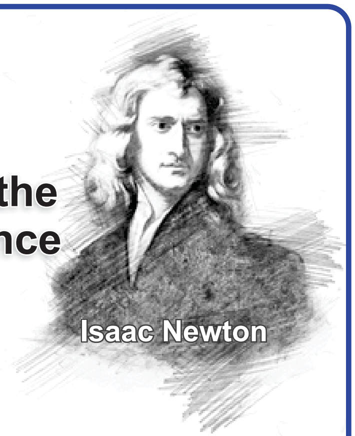
Worldviews, Universal Gravitation, and the Uneasy Acceptance of Action at a Distance



In the autumn of 1665, Isaac Newton had been sent home from school. He had not been forced to return to his birthplace because of bad behavior or poor performance. Indeed, he had just completed his undergraduate studies and was considered by his professors to be an unremarkable, but promising, student. The 22-year-old scholar had been sent home from Trinity College to flee the Great Plague of London, a disease outbreak that would eventually kill nearly 100,000 people, a fifth of that city's population. The plague had been raging since midsummer—its continued spread led city officials to order the university in nearby Cambridge to close. For the next two years, young Newton would spend nearly all his time at his mother's farm at Woolsthorpe, in Lincolnshire.

Later in life, Newton would recount that on this farm, taking tea in the orchard, the fall of an apple inspired his thinking regarding universal gravitation. Of course, we can never know for sure whether the apple was indeed Newton's muse. What we *do* know, evinced by Newton's notebooks from the plague year, is that Newton was not using his temporary exile for leisure. Between 1665 and 1666, Newton invented differential and integral calculus, conducted investigations that revealed white light is composed of many colors, and began calculations that would be crucial to his proposal that a single force governed both the fall of apples and the movement of the heavens.

In his notebook, Newton's contemplation of gravity begins with a query first posed by Galileo Galilei. Though Galileo had died twenty-three years before, his 1632 *Dialogue Concerning the Two Chief World Systems* had only been translated into English in 1661 and so provided new fodder for Newton's voracious reading habits. In that work, Galileo observed that objects placed upon a horizontal rotating wheel, such as a potter's wheel, fly off in all directions. What force keeps animals, people, and buildings on Earth's surface when it spins more rapidly than any disk for throwing pots? Pondering this question, Newton decided to calculate the force required to maintain an object's circular path on Earth's surface. The result of his calculation gave a version of the familiar formula $F = (mv^2)/r$, describing circular motion.

1. Even though Newton was mostly solitary during this period of his life, in what sense was he still collaborating with other scientists? Why is collaboration such an important aspect of scientific work?

To check his result, Newton calculated the force that would be required to maintain the moon's orbit, as he knew the speed of the moon's orbit and its approximate distance from Earth. This exercise showed that if the moon behaved as objects nearer Earth's surface do, and if the force on the moon is just sufficient to counter the centrifugal force (thus keeping it from flying off from its orbit), then the consequent value of that gravitational force on the moon was less than that on the surface of the earth by a factor of ($1/r^2-1/R^2$), where r is the earth's radius and R the moon's orbital radius. With this calculation, Newton had produced the seed of an inverse-square law for the force of gravity!

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Note that Newton is using mathematics to understand how the natural world works. Galileo, Einstein, and many other scientists take this same approach. Not all scientists do experimental work, and this illustrates that no single scientific method exists. Scientists use whatever methods are appropriate for their work.

Unfortunately, at this point Newton's investigations ceased. His calculations did not quite match the moon's observed behavior (we now know his value for R was too small). Perhaps this discrepancy discouraged him, or perhaps his concurrent work in mathematics or optics was simply more absorbing. For whatever reason, Newton would not return to questions of gravitation for nearly twenty years. However, this investigation, inspired by falling apples and spinning wheels, provided the foundation for a breakthrough that would change the face of science forever.

Isaac Newton, adapted from portrait by Godfrey Kneller

While Newton would eventually propose a radically new way of thinking about motion and gravitation, his ideas were necessarily built on earlier ones. The period in which Newton lived was one of both political and philosophical tumult, as old ideas and new jostled for recognition and power. To better understand Newton's ideas and their place in the intellectual arena, one must examine the older ideas that still held sway in the 1600s.

Words like "discovered" and "revolutionary" are often used to describe the contributions of scientists, especially noteworthy individuals like Newton. However, they carry the risk of misrepresenting the process of science. As you read this story, note how Newton's contributions, while incredibly insightful and deserving of admiration, arose over time and are linked to the work of others. Ideas, however novel, are never without a foundation and they do not suddenly arise in a final form as the word "discovered" implies.

A Growing Universe: Aristotle's Concentric Cosmos

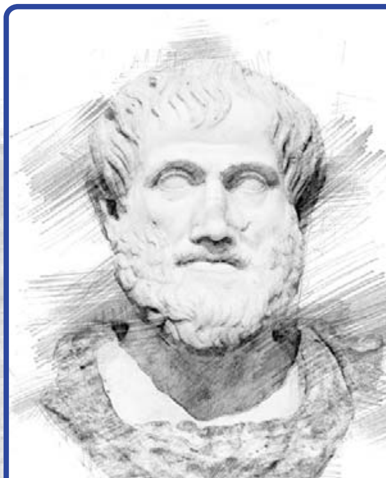
At Cambridge, Newton was formally educated in the natural philosophy of Aristotle. Aristotelian philosophy had reigned in Western universities since their founding in the thirteenth century, when Thomas Aquinas revised its tenets to accord with Christian doctrine. At the core of Aristotle's philosophy were two central assumptions. First, Aristotle strove to explain the universe as humans on Earth's surface could observe it. He did not envision a god-like observer beyond the stars looking in; rather, he made sense of his world from the ground up. Aristotle's picture of the universe began with the centrality and immovability of Earth, as all could sense that Earth was solid and still. From this base, Aristotle's universe was made of concentric shells of matter, each situated to best explain some aspect of observed experience.

Second, Aristotle was, foremost, a naturalist; that is, he observed living things and saw in them the model for all the universe. In his observations of trees, he saw that acorns, when left undisturbed, grew into oaks. In his observations of sheep, he saw that a tiny lamb, if not afflicted by illness or slaughter, would grow to be a ram or ewe. Observing humans, he saw that babies became adults in their natural course. When studying living beings, Aristotle asked of each thing what its goal was. What was its direction? What was its purpose?

When his thoughts turned to the material world, Aristotle's method was the same. Greek philosophers before Aristotle had proposed that all matter on Earth was composed of four elements: earth, water, air, and fire. In this worldview, everything contains all four elements, though the proportion of the elements in each thing differs. Furthermore, elements can be changed into one another. For example, liquid water can be frozen to become composed primarily of earth, or evaporated to become mostly air. Aristotle formalized this view and added to it an idea of objectives, or purposes, toward which each element strove.

For instance, Aristotle would say that a stone lying in a field is at rest because it is composed of the element "earth," and this element's "natural place" is nearest the earth. Should a wandering child pick up that stone, it would feel heavy: this pressure comes from the rock's desire to be nearer the earth. And when that child releases the stone, its drop will be due to its purpose as a stone which is to be near the earth. The stone behaves as it does because of *what it is*. Conversely, picture a scholar blowing out his candle flame. If his breath is insufficient to extinguish the flame, it will dip and flicker under the breeze, and then jerk back upright when the blowing stops. This behavior owes to the flame's fiery nature: as fire composes the outermost terrestrial shell in Aristotle's system, beyond even the air, all things made of fire on Earth's surface aspire upward.

Ultimately, Aristotelian philosophy sees two sorts of motion on Earth: (1) natural motions that occur because of the fundamental nature of objects and therefore require no force, and (2) violent motions that require an animate being to exert force. Lifting a stone is violent; the stone's fall is natural. Blowing on a flame is violent; the flame's recovery, natural. Violent motions begin when a thing is moved from its natural place; they end when that thing either returns to its natural place or when the being exerting the force ceases to do so.



Aristotle

Notice the set of definitions and assumptions that form the basis of Aristotelian physics. While some of these assumptions appear highly questionable from a modern perspective, all scientific ideas are based on certain foundational premises. As you read on, consider the assumptions about the world that Descartes and Newton make, and the way they define fundamental quantities.

Aristotle, adapted from Lysippos - Jastrow (2006), Public Domain, https://commons.wikimedia.org/w/index.php?curid=1359807

Why Earth could not move in this system should now be clear. If all earthly matter adhered to Earth's surface because the fundamental nature of such matter is to seek the center of the universe, then Earth in motion made no sense because matter would not have a natural place where it ought to be.

Less clear is how such a system accounted for the perceptible motions of the heavens. If things composed of earth (and to a lesser degree, water) aspired toward the universe's center, and things composed of fire (and, less, air) sought a place above Earth's surface, how to explain the unchanging circular paths of the sun, the stars, and the visible planets was perplexing. This motion was unlike either the fall of stones or the rise of steam as the heavens appear constantly in motion, and yet perpetually unchanging. As with earthly things, Aristotle explained the action of the heavens by appealing to their elemental nature. In his system, everything above the moon's orbit was composed of the most perfect of the elements, the fifth element known as *aether*. Unlike the other four elements, nothing could change to or from aether. Its natural motion was in the endless uniform circles of the heavens.

While Aristotle's description of the universe seems odd to the modern reader, it held great appeal for generations of scholars. This appeal lay in its comprehensive nature, its carefully argued tenets, and its provision not only of descriptions, but also of causes, for all motion. A replacement for Aristotelian philosophy would have to explain everything from rolling rocks to growing seeds to whirling planets. It would have to out-argue Aristotle and his devotees while explaining not only what happened, but why it happened.

A Crowded Universe: Descartes' Vortices

While Aristotle's thinking formed the foundation of Newton's education in natural philosophy, he also studied the work of Rene Descartes who put forth a comprehensive description of mechanics that challenged Aristotle's worldview. Descartes was not the first to question the Aristotelian orthodoxy; he built on the work of several Renaissance thinkers. For instance, the astronomer Nicolas Copernicus proposed a sun-centered universe, and the alchemist Paracelsus stressed the need to derive knowledge about nature from direct laboratory experience rather than from Aristotle's writings. By the early seventeenth century, when Descartes wrote, some in academic society thought that the Aristotelian worldview was failing. Descartes was able to fill, at least for a while, this growing void.

René Descartes

In Descartes' worldview, first presented in his 1630 text *The World*, matter did not have an Aristotelian sense of purpose; things had no inherent nature that would guide their behavior. Rather, only physical, mathematical features such as size, shape, weight, and motion were in Descartes' conception of matter. For Descartes, the only way that matter could affect other matter was through physical collision, and he sought to describe the entire universe as matter in motion. For Descartes, the universe was *mechanistic*: everything in it, from the spinning planet to the growing plant to the human body, was in fact an ingenious machine. Run entirely by moving matter, these machines had no more inherent purpose than a piece of clockwork.

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Descartes' description of the universe was influenced by the novel technologies of his era: mechanical clocks and other machines. Social and historical contexts always, to some extent, influence the thinking of scientists.

Descartes imagined that in the beginning of the universe, God provided a quantity of uniform matter and a quantity of motion, both of which He would maintain to prevent the machine of the universe from running down. Large pieces of matter in motion rubbed against one another and eventually produced three different sizes of material particles, constituting three different kinds of matter. The finest particles would coalesce into the bodies of the sun and stars, and swirl around them in vast whirlpools. These celestial whirlpools would attract coarser particles of matter. The mid-sized particles of matter, spherical but rough, would form smaller vortices around the stellar ones. The largest, coarsest, most-irregular particles would form Earth and everything on it, the other planets, and comets.

For Descartes, all motion could be account for by the swirling of matter. On Earth, a stone tossed into the air fell back again because the airy matter was moving outward faster than the stone was, and the forces exerted by the outward swirling of this airy matter upon the stone would push it back to earth.

This universe was a crowded one: it consisted of nothing but matter, and matter was therefore everywhere. No space exists without matter in it, and no matter ever moved without having been pushed by another piece of moving matter. Descartes' critics complained that, in spite of his enthusiasm for mathematics and experiment, his worldview could be

René Descartes, adapted from Frans Hals (1997) De eeuw van Rembrandt, Public Domain, https://commons.wikimedia.org/w/index.php?curid=2774313 supported by neither. In spite of these criticisms, however, Descartes gained many followers who strove to explicate his model mathematically and explore its experimental implications. And whether or not they subscribed to his philosophy, nearly all scholars of the 1600s would have been familiar with, and curious about, Descartes' ideas.

A Lonely Universe: Newton's Action-at-a-Distance

Newton's return to questions of gravitation was prompted by a 1684 visit by the astronomer Edmund Halley. In the eighteen years since his apple orchard calculations, Newton had become the Lucasian Professor of Mathematics at Cambridge and a member of the Royal Society, a fellowship of natural philosophers founded in 1660. Halley visited Newton at Cambridge with a query posed by the membership of the Royal Society: what path would a moving body in orbit around a stationary body trace, if the force attracting the orbiting body to the stationary one varied inversely by the square of the distance between them. Newton replied promptly that the path would be elliptical. When asked how he replied so quickly, he answered that he had already done the calculation. However, he was not able to provide his proof—the paper had been lost. Promising to reconstruct it, Newton retreated to his study.

Several months later, Halley returned to receive a tract working out the proof of elliptical orbits resulting from an inverse-square relation between gravitational force and orbital distance. However, the full result of Newton's thinking about gravitation would not be published for another two years, a period that Newton reportedly spent in a state of extreme distraction. He was known for missing meals, appointments, and lectures, and turning up to the College dining hall in a dressing gown.

The product of these two years of intense study was his great *Philosophae Naturalis Principia Mathematica*, ("The Mathematical Principles of Natural Philosophy"), often just called the *Principia*. This work examined force, motion, and matter in classical, geometrical form, culminating in a "System of the World" that described terrestrial and celestial motion in the same terms. The continuity of forces is why we call Newton's gravitation 'universal.' The *Principia* began with a series of definitions. First, he defined mass to be the quantity of stuff of which a body was composed, later to be distinguished from weight, which was the force that gravity exerts on that quantity of stuff. Next, he defined the quantity of motion possessed by a given mass as equal to its inertia.

Newton's work in the *Principia*, while groundbreaking, was not entirely novel. It rested on rules of motion and collision, introduced by Descartes and refined by his follower Huygens, which saw the principle of inertia as a given. Thus, Newton's crucial first law, "Every body preserves its state of being at rest or moving 'uniformly straight forward' except insofar as it is impelled to change its state by forces impressed," was not a new idea.

Newton's second law of motion, stating that "a change in motion is proportional to the motive force impressed and takes place along the straight line in which force is impressed," was more novel. In fact, this relationship or law was the first introduction of the idea that the nature of a force could be deduced by observing the effect of that force. This aspect of Newton's conception of force is what made possible, back in 1666, his inferring the strength of the gravitational force by calculating the strength of the centrifugal force on the moon.

The third law of motion, giving the now-familiar maxim that "For every action there is always an opposite and equal reaction," extends this second law to the universal, stating that every force causing a change in motion occasions a reaction of equal force.

2. We often credit certain scientific ideas, like "Newton's Laws," to specific scientists. In what sense ought these ideas be credited to individuals? In what sense does this inaccurately portray the development of scientific ideas?

Perhaps the most novel and controversial aspect of Newton's definitions was his abandonment of Descartes' insistence that motion could only occur as a result of collisions. In Newton's universe, bodies could act on each other without direct contact. Newton only spoke of "forces," which act on bodies to change their speed, their direction, or both. In Newton's geometrical proof of elliptical orbits for Halley, he modeled the movement of the orbiting body as a polygonal path produced by a series of straight-line inertial movements punctuated by a series of force impulses toward the central body. When this polygon was calculated with an infinite number of sides, the curved path of elliptical motion that was produced was identical to that demonstrated in 1618 by astronomer Johannes Kepler to be the best model for describing observed planetary motions. In Newton's "System of the World," the third book of the *Principia*, he shows that an acceptance of his three laws of motion allows one to mathematically produce Kepler's laws of planetary motion: a truly striking result. But he did not explain what caused the inverse-square force.

3. A great strength of Newton's fundamental ideas about force and motion is its ability to reproduce Kepler's laws of planetary motion. Why might scientists find this ability (i.e., the coherence of ideas) so valuable?

In fact, Newton repeatedly refrained from identifying such a force. In the *Principia* he wrote:

> I use the word “attraction” here in a general sense for any endeavor whatever of bodies to approach one another… I use the word “impulse” in the same general sense, considering in this treatise not the species of forces and their physical qualities but their quantities and mathematical proportions.

Newton's struggle with the nature of the forces is indicative of broader conflicts in his thought. Like most of his peers, he had deeply absorbed the mechanistic philosophy of Descartes in his youth. The notion that anything besides colliding matter could cause motion was absurd to Newton. And yet, his idea of gravitational attraction is a force occurring between objects with no physical interaction. At the very time when science was seeking to separate itself from occult forces, Newton's law of universal gravitation introduces action-at-a-distance with no suggestion of an explanation that might replace a mechanistic explanation. Rather than proposing an explanation with no evidence, Newton would, repeatedly and insistently, refuse to state one.

4. Newton has put forward a universal gravitational law, but with no theory to explain it. People wrongly think that theories become laws with enough supporting evidence. However, scientific laws express relationships between phenomena, while scientific theories explain (i.e., account for) laws. Why are Newton and his contemporaries bothered with having no theory to explain the law of gravity? What does this imply about the value of theories in science?

Some historians suggest that Newton's eventual willingness to give up the Cartesian devotion to matter in motion was due to his ongoing engagement with chemical and alchemical study. In chemistry, certain substances combine readily with certain other substances, while refusing to combine with others. The behavior of matter in a chemical setting, in particular its various attractions and repulsions, was difficult to explain within a Cartesian worldview. These interactions were far easier to account for if fundamental laws of attraction and repulsion between particles of matter were possible .

Others point to some of Newton's other writings to show that at least much of the time, the cause of gravitational forces for Newton was the presence and action of God. In the second edition of the *Principia*, Newton wrote of God:

> He endures always and is present everywhere, and by existing always and everywhere he constitutes duration and space… God necessarily exists, and by the same necessity he is *always* and *everywhere*. It follows that all of him is like himself: he is all eye, all ear, all brain, all arm, all force of sensing, of understanding, and of acting, but in a way not at all human, in a way not at all corporeal.

So perhaps for Newton, discussion of causes was irrelevant because the ultimate, final cause of all things was always the eye, ear, brain, and arm of the Divine. Where Descartes' universe had been crowded with matter, Newton's was composed of small masses in vast space—space filled only by God.

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Note how for Newton and many scientists, science and religion are not necessarily at odds with one another. The history of science makes clear that the interaction between science and religion is complex and not that of constant conflict.

As one might expect, others of the Cartesian school were far less accepting of Newton's causeless forces. In an anonymous review in the leading philosophical journal in France, a critic wrote of the *Principia*, “In order to make an opus as perfect as possible, M. Newton has only to give us a Physics as exact as his Mechanics. He will give it when he substitutes true motions for those that he has supposed.” Clearly, this critic (and the many continental natural philosophers who agreed with him) did not see mathematical descriptions of forces as equivalent to the sorts of explanations provided by Descartes's vortices, or even Aristotle's purposeful elements.

Over time, though, Newtonian philosophy became increasingly accepted, due in part to its early popularity among certain members of the Anglican Church.

Newton wrote often of theological matters and broadly encouraged the use of his natural philosophy for theological ends: the still-running Boyle Lectureship, named for its founder Robert Boyle, was founded with the purpose of exploring the role of God in Newton's views on nature. These popular lectures, each published in book form, were one of the first ways by which many Britons learned of Newton's teachings.

In 1703 Newton became head of the Royal Society, and, with the aid of powerful friends, his ideas became the new orthodoxy during his tenure. Though frail and ill in his old age, Newton continued to preside over Royal Society meetings. Passing in his eighty-fifth year, the natural philosopher had lived to see his worldview take hold not only in his own country, but also in Descartes' France, where a new generation of philosophers embraced Newton's theories.

Newton, like all those who studied the natural world up to his time, saw himself as a natural philosopher (the terms "science" and "scientist" would not become commonplace for over a century). He was conducting what we today refer to as "basic science" – seeking to understand the natural world without consideration of its utility for technology and society. But note how Newton's ideas would later be crucial for the space program and many other technologies. Today, governments fund basic science research knowing that it often provides knowledge that applied science research (i.e., targeted toward a desired technological end) does not.

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Partial support for this work was provided by the National Science Foundation's Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. 0618446. Project Principal Investigator: Michael P. Clough. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.