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On Galileo's Contribution to Modern Science by Bridging Two Antiquated Scientific Sects

In a world of increasing critique of Aristotelian physics, Galileo's freefall experiments helped bridge the gap between philosophy and science and between the two views of science: mathematics as abstract quantities used only in theoretical calculations versus physics as qualitative causalities of change. Galileo was a catalyst for turning a world polarized and paralyzed between qualitative philosophies and abstract mathematics into a world of experiential realities and quantitative, operative mathematics based on experimentation, observation and demonstration. His discoveries and innovations planted a seed which grew into the modern scientific method.

Aristotelian Physics

Aristotelianism is a worldview and philosophical tradition based on the works of Aristotle (384 - 322 B.C.E.). Aristotelian science is concerned with theoretical explanations for motion and is more interested in qualitative causality than quantitative explanation and application.

In this system, mathematics was viewed as suppositional, dealing with abstract quantities used to account for appearances and make calculations more convenient. Mathematics was not used to describe the truths of nature. Peter Dear notes that "for Aristotle mathematics, the consideration of abstract quantities, was inappropriate to physics, the consideration of substantial qualities and the causality of change." (Dear, 174) In fact, Aristotelians felt that mathematics could only truly describe the movement and behavior of heavenly objects, the only objects with perfect regularity.

This is not to say that Aristotelians did not try to describe the motion of terrestrial bodies. Mary J. Henninger-Voss briefly describes the Aristotelian view of non-heavenly motion in her article "How the "New Science" of Cannons Shook up the Aristotelian Cosmos":

> "Animals and plants moved by virtue of their" souls," and in animate ones (like cannonballs) moved either "naturally" to seek their proper zone in the universe or "violently" through the motive force imparted (usually) by an animate being. The natural motion of things without souls was rectilinear only, and depended on the essence of their composition. "Heavy" things moved straight down toward their place at the center of the universe, while "light" things moved straight up toward the sphere of the moon."

As can be seen in this passage, Aristotelian physics used qualitative terms like 'heavy' and 'light' to describe the weight of an object and 'natural' and 'violent' to describe the motion of an object. Qualitative terms only mean something in the context of a comparison, either as a continuum (degrees of heaviness or lightness) or as a mutually exclusive dichotomy (natural or violent). Even speed was a relative, qualitative term and would never have a measurement assigned to it, only proportionality to other qualitative terms. In the absence of mathematics and quantitative measurements, Aristotelian physics describes the motion of terrestrial objects in terms of ratios and qualitative vocabulary.

Aristotle had implied that the speed of an object was related to the resistance of the surrounding medium. The density of the medium was thought to deter the natural motion of an object in free fall or in violent motion. In relational terms, the average velocity of a moving object was directly proportional to the external force and inversely proportional to the density of the medium and the weight of the object. Of course this means that velocity could never be zero while any force at all is acting upon the object. This does not match real observations and so Aristotle added a stipulation that the force or forces must be greater than a certain, definite quantity. Israel E Drabkin asserts that Aristotle's failure to realize that fiction and the resistance of the medium were not proportional to velocity but that they should be subtracted from velocity meant that he had to add stipulations, such as the amendment made to the proportion of forces to velocity. (Drabkin)

Aristotle's physics also posit that if two objects, one twice as heavy as the other, are in free fall, the heavier of the two will fall twice as fast. This postulate had been known to be false for centuries. In the sixth century, John Philoponus, a writer and philosopher, critiqued this idea:

> "If you let fall from the same height two weights, of which one is many times as heavy as the other, you will see that the ratio of the times required for the motion does not depend on the ratio of the weights, but that the difference in time is a very small one." (Drake, 9)

The idea of the resistance of the medium as related to its density also clashes with the Aristotelian idea of violent motion. This was the idea that an object in violent motion needed a continuous application of force. When the mover imparts a force to an object, it applies the same force to the surrounding medium which continues to act on the object after it has left contact with the mover. It is hard to reconcile this idea with the notion that the velocity of the object was inversely proportional to the density of the medium. (Drabkin)

These logical but misled assumptions characterized most of Aristotle's physical 'laws' or explanations. However, even though the tools to conduct the necessary mathematical experiments and measurements to truly explain the phenomenon called 'motion' had been available for centuries before the 1600s, the generally accepted roles of math, science and philosophy stopped such attempts before they were undertaken.

Confrontation of Aristotle

Although mathematics, measurement and technology were not used in the unraveling of nature's mysteries, they did not lie dormant in 17^{th} century society. Merchants, craftsmen and engineers all relied on operative, quantitative mathematics. In fact, the needs of the military for mathematics relating to projectile motion may have been a springboard for the development of the scientific method and the modern role of mathematics.

During the early 16^{th} century, mathematician Niccoló Tartaglia was studying military artillery and cannons in particular. In 1537 Tartaglia published his *Nova Scientia* (New Science). He wrote it to "give rules to the art of bombardiers, and draw from it whatever subtlety possible… because in truth (as Aristotle in Book VII, chapter 20 of the Physics), 'from particular experiences, we grasp universal knowledge'." (as translated by Mary J. Henninger-Voss). We may draw from this epistle that Tartaglia was not, in fact, seeking to disprove or critique Aristotle. However, his result had serious implications in the movement toward modern science. In order to move away from Aristotelianism, the clean lines and clear-cut roles of different disciplines had to be blurred so that one could think outside the box. Tartaglia, either because he did not entirely understand Aristotle's explanations of motion or because he is trying to reconcile Aristotelianism with useful physical equations, does indeed blur the lines. (Henninger-Voss)

Where Aristotle defined velocity as inversely proportional to the resistance of the surrounding medium, Tartaglia defined velocity as directly proportional to the "hole" cause in a resistance because of the larger holes left by larger projectiles landing. This is a more 'Euclidian' way of looking at ratios.

Also, because Tartaglia was working with machines, he felt that mathematic could be used to describe their motion because it was regular like heavenly bodies. This conclusion allowed Tartaglia to create equations for terrestrial bodies without upsetting Aristotelianism. Though his intention seemed to be to create useful tools for the military without critiquing the dominant philosophy, "Tartaglia's dynamics eviscerated Aristotelian terms of projectile movement, and filled the categories of physical causality with… the experiential realities of war" (Henninger-Voss, 376). According to Henninger-Voss, "the entire new science is possible because Tartaglia is willing to make a physical equation of what Aristotle mentions as only an analogy". In 1638, 101 years after *Nova Scientia* was published, it is Galileo Galilei who truly brings measurement from its practical employ with merchants and artisans into the scientific world with the publishing of his *Due Nuove Scienze*, or Two New Sciences. While many scientists contributed to the creation of modern sciences, according to John Herman Randall, "the conception of the nature of science, of its relation to the observation of fact, and of the method by which it might be achieved and formulated, that was handed on to his successors by Galileo." (Randall, 177)

Tartaglia also had another gift for Galileo. He had translated Euclid's *Elements* with a correct version of Book V which contained an important definition of ratios which had been unavailable to medieval scientists. This definition of ratios was: "Magnitudes are said to have a ratio to one another which are capable, when multiplied, of exceeding one another" (Drake, 25). Tartaglia concluded that this definition excluded only infinite and null values from having ratios to other values. Aristotelian physics postulated that curved and straight magnitudes could not have ratios to each other. Tartaglia's correct translation revealed that there could be ratios between the curved and the straight and helped further challenge Aristotlenian physics' ability to explain natural phenomenon. (Drake)

Galileo's experimentation

Having studied under Ostilio Ricci, the court mathematician for the Medici family and a former pupil of Tartaglia, Galileo was familiar with Tartaglia's work. Also, because he learned math from independent mathematicians and not from university professors he was not predisposed to the Aristotelian view of the abstract role mathematics versus philosophical causal preconceptions.

Like Tartaglia, Galileo was interested in motion, and specifically the behavior of moving objects, not the causal explanations. His advantage over Tartaglia was an understanding the deficiencies of Aristotelian physics. Galileo challenged Aristotelian explanations and confronted the Aristotelian use of qualitative terms to describe natural phenomenon.

We can see his first conclusions about the nature of motion in his *de Motu*, published in 1590 while he was teaching at the University of Pisa. In this work, Galileo examines the nature of falling bodies and the meaning of the terms 'lightness', 'heaviness', 'speed' and 'force' in relation to the behavior of an object in free fall. He cites the work of Archimedes on floating bodies to help disprove Aristotle's postulations about the inversely proportional resistance of the density of a medium to the speed on an object passing through it. Galileo also fits the qualitative terms of Aristotle to his own observations. 'Lightness', for example, becomes the ability of an object to stay in the air instead of a natural tendency of an object toward the center of the moon instead of the center of the earth (the opposite of heaviness which was the tendency of an object toward the center of the earth instead of the center of the moon). His conclusion, as demonstrated in the famous and perhaps mythical leaning tower of Pisa experiment, was that objects of the same material would have equal speeds of fall no matter their weights. (Drake)

In *de Motu*, Galileo also takes a preliminary look at projectile, a combination of violent and natural, motion and the role of the medium. He studies the 'impressed force', the force acting on an object, as a qualitative term. The impressed force is directly proportional to the heaviness of the object and diminished over time. This 'impressed force' is unique in that it places resistance in the object instead of the medium. Galileo also unites the previously divided 'violent' and 'natural' motions. An object may experience both an impressed force from a mover and a downward motion due to gravity. The fall of a projectile is explained by the diminishing of the impressed force until the motion due to gravity takes over. (Voss)

In 1592, Galileo begins teaching at the University of Padua and experimenting with the particulars of free fall with an inclined plane. Having rejected the Aristotelian notion that behavior can only be explained with causal philosophies, he seeks to use experimentation, observation and quantitative, operative mathematics to describe the behavior of falling bodies.

In order to establish a relation between the distance traversed by a falling body and the time it takes, Galileo knew he needed to equalize one and study the other. He first sought to equalize time and measure the distance traversed in each uniform piece of time. To make the fall slow enough to measure, Galileo rolled a ball down a 1.7° inclined plane. The plane had a groove in the center and was strung with cat gut like a lute. The gut served to mark the distance covered in each time frame and also made the passing of the ball by each mark audible and easier to pinpoint.

The results of this experiment were not to be conveyed in abstract, philosophical, Aristotelian terms. They were to be quantifiable observations. In the absence of a clock, let alone a metronome or stopwatch, Galileo used the resources available to him: a lute-playing father and a musical ear. As Drake notes in *Free Fall*, 'all units of measure appear to be arbitrary, and any set can be related to any other' (drake, 81). The beats per second used by Galileo made no difference, only that they were consistent and that their order-of-magnitude was convenient for the task at hand. Once he had equalized the time between each 'fret', he measured the distances with a ruler he had created. This ruler was 60 *punti* long. In modern metric system terms, a *punto* is .94 mm. Galileo recorded that his ramp was 2100 *punti* long and that the elevated end was 60 *punti* high, yielding the 1.7°.

From these quantitative observations, Galileo could perform mathematical calculations about real, observable behaviors. He found the total distance between one fret and the previous fret increased in a uniform way. Galileo also found that the ratio of the distance between each fret and the fret before it to the distance between the start and the first fret yielded the odd number sequence. The ratio of the accumulative distance from the start to each fret to the distance from the start to the first fret yielded the perfect squares. This indicated to Galileo a relation between distance and time squared. However, Galileo was seeking mathematics which described true, natural phenomenon and time squared was not something he could visualize. It was not until after he conducted experiments with pendulums and long ramps that he arrived at his law of free fall.

Of course it should be mentioned here that, although Galileo was using mathematics to describe natural behavior, he was working exclusively in ratios and not in equations or algebra, as a modern scientist might assume from the term 'mathematics'. This means he was searching for natural truths in the form of relationships and proportionalities and not in the form of equations.

Galileo also sought the truth about the behavior of bodies in free fall with experiments with pendulums. He observed the proportion of the length of the pendulum to the time needed to complete a cycle (from its starting point to the point where it stopped and came back the other direction). Galileo thought the angle from which the pendulum fell would not affect the outcome. This was because when he started two pendulums of equal lengths from different angles he observed that the time to complete one period or cycle was the same for different arc distances. A larger angle yields a longer arc distances but also results in greater speed and completes a period in the same amount of time as a smaller angle with a smaller arc distance and less speed. Thus, Galileo assumes that the angle of the pendulum does not affect the behavior of the pendulum or his observations. This misconception caused him some difficulties in later calculations.

From these pendulum experiments, he discovered that the length of the pendulum was proportional to the time of one period of cycle squared. This confirmed that distance is proportional to time squared. In order to better understand this relationship, Galileo designed an experiment to equalize distance and observe the resulting times.

This experiment was conducted on a long ramp. Galileo marked uniform distances on a long ramp and then measured the time duration between each mark. In order to measure the time, he constructed a 'water clock'. A water clock was an elevated bucket with a set, consistent amount of water which was released through a tube during the time interval to be measured. The water released was weighted and then placed back into the bucket to maintain a constant water level. Galileo may have used his thumb to cover the end of the tube; though it's possible he had a more precise flow moderation device. The standard unit of weight used was the grain (in modern terms 1/480 fluid ounce). He adapted a unit of time, the tempo, which was equal to the flow of 16 grains. This means the flow rate of Galileo's water clock was 16 grains per tempo (approximately 3 fl. oz per second). Such quantitative measurements of natural behaviors would never have been used in Aristotelian physics. It is these measurements and observations which lead Galileo to his law of free fall.

His also devised a way to make his long ramp observations easier to accomplish, instead of attempting the measure the time frames for each distance, between the 4^{th} and 5^{th} mark or 5^{th} and 6^{th} mark for example, individually while the ball was rolling along the entire distance. In order to calculate the time for the distance between the start and the 1^{st} mark, he measure the time between the 7^{th} and the 8^{th} (the 8^{th} being the last mark). Then, to determine the time for the distance from the 1^{st} to the 2^{nd} mark, he subtracted the time between the 7^{th} and 8^{th} marks from the time between the 6^{th} and 8^{th} marks. In this way he could measure the time between each mark and the end of the ramp and then use mathematics to determine the time between each mark individually. This represents another way in which Galileo used math in a practical, operative way that was entirely applicable to natural phenomenon.

In the long ramp experiments, Galileo observed a relation between distance and time squared. By 1604 Galileo had confirmed the distance to time squared ratio which led him to recognize the law of free fall that "distances from rest are as the squares of the elapsed times" (Drake, 1). He also again revealed a uniform increase in the times for each distance, just like the uniform increase in the distance for each time frame on the inclined plane. This verifies his idea of uniform acceleration in free fall.

In 1608 he arrived at the parabolic trajectory of horizontally launched projectiles. This impacted the Aristotelian vision of violent versus natural motion by stating that the motion of a projectile was a 'mixed' motion with the impressive force imparted to the object and the downward pull of the object's own weight acting on the object simultaneously. (Drake)

In 1615 Galileo began to circulate his essay *Galileo's Considerations on the Copernican Opinion.* This document helps clarify Galileo's feelings towards the Aristotelian view of the roles of mathematics and philosophy and towards mathematics as a way to describe the truths of nature. Galileo identifies two types of suppositions, the primary type is associated with truths of nature and the secondary type encompasses imaginings and hypotheses which account for appearance but hold no truth. Galileo is interested only in the primary type of supposition. He cares not for saving appearances on the behalf on the Aristotelian majority or even the Catholic Church. Galileo describes Copernicus as asking, 'Can things satisfactory in calculation and appearance also truly happen in nature?' Galileo's answer is yes. (Finocchiaro)

His main attempts to convince others of this fact come in 1632 with the publishing of his *Dialogue* and in 1638 with the publishing of *Two New Sciences*. The *Dialogue* is also the first public announcement of his law of fall:

> "…the spaces passed over by the body starting from rest have to each other the ratio of the squares of the times in which those spaces were traversed. Or we may say that the spaces passed over are to each other as the squares of the times" (dialogue p 221-2; as translated in Drake, 68)

The *dialogue* also challenged the Aristotelian notion that the motion of descending bodies was uniform and stated that, from rest, they experience uniform acceleration according to the ratio given in the law of fall. The definition of uniform acceleration is further explained in *Two New*

Sciences as “motion in which equal increments of speed are acquired in equal intervals of time” (drake, 67).

These works were received with mix feelings by Galileo’s contemporary scientific community and inspired both admiration and ridicule. Though he was scrutinized by the Catholic Church’s inquisition and placed on house arrest, his accomplishments and discoveries were fully appreciated by the generations of scientists who came after him.

Galileo’s long term impacts

Though often unappreciated in his time, Galileo’s work changed the face of science and the way we understand the world around us. He proved that mathematics could describe nature, that the observable world could be measured and quantified, and that experimentation and observation were the core of the new science.

Galileo refused to accept that natural behaviors could not be understood with proper observation and explained with quantitative mathematics. He proved that natural, terrestrial phenomenon and behaviors could be described by mathematics, not just ‘perfectly regular’ heavenly bodies. As Paola Monari so adequately puts it, “If the great book of nature is written in mathematical language - as Galileo thought - it belongs to science the task of searching for the numerical relationships between observed quantities” (Monari, 246).

Galileo, by using quantitative measurements to yield laws in the form of proportions, shows that the quantifiable observations themselves, and not the specific units chosen, are the basis of good inquiry. Measurements are tools that make our comparisons and analyses consistent, convenient and transferable. Close observation and critical analysis are the skills which make use of the specific units of measurement.

Galileo's most important contribution to the evolution of science and the later birth of the scientific method was the bridge between the previously isolated worlds of abstract mathematics applied only to the heavens and of qualitative philosophies about natural behavior with no useable knowledge. His experiments proved there was a middle ground where mathematics could apply to natural behavior and where philosophies about behavior could contain useable knowledge. It was possible to describe mathematically and intellectually how things behaved in the natural world.

From this conclusion, later inquisitive scientists like Newton took the next step and discovered why things behave as they do in the natural world. Galileo's law of free fall led to the discovery of gravity and his work with projectile motion helped pave the way for calculus. Because Galileo had drawn the curve of a projectile as the relation between distance and time squared, he had drawn a parabolic curve. In modern calculus, the equation for a parabola is $y^2 = 2px$ where x and y represent the coordinates of any point along the parabola and p represents the x coordinate of the focus of the parabola (the point at which any ray coming into the parabola will reflect through). This equation reflects Galileo's decades earlier discovery of the distance to times squared relationship. Even the fact that an xy plane for graphing exists is in part due to the fact that Tartaglia and Galileo asserted that the motion of a projectile was not composed of mutually exclusive violent and natural motions but of a combination of the impressed force and the downward pull of weight.

The modern scientific method, which stresses experimentation, observation and demonstration, reflects the way in which Galileo lived his scientific life. In a metaphorical sense, Galileo's fertilization of modern science was so widely influential that there is not a discipline which does not show some of his own scientific characteristics.