidden" entities, properties and mechanisms would receive from its indirect confirmation only by its ability to predict confirming results at the observational level. Whatever the problems with induction may be, there is a sense in which inductive reasoning can be distinguished from more general "hypothetico-deductive" reasoning, and there is good reason to agree with Newton that his laws of motion receive their support from the narrower, and hence allegedly more secure, kind of inference.

Newton's most self-conscious reflection on methodology, in particular on the grounds for belief in a fundamental physical proposition, comes in an initial prefatory section to Book III of the *Principia* that gives its title to this section. The material is plainly intended to provide the basis for the reasoning that will support the inference to the universal law of gravitation. It is the grounds for that law that provides the content of the first part of Book III, and the application of that law in conjunction with the dynamical laws in order to account for the laws describing the heavenly motions that is the bulk of the remaining content of that Book.

There are four famous "Rules of Reasoning":

Rule I: We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearance.

Rule II: Therefore, to the same natural effects we must, as far as possible, assign the same causes.

Rule III: The qualities of bodies which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.

Rule IV: In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may be made more accurate, or liable to exceptions.

It would be a mistake to think of Newton as here proposing some general grand epistemology in the manner, say, of Descartes. He is, rather, adducing just those rules he thinks will appeal to all rational readers as unquestionably sound, and which will be sufficient to allow him to justify his claims to the effect that it is universal gravitation that is sufficient to provide the needed dynamical basis for all the heavenly motions, and to defend those claims from possible "alternative hypotheses" likely to be flung at him by Cartesian opponents of his work.

Rules I and II are invoked in Proposition IV, the proposition that first associates earthly gravity with a cosmic dynamical force. We can infer from the work of Book I that the cosmic forces are centripetal, for they obey the "equal area" law of Kepler. We can infer that this cosmic force diminishes with distance as the inverse square, for the orbits of the heavenly bodies are ellipses with the attracting center as a focus (and by other subtler facts in the case of the moon). But measurement of the acceleration of gravity at the surface of the earth shows that such gravity at the distance of the moon, having fallen off by the inverse square of distance, will be just the amount of cosmic, centripetal force needed to hold the moon in its orbit. So the force holding the moon in its orbit must be just that gravity: "And therefore (by Rules I and II) the force by which the moon is retained in its orbit is the very same force which we commonly call gravity; for, were gravity another force different from that, then bodies descending to the earth with the joint impulse of both forces would fall with a double velocity . . . altogether against experience." We need only the amount of the one accelerative force to get the correct acceleration of rock on earth and of the moon in the heavens, and since the effect is "the same" in both cases (appropriately modified in magnitude by the inverse square law) the cause of the acceleration must be the same.

In Proposition V it is argued that the similarity in effect of the moons of Jupiter, the moons of Saturn, and the planets in their relation to Jupiter, Saturn and the sun respectively, to that of the moon in its relation to the earth tells us, by Rule II, that it is "no other than a gravitating force" that retains all these other satellites in their orbits as well. This is defended in a "Scholium" to the proposition by reference to Rules I and II, and to Rule IV as well. Presumably the reference to the last rule is to deny the opponent the right to suggest that some other hypothesis could also do justice to the behavior of the satellites other than the earth's moon. For in their cases we don't have the argument that backed up gravity as the force used in Proposition IV. But here Rule IV tells us that we need not hesitate in our induction just because of the mere presence of other hypotheses as possible explanations of the phenomena.

Rule III is especially interesting. Its purpose is expressed in an exegesis immediately following the presentation of the rule itself. First it is argued, presumably against Cartesian rationalism and its skepticism of the reliability of the senses, that "all qualities of bodies are known to us by experiments." According to the Rule then, "we are to hold for universal all such as universally agree with experiments." Here quantity of matter (*vis insita*, inertial mass) is likened to such other properties as spatial extension, hardness and impenetrability, and mobility. That all bodies have such features, Newton claims, "we gather not from reason, but from sensation."

"Lastly, if it universally appears, by experiments and astronomical observations, that all bodies about the earth gravitate toward the earth, and that in proportion to the quantity of matter which they severally contain; that the moon likewise, according to the quantity of its matter, gravitates toward the earth; that, on the other hand, our sea gravitates toward the moon; and all the planets toward one another; and the comets in like manner toward the sun; we must, in consequence of this rule [Rule III], universally allow that all bodies whatsoever are endowed with a principle of mutual gravitation. For the argument from the appearances concludes with more force for universal gravitation than for their impenetrability; of which, among those in the celestial regions, we have no experiments, nor any manner of observation."

From observation we learn of the irreducible primary properties of matter available to hand for experimentation. By observation we can extend some of our attributions even to the heavens. Then, by the universalizing permitted by Rule III, we can finally arrive at the full attribution of the relevant properties to all matter in general. Thus we are able to project our earthly experience into a general description of the heavens as well.

What about the curious "which admit neither intensification nor remission of degrees" qualification in the statement of Rule III? It isn't completely clear what Newton is concerned about here, but perhaps the last sentence of the discussion following the statement of the rule gives us a clue: "Not that I affirm gravity [that is, weight] to be essential to bodies: by their *vis insita* I mean nothing but their inertia. That is immutable. Their gravity is diminished as they recede from the earth."

Newton is aware of just how subtle the connection is of mass to weight. In the "Definitions" of Book I he told us that we could measure the quantity of matter in a thing by its weight. And in his discussion of gravity he is brilliantly clear on the fact that both the passive and active gravitational charges of an object must also equal its inertial mass. But the mass is not the weight. The weight is a matter of a *relation* between the object, and the earth that is gravitationally attracting the object. Change the spatial relation of object to earth and you change the object's weight. But the object's mass (and its intrinsic gravitational charges for that matter) do not change. Our "universalizing" of the properties of what is in hand to properties of things everywhere and anywhere must confine itself to those properties intrinsic to the object, and not be applied to those which hold of the object only because of its special relations to objects external to it and which may "intensify or diminish" as those relations change.

Of course Newton has not provided any infallible recipe to tell us which of the properties we experience as universal of things in our experience really are "intrinsic," and which might very well turn out to be, in the end, merely relational. It was, after all, a great discovery of Newton and his contemporaries that weight was in fact not intrinsic but relational. But, as has been said, it would be misleading to think of Newton's rules as proposals for the foundations of epistemology. They are safeguards against polemic and misguided skepticism toward the results of his mathematical physics, especially toward his revelation of the universal law of gravitational attraction and its role in accounting for the heavenly motions.

Suggested Reading

For an introduction to Aristotle on motion see J. Barbour, *Absolute or Relative Motion?*, Cambridge: Cambridge University Press, 1989, ch. 2, "Aristotle: the First Airing of the Absolute/Relative Problem." On Descartes' relationism see D. Garber, *Descartes' Metaphysical Physics*, Chicago: University of Chicago Press, 1992, ch. 6, "Motion," and Barbour, ch. 8, "Descartes and the New World." For Leibnizian relationism see H. G. Alexander, *The Leibniz–Clarke Correspondence*, Manchester: Manchester University Press, 1956, especially the editor's introduction and Leibniz's 3rd. paper. For Cambridge Platonism and its influence on Newton see A. Koyré, *From the Closed World to the Infinite Universe*, Baltimore: Johns Hopkins University Press, 1957. For an outline of the development of Newton's metaphysics of space and time see Barbour, ch. 11, "Newton II: Absolute or Relative Motion?" Newton's reflections on space and time in his mature work can be found in I. Newton, *Newton's Principia*, translated and edited by F. Cajori, Berkeley: University of California, 1947, Book I, "Definitions," and, especially, "Scholium to the Definitions." See again Barbour, ch. 11, "Newton II: Absolute or Relative Motion?" For some contemporary philosophical commentary on the Newton–Leibniz controversy over the nature of space and time see L. Sklar, *Space, Time and Spacetime*, Berkeley: University of California, 1974, ch. III, "Absolute Motion and Substantival Spacetime," and J. Earman, *World-Enough and Space–Time*, Cambridge, MA: MIT, 1989, ch. 6, "Substantivalism: Newton versus Leibniz." For Huyghens difficulties with the issues of relationism see Barbour, ch. 9, "Huyghens: Relativity and Centrifugal Force." Newton's thoughts on method in science can be found in Newton, *Principia*, Book I, "Scholium to the Laws," and Book III, "Rules of Reasoning in Philosophy." To see how Newton applies his rules to justify his theory of universal gravitation see *Principia*, Book III, "Phenomena," and, especially, "Propositions (I through VII)." Newton's "hypothesis" about the nature of matter and forces in general can be found in I. Newton, *Opticks*, New York: Dover, 1952, "Query 31." For a condensed history of the "least action" principle and the difficulties it raised for the Cartesians, see R. Dugas, *A History of Mechanics*, New York: Dover, 1988, Part III, ch. 5, "The Principle of Least Action."