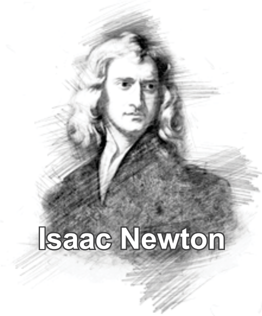
Rejecting Common Sense

Science and Newton's First Law of Motion


Isaac Newton

The core of the Scientific Revolution that occurred during the 16th and 17th centuries is often located in the major developments that occurred in the field of astronomy. Indeed, many historians mark 1543, the publication of Nicholas Copernicus's *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*), as the beginning of the scientific revolution and 'modern science.' Copernicus's heliocentric universe, in which the earth rotated around the sun, dethroned Ptolemy's geocentric universe, in which the sun rotated about the earth. The work of Johannes Kepler would further articulate this new vision of the heavens. Kepler rejected the perfectly circular shapes of orbits in favor of elliptical orbits in 1609. These elliptical shapes, described mathematically in Kepler's three laws of planetary motion, solved many of the outstanding problems in Copernican astronomy which assumed circular orbits.

Kepler's laws and other mathematical descriptions were useful for prediction and description, but did little to explain the whys and hows of celestial bodies. Why do planets move in orbits? What keeps them there? How do bodies move in the first place? At the heart of these questions was a need to understand the nature of motion, particularly the problem of its *generation* and *perseverance*. Ideas regarding these problems have changed significantly over time. From a moving force to impetus to inertia, thinkers had very different ideas about the nature of motion. What did ancient and Medieval thinkers, such as Aristotle and Jean Buridan, think about motion? How did Galileo Galilei and René Descartes modify this understanding? And why was Newton's principle of inertia the foundation of his celestial mechanics?

The development and eventual acceptance of ideas occurs over many years and progress is rarely straightforward. The scientific revolution that occurred during the 16th and 17th centuries represents a significant break in important ways from prior ways of understanding nature, but not in all ways. The very nature of thinking entails working with prevailing ideas, and the scientific revolution made use of medieval ideas about the natural world that drew from Greek, Roman, and Islamic thinking about nature. Revolutions refer to significant changes in thinking, not a total break with the past.

Aristotle (384–322 B.C.) had a broad concept of motion. Motion didn't just mean bodies moving through space in a period of time. It also included more complex changes such as the growth of a seed into a plant, or the education of a child to an adult. Motion was any sort of change, and was about realizing some potential, whether it was a rock realizing its potential of moving closer to the center of the universe, or a baby reaching its potential as an adult. All of these changes required a cause, an agent that would continually produce the change. Motion did not just happen on its own but had to be actively sustained: *Omne quod movetur ab alio movetur* ("All that is moved is moved by something else.").

Concerning *local motion*, the motion we are familiar with as moving rocks, bodies, and planets, Aristotle saw two types: natural motion and violent motion. In natural motion, objects move to where they 'naturally' belong, according to their composition. Rocks, for instance, belong at the center of the universe, and thus would naturally move toward the ground. Further, two main types of natural motion were thought to exist: celestial motion, which was uniform, circular, and perpetual; and terrestrial, which was rectilinear, up or down, and finite. This distinction between rectilinear (straight line) and circular motion, and the strict difference between the motions of the heavens and motions on earth, would persist for centuries. A violent motion was a motion against natural inclinations. For instance, throwing a rock up was a violent motion, one that would eventually be overcome by its natural motion toward the ground. Violent motion was also that which moved an object out of its natural state of rest. Objects strove to return to their natural state of rest, and thus a force was necessary to sustain motion. 'Common sense' evidence for Aristotle's views was all around: projectiles and bodies on earth needed something to sustain their motion, otherwise their motion died away.

While many of Aristotle's ideas may now seem peculiar, they nevertheless formed a coherent system. Aristotle's broad view of motion, that included changes such as growth, influenced the way he explained "local motion." For Aristotle, as with all scientists, ideas don't exist in a vacuum; scientists' ideas in one area are influenced by their broader ways of thinking about the world.

Given this conception of motion, Aristotelians had trouble explaining the movement of projectiles. Why would a rock continue to move after it has left, say, a sling? Aristotle argued that the medium in which the projectile traveled, such as air, provided the force to keep the object moving. The motion still dies away, as the medium can only maintain some of the motion while also destroying it through air resistance. Because of the importance of the medium, Aristotle maintained that motion in a void was impossible. Interestingly, a part of Aristotle's argument against the possibility of motion in the void was that an object would move forever without external resistance, and he thought that this infinite motion was impossible.

Aristotle's understanding of motion was qualitative. Mathematics could not be used to understand motion, according to Aristotle, because mathematics was something that described static, changeless phenomena. Motion, which was by definition a form of change, could not be described by these principles. Motion was a quality, not a quantity. Numbers were used to describe quantities such as length or time, but not used to describe the essential workings of the world and universe.

Aristotle's ideas of motion were accepted for centuries, but not without critique. Medieval natural philosophers addressed the projectile problem, and the problem of motion in general, in a different fashion. Like Aristotle, they argued that something had to sustain motion, otherwise it would die away. They also saw a distinct difference between rest and motion. But unlike Aristotle, they argued that the constant force came not from the medium, but from the moving object *itself*. The projector, besides giving initial motion to the projectile, also imparts an *impetus* on it. This impetus was thought to be a force internal to the object that maintains its motion. This idea is often attributed to Jean Buridan (1300-1358) who wrote that impetus was:

> a thing of permanent nature, distinct from the local motion in which the projectile is moved….And it is probably that that impetus is a quality naturally present and predisposed for moving a body in which it is impressed, just as it is said that a quality impressed in iron by a magnet moves the iron to the magnet. And it also is probable that just as that quality (the impetus) is impressed in the moving body along with the motion by the mover; so with the motion it is remitted, corrupted, or impeded by resistance or a contrary inclination.

This impetus was thought to be proportional to the velocity and matter (mass) of the moving object. Heavier objects thus acquired more impetus than lighter ones, and were harder to move from their paths. Impetus, like Aristotle's views, was based on daily experience; one could detect a rock's impetus, for example, by simply standing in its path. The blow imparted by the rock upon impact was evidence of its internal force.

Despite the introduction of the impetus view, medieval philosophers still accepted many of Aristotle's premises regarding motion. Galileo Galilei (1564-1642), however, challenged many of these assumptions. In his *Dialogue on the Two Chief World Systems*, among other works, Galileo attacked the 'common sense' ideas that undergirded the then accepted systems of celestial mechanics. First, Galileo challenged the notion that the natural state of an object is rest. Galileo used the example of a ball moving down a horizontal plane. Imagining a frictionless plane and a perfectly round ball, he argued that the ball will roll forever unless met by some sort of resistance, such as friction as is encountered in real situations. A ball cannot start moving on its own accord, nor can it stop itself. Rest, therefore, is no more natural than motion. Second, Galileo discarded Aristotle's broad notions of motion and simply discussed 'local motion.' Local motion, the movement of rocks and planets, was the only kind of motion. No need existed to complicate the picture by including seeds or babies. Third, given this more limited notion of motion, Galileo eliminated the need for objects to move toward some potential goal. A rock for Galileo was 'indifferent' to motion.

Unlike Aristotle and the impetus theoreticians, Galileo thought that mathematical principles were crucial for understanding not only celestial motions but also terrestrial, everyday motions. Galileo's use of mathematics for both situations implied that celestial and terrestrial motions were much more similar than had been argued previously. Considering the ideal case of an object falling through an airless void, Galileo reasoned the object gains a certain amount of speed per unit of time. Galileo generalized this idea into the idea of uniform acceleration in a straight line, and mathematically demonstrated that objects fall a distance proportional to the square of the time of the fall. Galileo used inclined planes to verify his ideas, as it offered him a more idealized laboratory with which to work rather than dropping objects. Armed with this knowledge, Galileo tackled the problem of projectiles. Galileo used mathematics to show that projectiles traveled in a parabolic path, one that could be computed by considering the compounded 'vertical' and 'horizontal' directions of velocity separately (a 'parallelogram' of velocities).

1. Many people wrongly believe that scientists begin by making extensive observations of the natural world, and then form their ideas by analyzing those observations. How does the way in which Galileo formed his ideas indicate that this is not the case? What role, if any, did observation play for Galileo? How does a mathematical approach to understanding the natural world counter the typical model of "the scientific method"?

While Galileo used mathematics to provide several important insights into motion, his ideas were not always consistent with those that Newton would eventually put forth. Although Galileo held that bodies were indifferent to motion, at other times he argued for a force inherent in an object, an impetus-like assertion. For example, a pendulum's downward movement was due to the force of gravity, but an internal property of the pendulum drove it back to its original height on the other side. Galileo's mechanics also kept the strict distinction between circular motion and rectilinear motion, even while introducing straight-line acceleration. Galileo, like Aristotle and Buridan, was asking the commonsense question "What keeps objects moving?"

The natural philosopher René Descartes (1596-1650) reframed the problem of motion. Descartes thought the real question was: what *stops* objects from moving? Descartes thought that uniform rectilinear motion was not a process that needed a cause, whether it be the actions of a medium (Aristotle) or an internal impetus (Buridan, Galileo). Instead, uniform motion was a state; rest, too, was a state. This eliminated a distinction between rest and motion that had been in place for centuries. In his *Principia Philosophiae* of 1644, Descartes wrote:

> 1. Any particular thing, in so far as it is simple and undivided, remains always to the best of its ability in the same state, nor is ever changed [from this state] unless by external causes.
> 2. If [a body] is at rest we do not believe it is ever set in motion unless impelled thereto by some [external] cause. Nor is there any more reason if it is moved, why we should think that it would ever of its own accord, and unimpeded by anything else, interrupt this motion.

According to these claims, a body in motion or at rest stayed in that state unless something else acted upon it. Constant uniform motion needed no cause; only changes in motion needed a cause, i.e., a force. The only reason why motion on Earth wasn't infinite was due to external impediments, such as friction or air resistance. No mention is made here of an 'internal,' impetus like force, as a force was only needed for a change in motion.

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Our everyday experience and thinking are that force is required to maintain an object in motion. Notice that Descartes's insight for understanding motion required abandoning that common sense view of experience. Progress in science has often been made not by observing new phenomena, but by conceptualizing phenomena in a radically different way. New scientific ideas are sometimes spurred by new data, but also at times by reinterpreting data and phenomena. Yet, as we will see, Descartes' ideas did retain vestiges of previous thinking.

Despite the similarity of Descartes' ideas to what Newton would later state as the first law of motion, many of Descartes' ideas reflected the influence of Aristotle. For instance, Descartes regarded uniform motion and rest as different bodily states, whereas Newton put forth that they are the same state. Moreover, Descartes thought that motion and rest 'persisted' because of the direct action of God at every instant in time. Descartes, and others before him, still couldn't explain circular motion, the motions of planets in orbits. Rectilinear motion could be explained with the principle of inertia, but circular motion could not. To account for circular motion, the idea of an internal, impetus-like, force was preserved to explain what kept objects on their curved paths. Newton, too, would hold on to the idea of internal force for many years, although as we shall see, he eventually found a way to reconcile circular motion and the principle of inertia.

Isaac Newton was born on January 4, 1643, and in his youth showed an inquisitive mind and an aptitude toward working with machines and building replicas, often improving the designs in the process. For example, he made a replica of a local windmill and improved its design. He also built a sundial that marked off time, dates, solstices and equinoxes. His family and teachers noted his mechanical inclination at this early age, but also concern at his apparent disinterest in normal school work. A contemporary commentator, William Stukeley, claimed that such childhood pursuits honed his faculties of reason and experimental acumen, skills that would be important for a "born philosopher" who would eventually "[unfold] the economy of the macrocosm."

Newton arrived at Cambridge University on June 5, 1661. As a student at Cambridge, Newton was exposed to the intellectual debates of the time, not only in mathematics but also in philosophy and other subjects worthy of a classical education. Beyond reading Aristotelian and theological works, Newton showed great interest in mathematics. Just as in his early youth, Newton did not simply imitate what he learned, but innovated as well: by 1666 he had developed the fundamental theorem of calculus and his calculus of 'fluxions.' This work was published in an essay in October 1666, and established Newton as one of the world's finest mathematicians.

As Newton worked on mathematics, he also began to explore the mysteries of mechanics. He would use much of his mathematical understanding and innovations to build his revolutionary system of mechanics. His early thoughts on mechanics are written in his "Waste Book," a college notebook that collected his thoughts on many topics. In early 1665 this Waste Book contained over a hundred axioms of motion. Some of these axioms, including a seed of the principle of inertia, would be merged and reformed into the laws of motion of his famous

Principia. In another notebook, under the heading "Certain Philosophical Questions," Newton took notes on his readings of Descartes and Aristotle. In "Of Motion" and "Of Violent Motion," Newton attacked Aristotelian notions of motion, especially projectile motion. He argued that the motion of a projectile after the initial projection was due to its "natural gravity." Here Newton was referring not to the gravitational force, but rather an "inherent motility" which keeps the object moving, an idea similar to the medieval theory of impetus. Newton stuck to a quasi-impetus conception of motion through much of his work on mechanics, even through the initial stages of writing the *Principia*.

Even though his ideas would come to challenge the impetus view, notice how Newton initially adopted a view that resembled it. As you read on, consider the ways in which Newton's ideas changed, and the reasons for these shifts.

After reading Descartes's *Principles* and Galileo's *Dialogue*, Newton appeared to partially accept the principle of inertia. In 1665, writing in a section of the Waste Book titled "Of Reflections," he began with a conception of motion similar to what Descartes had produced: "Ax:100 Every thing doth naturally persevere in yt state in wch it is unlesse it bee interrupted by some externall cause, hence…[a] body once moved will always keepe ye same celerity, quantity & determination of its motion." Yet Newton was not committed to this idea, and abandoned it when examining the cases of circular motion and collisions.

Note how Newton's thinking straddles the ways that natural philosophers have thought about motion along with his efforts to better make sense of it. Thinking, by its nature, is done in the context of current knowledge. So, even revolutionary thinking is not entirely new, and it emerges over time.

Newton summarized his early work on mechanics in a paper called "The laws of Motion," but these 'laws' were not the ones eventually written in the *Principia*. On one hand he had an idea of motion akin to the principle of inertia when dealing with rectilinear motion. On the other hand, his ideas about circular motion pushed him further away from inertia and towards an inherent force in a body. Newton argued that a body in circular motion wishes to recede from the center, and that this 'centrifugal force' seemed to be internal to the object. This force was opposed by a force pulling the object in to a central point. He thus saw circular motion as the product of an equilibrium of forces. But the equilibrium only made sense given an internal force inherent in the circularly moving object. Newton couldn't accept inertia, which denied any principle of internal force, because he would be left without an explanation of circular motion.

Newton was stuck: on the one hand, he argued that only an *external* force could cause a change in speed. This was inertia. On the other, Newton explained uniform circular motion as a result of an *internal* force! Thus, his system explained two different cases of uniform motion with different conceptions of a force. Despite this inconsistency, Newton's adherence to the internal force would remain for many years.

2. While Newton's ideas about circular and rectilinear motion were inconsistent, he would eventually develop a way to describe all motion using the same set of general laws. Why might scientists seek coherence in their ideas that will apply to all situations rather than have different laws for different cases?

Almost two decades after writing "The Laws of Motion," Newton was prompted to revisit his youthful work on mechanics by a visit from the astronomer Edmund Halley. Halley wanted to know the shape of an orbit caused by a force of attraction inversely proportional to the square of the distance. Newton is reported to have responded, "it would be an ellipse." When Halley asked him how he knew, Newton said "I have calculated it." But he could not find his calculations and promised Halley he would recreate them and send it to him.

In response to Halley's visit, Newton returned to the study of mechanics and in 1684 published *On the Motion of Bodies in an Orbit*. Here, Newton first introduced the notion of a "centripetal" force, but he still espoused an impetus view, in which motion is sustained by an internal force: "And [I call] that by which it endeavors to persevere in its motion in a right line the force of a body or the force inherent in a body;" and "By its inherent force alone, every body proceeds uniformly in a right line to infinity unless something extrinsic hinders it."

Newton continued to struggle with the lingering problem of circular motion, and finally decided to abandon the idea of internal force in favor of the principle of inertia. Newton originally understood circular motion as a battle between the 'inherent force' of centrifugal motion and the centripetal force pulling it to the center. But correspondence with the natural philosopher Robert Hooke gave him a different idea: instead of an equilibrium of forces, circular movement was actually the result of a *disequilibrium* – uniform rectilinear motion constantly deflected by a force pulling in from the center. Fully working through the implications of this idea convinced Newton to finally drop the internal force for the principle of inertia.

3. While Newton did a great deal of work on his own, in what ways did he draw upon others to develop his ideas about motion? How does this illustrate the importance of collaboration in science?

What had originally confused Newton about circular motion was that the constant action of the centripetal force caused no change in the body's speed. An unbalanced force, as Newton understood it, would cause a change in speed; however, an orbiting body had no such change. This is why he added the 'internal' centrifugal force, the tendency to move away from the center of the circle, to create an *equilibrium* of forces and explain why there was no change in speed in circular motion. His new conception of motion, as a disequilibrium, thus changed Newton's understanding of acceleration: circular motion, representing constant changes of direction, was also a form of acceleration! A body, moving in a straight line, was 'deflected' from its course by the unbalanced centripetal force. The centrifugal force was thus a non-existent illusion. Importantly, this similarity between changes in speed and changes in direction broke down the barrier between straight-line motion and circular motion. Both operated under the same principles, and it was the principle of inertia that would allow Newton to unify them.

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Notice that Newton did not arrive at his laws of motion directly or quickly. His thinking about motion was filled with missteps and false starts, and only through extensive examination did he refine his ideas to those that we know today. New ideas in science rarely come about in flashes of insight; rather, they take great time and effort to develop.

Newton's original definition of inherent force in *De motu* was:

> The inherent, innate, and essential force of a body is the power by which it perseveres in its state of resting or of moving uniformly in a right line, and is proportional to the quantity of the body. It is actually exerted proportionally to the change of state, and in so far as it is exerted, it can be called the exerted force of a body.

In a later revision, he moved the inherent force from a 'body' to 'matter.' He called this *vis inertiae*, the force of inertia. This eventually became what we know as *mass*. A further revision emphasized that the internal force was not the cause of uniform motion, further destroying the hold of the impetus-like ideas. Newton now had an inertial principle which stated that objects stayed at rest or moved at uniform speed in straight lines unless otherwise disturbed. Uniform circular motion was not plain inertial motion, but rather the result of the 'compound' of an object's velocity and a force, such as gravity, pulling the object toward a central point. Newton's 'inherent force,' and prior conceptions of motion, became footnotes in history.

Newton's *De motu* would eventually become the massive *Philosophiae Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), published in July 1687. The first law as written in the *Principia* is "Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by a force impressed on it." The inherent force was gone from the statement. The principle of inertia – his first law – formed the foundation of Newton's mechanics, and by extension his celestial mechanics. The gravitational force, inversely proportional to the square of the distance between the two objects, was what made planets fall into the elliptical orbits that Kepler had described years ago. Though Newton declined an opportunity to describe what gravity actually 'was,' his work nonetheless finally gave an account both of motion on Earth and in the heavens.

4. Newton did not collect any novel data, and yet he created a radically new way of thinking about motion, one that is still taught in classrooms today. If not to account for new findings, why were Newton's ideas about motion scientifically preferable to the ideas that came before? What does this illustrate about the goals of science?

Rejecting Common Sense: Science and Newton's First Law of Motion
written by Robert Schombs, Jacob B. Pleasant, and Michael P. Clough

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