The Warden of Time and Space

Part 2: Newton's Principia.

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I believe the souls of five hundred Sir Isaac Newtons would go to the making up of a Shakespeare or a Milton.
—*Samuel Taylor Coleridge*

The achievements of great writers, painters, and musicians are accessible to a general audience in a way that the achievements of great scientists are not. In deprecating Newton's genius, the great poet and critic Samuel Taylor Coleridge was retailing a familiar humanist theme, that mere science lacks the exquisite depth and resonance of great art and indeed should be regarded as inferior to it. At the opposite from Coleridge's disdain is the equally uninformed idolizing of an Albert Einstein or a Stephen Hawking: the Scientist as celebrity. But those are not the only alternatives. With a little patience, the outlines of Newton's achivement can be grasped by anyone who is reading these words.

Newton's masterwork is the *Philosophiae Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), commonly known as the *Principia*. The first edition appeared in 1687, the second in 1713, and the third and final edition in 1726. Newton wrote the *Principia* in Latin, and until recently there has been only one complete translation into English, that of Andrew Motte in 1729. While adequate, Motte's translation was flawed in many ways, and, as old books are prone to do, it became a bit of a linguistic fossil over the years as its prose remained the same while the language around it changed.

In response to these concerns the University of California Press brought out an elegant new edition in 1934, nicely bound in leather, with a revised translation by Florian Cajori. Cajori did not prepare a fresh translation from scratch; he simply tried to "defossilize" Motte's English so modern readers could understand it. This Motte-Cajori version has been definitive since its introduction and continues to reside in some very respectable places on bookshelves throughout the English-speaking world; perhaps its most common residence is between Pascal and Locke

as volume 34 of Britannica's *Great Books of the Western World*.

The archaisms that Cajori removed from Motte's translation include such delightful obscurities as "duplicate ratio," which means simply "square of the ratio"; "subduplicate," which means "square root"; and my favorite, "subsesquiplicate ratio," which means "ratio of 3 to 2." (Nostalgic scholars of the English language often lament about how the language has atrophied over the years. I am sure that the reader will agree the loss of these delightful terms is nothing less than tragic.) These editorial changes are not substantive and most certainly resulted in a clarification of the text.

But Cajori made other changes as well. He "updated" Newton's physics in some questionable ways. At the time that Newton wrote the *Principia*, nature was interpreted within the context of the Aristotelian tradition, which understood changes in nature as coming from "within" things, out of an autonomous, almost organic sense of self-direction. Objects possessed an inner teleological "drive" to change.

Rocks fell down because it was their nature to "seek" the center of the universe. Fire rose up because it was "seeking" the top of the terrestrial realm. This Aristotelian understanding was overturned by an emerging paradigm which understood change mechanically, rather than organically. Within the mechanical paradigm, change was understood to come from without, mainly as the result of bodies pushing and pulling on each other by being in contact. But while Newton's work may have led to what became known as a mechanical description of nature, this was far from how he saw it; indeed, as we shall see, one of his major challengers was Descartes, who had an even more mechanical model of the universe.

If you go looking for a statement of Newton's First Law of Motion you will find the following, or something very similar (there is no "standard" formulation although the precise meaning of the law rarely, if ever, differs due to individual variations): An object at rest tends to stay at rest and an object in motion tends to stay in motion with the same speed and in the same direction unless acted upon by an unbalanced force.

I found this particular version on the very first Web site that was returned in response to a search for "Newton's First Law." It is basically the same as the version I learned and relearned in high school, college, and graduate school. It is the version that I teach to sophomores in my course on Newtonian mechanics at Eastern Nazarene College. It is essentially the same as the version that Cajori produced in his update of Motte. But it is not entirely faithful to Newton's original formulation.

In all three editions of Newton's Latin versions of the *Principia* he used the Latin verb *perseverare* to describe what a body does in the absence of an external force. Motte translated this correctly as "persevere." Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.

Now persevere has a decidedly organic, teleological connotation. That big rock that the backhoe could not dig out of my front lawn is not, it seems to me, persevering; it is just sitting there. Persevere is something that you do, not something that is done to you. After all, is not perseverance a traditional human virtue that we teach to our kids? We want them to persevere, even in the presence of an external force—to keep on walking "in a right line" while their companions veer off into mischief. Perseverance connotes volition, or self directedness. And it is entirely likely that Newton's intuition, and most assuredly his vocabulary, would have oriented him toward the notion that a body moved, at least in part, in response to some sort of inner drive. If a body is sailing through empty space, alone, with no other bodies nearby, with no pushing or pulling happening, it is persevering in its motion.

The traditional Aristotelian intuition was that this body was moving under the influence of some sort of natural inner drive that kept it going. Otherwise why was it moving? Things don't just happen for no reason. How can the absence of an external force cause anything to happen? Don't causes need to be present? As the Newtonian tradition matured, this particular understanding was discarded in favor of a more mechanical explanation. And so, when Cajori was updating Motte's translation of Newton, he changed this central text to read

"Every body continues in its state of rest or uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it." Completely gone is the more nuanced suggestion that the motion of a body might have something to do with an internal drive or volition.[1]

I have labored this apparently minor point because it serves in many ways as an example of the larger problem that has confronted those who would try to understand the accomplishment of Isaac Newton. Newton was not a twentieth-century figure who appears mysteriously in the seventeenth century. He is very much a man of his time, with all that implies about paradigms, vocabularies, intuitions, assumptions, prejudices, and so on. He may not have been an Aristotelian, but neither was he a Newtonian.

The Hidden Architecture of the Universe

Whoever studies the Principia in awareness of the works of Newton's predecessors will share the high value assigned this work ever since its first publication in 1687 and will rejoice that the human mind has been able to produce so magnificent a creation.
—I. Bernard Cohen

Many scholars lamented the flaws in the Motte-Cajori version, but an entirely new translation demanded a combination of linguistic, mathematical, and historical skills possessed by very few. After completing a scholarly edition of Newton's Latin text, I. Bernard Cohen—whom Richard Westfall, Newton's premier biographer, has called the "dean of practicing Newton scholars"—undertook a new translation into English with the help of Anne Whitman; Julia Budenz assisted in preparing the work for publication. This new rendering of Newton's masterwork was issued by the University of California Press in 1999, almost 300 years after the Motte translation. In addition to a translation of Newton's third edition, it includes a guide to the *Principia* by Cohen, running to almost 400 pages.

A good example of the subtlety and clarity Cohen brings to the task can be found in his treatment of what Newton calls *vis insita*. This is often rendered "innate force," but Cohen suggests that "inherent force" is actually more accurate. It turns out that

this particular detail has received quite a bit of scholarly attention. Just what did Newton mean when he spoke of the "force of inertia" (*vis inertiae*)? Inertia is one of the most important concepts in all of mechanics and one of the central elements of the *Principia*. The idea that bodies, once in motion, will continue to move on their own, precisely because there is not a force to "stop" them, was bizarre and revolutionary in the seventeenth century—so revolutionary that Newton took to calling this tendency a "force."

But inertia is not a force, despite our continued use of colloquialisms like "force of inertia." Readers have no doubt heard people refer to the "force" that, for example, propels them forward in their car when someone puts on the brakes. This is a misnomer. There *is* a force on the car from the braking that slows it down; without any similar force to slow the passengers, they continue to move forward, as if there were a force on them. The appearance of such a force has nothing to do with the passengers and everything to do with the car around them. Physicists would refer to the car as a "frame of reference." There is a force on the frame of reference moving it with respect to things within the frame of reference—in this case, the passengers.

This point deserves attention because we would really like to know just how clearly Newton understood the actual character of inertia, one of the most critical elements in the passage from Aristotelian to modern mechanics. Did he think of inertia as some sort of Aristotelian, or Cartesian, innate tendency arising from within the body?

Or was his understanding more modern than that? Did he have a modern understanding but use seventeenth-century language to express it, much the same as we speak of sunrises, long after we have stopped believing that the sun moves and the Earth stands still?

In any event, Cohen argues, on the basis of several statements that Newton made in later editions of the *Principia* and elsewhere, that *vis insita* is legitimately rendered "inherent force." This makes Newton less Cartesian, a distinction he would

certainly applaud. Nevertheless, Cohen concludes that "Newton (if only on an unconscious or psychological level) has not fully abandoned the ancient notions that every motion must require a 'mover' or some kind of moving force, even if a very special kind of internal force."

It is in Book 1 of the *Principia* that we find the birth of the science of mechanics, that extraordinary union of pure mathematics and careful observation that was to become the model to inspire science for a century or more. Empirical observations about the natural world, like the fact that bodies of different weight fall at the same rates, are cast in rigorous mathematical language. Says Cohen, "There is nothing in the antecedent literature of the science of motion that has this same magnitude or importance." While it is certainly true that Galileo, Kepler, and others had glimpsed the mathematical promised land, none of them had set foot in it. Their contributions were partial, even muddled, and inconsistent in places. Not so for Newton, who strode confidently into that land and claimed it as his own.

In the seventeenth century, however, there were rules by which one was expected to play the game of science, and Newton found it very hard to get his scientific ducks all in a row without breaking these rules. For example, mathematical speculation was allowed to be free and unfettered. Creating imaginary mathematical worlds was perfectly acceptable; it was what mathematicians did. But suggesting that these imaginary mathematical worlds were actually descriptions of the physical world was not acceptable. This placed Newton in an awkward position.

He was discovering, as no one had before, that there was an extraordinary "fit" between the physical world that he could see out his window and the mathematical world that he was creating in his head. This discovery still inspires physics students to keep plodding away at seemingly intractable homework problems long after their roommates have gone to bed. Newton was perhaps the first to see clearly just how profoundly mathematical was the hidden architecture of the universe—the beams, pillars, and guy wires that held the whole thing together were indeed

mathematical. And not just in some mystical Pythagorean sense. Newton's vision was rigorous and defensible—but not by the epistemological standards of the seventeenth century.

If I may presume to guess what Newton really wanted to do in Book 1, I would suggest he was ready and eager to argue that this remarkable mathematical match-up between his physical observations and mathematical theorizing was so profound that his new "system of the world" just had to be true. This argument has since become a standard intuition among physicists, especially the mathematical deities of the field, like Paul Dirac, Albert Einstein, and Murray Gell-Mann; even lowly physics majors, en route to their b.s. degrees, work into the wee hours of the morning on homework, driven by the adrenaline generated by this aspect of their studies, listening to faint Pythagorean harmonies. But the assertion that a new theory should be accepted because of an extraordinary match between mathematics and physics was not one that made sense to everybody in the seventeenth century, which played by different epistemological rules.

So Newton was forced in Book 1 to argue that his presentation is "concerned with mathematics" only and that he is "putting aside any debates concerning physics." However, this bifurcation between mathematics and physics was very unnatural for Newton, and he found it impossible to sustain consistently throughout. He often used the term "attraction" to describe the interaction between the Earth and the moon, or the sun and the Earth.

Attraction, of course, is a physics term that purports to explain just what it is that the mathematics is describing. But, as we have come to understand just how profoundly mathematical the world is, this distinction can no longer be sustained. The linkage between mathematics and physics is now understood rather differently.

The real world is not something that we examine, understand and explain without mathematics, after which we construct a mathematical model to assist us in picturing reality or to facilitate numerical calculations of positions and velocities. The real world

is, rather, profoundly mathematical in ways that often make it entirely appropriate to equate understanding with mathematical understanding.

This point is worth stressing because it provides important insights into the ways that Newton was not only changing our understanding of the world but changing what it meant to say that we understand the world.

There were a great many brilliant scientists in seventeenth-century Europe—e.g., Descartes in France, Huygens in the Netherlands, Leibniz in Germany—who rejected Newton's explanation because the kind of explanation it provided was not considered to be a proper explanation. The prevailing metaphysical assumptions on which most of seventeenth-century science was based required that motion and forces be understood mechanically in the most simplistic sense possible. If an object at rest started to move, this could only be the result of something coming into physical contact with the object. The traditional Aristotelian rejection of forces that could act at distances had been reiterated and given new authority by Descartes. Forces could act between bodies only if they were in physical contact. "Action at a distance," as the alternative was known, was absurd, a retreat into the occult. To suggest that the Earth reached out through empty space and "pulled" on the moon was to speak nonsense, regardless of the mathematical precision with which this could be articulated.

The rejection of action at a distance, however, was a position fraught with its own set of difficulties, not the least of which was the challenge of explaining the motion of the moon around the Earth, or the planets around the sun. The time was past when the solid crystalline spheres of Aristotle could be invoked to explain the stability and regularity of the planetary motions. Or that there might be different laws of mechanics for heavenly bodies. Galileo, for example, had suggested that maybe there was a "circular inertia" that kept the planets in orbit about the sun and the moon about the Earth. By the end of the seventeenth century these options were no longer viable. A number of developments had undermined, once and for all, the traditional notion that the heavens were different from the earth

and could have their own separate set of physical laws.

The realization that the heavens and the earth form a unity—which was absolutely central to Newton's work—was an enduring achievement of the scientific revolution to which a great many thinkers had contributed. It is also a useful "spine" along which the history of astronomy can be succinctly arranged.

When Newton enrolled in Cambridge University in 1661, the curriculum was still largely unchanged from its medieval predecessor, and natural philosophy, in particular, was still dominated by the Aristotelian tradition, despite the advances of the previous century. Of particular relevance for understanding the context of Newton's work were the various elements of the Aristotelian astronomical tradition, the familiar geocentric cosmos explicated unappreciatively in the early chapters of astronomy books.

The Aristotelian cosmos looked like this: The Earth was at the center of the universe, fixed and immobile, the largest object in the universe (although there was as yet no "uni" to the universe.) Material objects traveled in straight lines toward the center of the Earth as they sought their "natural" place at the center of the universe. Any motion other than unfettered vertical trajectories was "violent" and could only occur in the presence of a persistent push or pull mediated by mechanical contact. There was no such thing as an external "force" that could produce motion. There were thus two distinct kinds of motion: "natural," emerging from within the nature of material objects as they freely sought the center of the universe, or "violent."

The Aristotelian "universe" was divided into two realms: an earthly realm, where the elements earth, air, fire, and water did their thing, and a heavenly realm, where everything was composed of that special heavenly material called "ether." (There was no such thing as empty space; all superficially empty spaces were really filled with ether.)

The boundary between the two realms was a huge crystalline sphere to which the moon was attached. The rotation of this large sphere was responsible for the regular revolution of the

moon about the Earth. Once the motion of this sphere, or any of the others that carried the planets, was initiated it would continue without change. Nothing in the heavenly realm ever changed in any way; even the speeds of the planets in their orbits were absolutely uniform. Occasionally the motion of planets did appear to change, mysteriously reversing direction temporarily during the retrograde part of their cycle.

This posed a challenge that was met with the creative addition of a number of extra spheres and a complex system of what amounted to "gears" as wheels turned within wheels turning within other wheels which carried the planets in their looping orbits about the Earth. It was all very complex and Rube Goldbergian. But it worked well enough to last for two millennia, partially because nobody could understand it well enough to fix it.

The basic rule for the heavens was this: Everything beyond the orbit of the moon is composed of an un-changing ether; the motion of these ethereal bodies must also be unchanging and circular or composed of compounded circular motions. Circles had been prescribed by Plato and Pythagoras as the most perfect shape, and thus the shape of perfect orbits.

The heavenly realm ended with an outer crystalline sphere, just beyond the orbit of Saturn, the most distant planet visible with the naked eye. The stars were attached to this outer sphere. The consistent motion of this outer crystalline sphere accounted for the regularity of the zodiac, on its annual march through the heavens.

Occasionally there was change in the heavens, such as when a comet would appear or those rare occasions when a star would go supernova and explode, greatly increasing its brightness. Comets were "explained away" as atmospheric phenomena, not unlike meteors. Supernovas were so rare that most people never saw one and those who did found them so exceptional and unrepresentative that they could be safely ignored, much as contemporary scientists tend to set aside an "outlyer"—a data point so far from the rest that it must be an anomaly, perhaps an electrical glitch or a malfunction of some sort in the measuring

apparatus.

The vast majority of celestial phenomena made perfect sense within the framework of this model. Those who scoff at it today often fail to note just how extensive was its explanatory prowess. To the naked eye all the stars most certainly appear to be at the same distance from the Earth. Anyone who has looked in innocent wonder at the night sky can easily sense the hemispherical dome overhead, with the stars all attached to it. We certainly experience the Earth as if it was at the center of the universe. There is indeed virtually no change in the heavens, in remarkable contrast to the earthly realm where relentless change is all but overwhelming. Planetary orbits are remarkably stable, and something must be holding them in place. And so on. Intuiting the reasons for the endurance of the Aristotelian worldview is really not that hard, especially if one is lying under the stars on a clear night.

The overturning and replacement of the Aristotelian cosmos is the quintessential scientific revolution, hopelessly over-emphasized as the paradigmatic model for understanding the advance of scientific knowledge. Prevailing paradigms, we are told, are overturned and replaced with new "incommensurable" ones. The roots of the revolution that overturned the Aristotelian tradition are buried deeply within the Aristotelian tradition itself, but digging out those roots is a scholarly project be-yond the scope of this essay. We will mention only the highlights.

The Dismantling of Aristotle

And new philosophy calls all in doubt,
The element of fire is quite put out;
The sun is lost, and the earth,
and no man's wit
Can well direct him where to look for it.
—John Donne

The dismantling of Aristotle starts seriously with that most famous of Polish clerics—after the current pope, of course—Nicholas Copernicus (1473-1543). Copernicus moved the Earth out among the other planets, helping to eliminate the distinctive and distracting central location of the Earth and to create the important distinction between the location of the sun

and the planets, a critical insight missing from Earth-centered cosmologies.

The Danish astronomer Tycho Brahe (1546-1601) observed comets and supernovas, and, because his observational techniques were so sophisticated, he established with certainty that comets and supernova were indeed in the heavenly realm. Brahe essentially destroyed the long-standing notion that the heavens were "perfect and unchanging." The infamous Italian Galileo Galilei made telescopic observations that showed that the surface of the moon did not look particularly "heavenly" and, whatever the moon was made of, it certainly gave the appearance of being the same stuff as the Earth. Furthermore, there were satellites orbiting around Jupiter, showing that not everything needed to orbit about the earth, as his critics believed, despite the earlier work of Copernicus, which was still not widely accepted.

Tycho's eccentric assistant Johannes Kepler (1571-1630) abolished the traditional circular orbits with his discovery, in 1609, that the orbit of Mars was elliptical and the sun was not at the center of that orbit but was displaced a bit to one of the two focal points of the ellipse. Kepler's critical breakthrough led him to discover his now famous three laws of planetary motion—orbits are elliptical with the sun at a focal point of the ellipse; planets speed up in a very predictable way as they move along that portion of the orbit that is closest to the sun; and there is a specific relationship between the time it takes a planet to go around the sun and how far it is from the sun.

Kepler's three laws identified an important relationship between planetary motions and the sun. This connection was so suggestive that Kepler speculated that the sun, in some mysterious way, perhaps analogous to magnetism, actually caused the planetary motions. But he was unable to make any progress on this, and it remained, together with Descartes's idea of vortices and Aristotle's crystalline spheres, just another speculative hypothesis about how the solar system works.

All the thinkers whose work so effectively undermined Aristotle had insights of varying significance into the new world order that

was about to be inaugurated by Newton. Galileo knew the moon was not made of ether or perfectly spherical, Kepler got the shape of the orbits, Descartes discovered inertia, and so on. Other thinkers, like Hooke and Halley, had begun to glimpse bits of the final picture. But these insights were piecemeal and, in some case, so partial and decontextualized as to render them all but inconsequential. Newton's achievement was a system of the world—a system in which a great number of physical phenomena could be almost fully explicated on the basis of a single idea. That idea, of course, was universal gravity.

Gravity provided a mechanism to hold the stars in place, doing away with the need for crystalline spheres; gravity provided forces to move objects on the Earth and in space, doing away with innate teleological drives; gravity provided a force to keep the planets orbiting regularly about the sun; gravity held the atmosphere of the Earth in place, while it hurtled around the sun at what must have seemed, to the horse-riding residents of the seventeenth century, to be a breakneck speed.

Newton's Law of Universal Gravitation looks like this:

$F = GMm/r$_

In words it reads like this: The force between two bodies, a large body with a mass M and a small body with mass m, is equal to the product of their masses divided by the distance between their centers squared. (The "big G" is the gravitational constant, the most important number in the universe. Its role is to make the actual force come out right despite the fact that the masses and the distances can be measured in different units—feet, yards, miles, and so on.)

This formula has all sorts of practical applications that the reader has used on many occasions. For example, the reader's weight is obtained by multiplying the reader's mass by the mass of the Earth and dividing by the distance between the center of the reader and the center of the Earth. The resulting number is the number that registers on the bathroom scale when you step on it in the morning.

But, as I mentioned above, gravity is a force of attraction

between bodies that need not be in contact. The ghostly fingers of gravity mysteriously reach out and tug on distant objects. And that was the old bugaboo, "action at a distance."

Here was the problem that confronted Newton: his formula allowed him to calculate, with remarkable precision, the force of the Earth on the moon. But how could Newton establish that the force on the moon actually originated in this way? Certainly the moon moved about the Earth as if there were a force like this, and this formula allowed him to calculate its value. But the force could not be measured directly. There was no empirical evidence whatsoever for the force itself. The primary epistemological warrant for such a force was the formula. But how does one argue from a mathematical equation to a physical reality? What is the link that makes this possible? Can such a claim ever be more than speculation?

When Huygens studied the *Principia*, he stated that it had never even occurred to him to extend "the action of gravity to such great distances as those between the sun and the planets, or between the moon and the Earth." He had not thought to do this because there was a much more plausible explanation, namely the "vortices of M. Descartes." Huyghens added that he would not hold against Newton his "not being a Cartesian, provided he does not give us suppositions like that of attraction." Keeping in mind that Huyghens was one of the greatest scientists of the seventeenth century and one of the few fully capable of understanding the *Principia* in detail, we can see in his preference for Cartesian vortices the battle that Newton had to fight.

Like Newton, Descartes had developed a "system of the world." But unlike Newton's, Descartes's system was fully mechanical, in accordance with the philosophical rules of the seventeenth century. Descartes's system was based on the idea of a huge vortex in the solar system, centered on the sun and swirling about like a tornado or, more benignly, like water going down a drain. In a vortex, the intensity declines as one goes out from the center. This explained why the outer planets moved more slowly—the vortex was weaker and slower out there.

By the standards of today, Descartes's theory of vortices was

hardly a theory at all. He could not calculate anything whatsoever. All he could do was argue, by a weak analogy with terrestrial vortices, that the vortex in the solar system would be stronger near the middle than at the edges. He could account for absolutely nothing beyond the simple, purely qualitative, observation that distant planets went slower than close ones and they all went in the same direction. Furthermore, what was the material that comprised the vortex? If the vortex of a tornado is made of air, and the vortex in the whirlpool of a drain is made of water, of what was the vortex of the solar system composed? The answer provided by Cartesian philosophy to this central question was very unsatisfactory: the vortex of the solar system was composed of some material reminiscent of Aristotle's ether.

Was there any direct evidence for this material? No. Then how do we know it is there? By the principles of mechanical philosophy that tell us that forces can only be communicated by objects in direct contact with one another; that "action at a distance" is absurd; that there can be no such thing as empty space and, if there were, "gravity" could certainly not travel through it. This constitutes the "evidence" for the material vortex that swirls around the sun, carrying the planets with it. Like any scientific paradigm, the epistemological rules for what is allowed resonate conspicuously (and suspiciously) with what is discovered.

Contrast this with Newton, who explained the motions of the planets in terms of a gravitational force between them and the sun, a force that grew weaker as the square of the distance between them. How much could Newton explain with this model? Plenty. Planets under the influence of such a force would travel in elliptical orbits precisely as they were observed to do. Such planets would speed up as they got closer to the sun and slow down as they receded from the sun precisely as they were observed to do. The planets further from the sun would go slower, not in some general qualitative sense, but precisely as they were observed to do. It was all very tidy.

Comparing the Cartesian and Newtonian systems on this point is very instructive. Descartes could explain, in a general sort of way, how the planets moved. They were caught up in some sort of cosmic swirling vortex. There was, of course, no direct

evidence for this vortex or the material of which it was composed, but the mechanism of its action could be visualized in a purely mechanical way. Anyone who had ever watched water run down any kind of drain or who had observed whirlpools could easily imagine how this might work. On the other hand, Newton could explain, in a rather precise way, exactly how the planets moved under the influence of gravity. But he could not provide a familiar mechanical model for how gravity worked.

Descartes's model was quantitatively imprecise but based on familiar mechanical analogies, while Newton's was quantitatively precise but based on a completely unfamiliar mechanism about which seemingly nothing could be said other than it existed. Descartes's model was highly physical, with almost no mathematical content; Newton's was highly mathematical with ambiguous physics. Preferences among the few European thinkers who could follow the debate derived more from philosophical starting assumptions than the models themselves. Finding a better example of incommensurable paradigms would be challenging.

The challenge of what constituted a proper explanation for the motion of the planets was at the heart of the Newtonian revolution. Understanding this challenge illuminates a number of issues. It explains, for example, why Huygens would say, "I have nothing against [Newton} not being a Cartesian, provided he does not give us suppositions like that of attraction." It explains why Newton would write that he was setting forth "principles of philosophy [physics]" which "are not, however, philosophical but strictly mathematical." And it explains, more importantly, just what kind of genius Newton was and how extraordinarily individual was his achievement.

This is the second article of a three-part series.