Experimental Scientific Method: Advancing Science Education Through Galileo's Mathematical Equations for His Studies on Gravity and Motion

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Abstract

This paper focuses on the experimental scientific method pioneered by Galileo Galilei as demonstrated in his works while he explored gravity and the motions of bodies. The ways by which his scientific method using mathematical experiments advance science education in the early decades of the seventeenth century are highlighted especially how the use of scientific method may either be discovered, refuted or enhanced in the pursuit of the truth. Through expository essay, the astronomical discoveries, heavenly motions, projectile motion, and laws of falling bodies introduced by Galileo through his mathematical experiments are expounded in this paper. Concepts and excerpts from his famous published writings helped in the analysis. While the immense and significant contributions of Galileo to science education, especially the experimental scientific method, are discussed, the ways by which they can be integrated in the curriculum are suggested. HPS lessons for conceptual understanding, application problems in science and mathematics, and experiential learning through derivation of formulas and scientific and mathematical experiments are strongly recommended. The conflict with the Catholic Church that the heliocentric philosophy of Galileo created, the consistency of science with the Bible, and Galileo's faith in God who created what his telescope revealed are also provided special spaces in this document.

Keywords: *experimental scientific method, Galileo Galilei, gravity, mathematical experiment, motion, science education*

Introduction

The acquisition of scientific and mathematical literacy is among the prime goals of education worldwide [1], [2] and [3]. While human endeavors progress, inquiry, critical and analytical thinking become the required skills of the 21st century [4], [5] and [6]. Hence, the provision of opportunities to hone these skills is but an indispensable element of an ideal education.

One great avenue to stimulate the application and thereby develop these 21st century skills is through the use of scientific method [7], [8] and [4]. When regarded in its truest sense, the scientific method is a complex process which does not strictly follow a linear set of procedures [7], [8] and [9]. A carefully planned, administered and validated experiment is irrefutable and worthy of consideration—whether it counters other beliefs or even the widely recognized discoveries.

In relation to this, scientific method requires creative and critical thinking to conduct a complex experiment where careful and repeated observations of a phenomenon are a primary ingredient. Analytical thinking sets in when finding the pattern and relationships between and among the variables being observed. Such an approach to scientific method can definitely meet the requisites of the 21st century science and mathematics education [4], [10], [5] and [11].

Building on this point, this paper highlights the experimental scientific method used and introduced by Galileo Galilei [12] and [13]. The wide range of remarkable inventions and discoveries of Galileo, some of which he discovered through serendipity, had proven the worth of the scientific method he pioneered which used a mathematical experiment [14], [7] and [15]. Indeed, science continuously improves and inquiry, critical and analytical thinking skills are necessary for one to correctly deal with these changes in science.

Who is Galileo Galilei?

There are many literature containing the biography of Galileo Galilei. Those include the accounts authored by Ashare [14], Gindikin [16], Helden [17], Machamer and Miller [18], Peterson [15] and Zanatta et al. [19]. Galileo Galilei was born on February 15, 1564 in Pisa, Tuscany, Italy. He was the oldest son of the musician Vincenzo Galilei who performed experiments with the young Galileo on the relationship between pitch and the tension of strings. In 1581, when he was in his fourth year of studying medicine at the University of Pisa as his father wished, he decided to focus in mathematics and philosophy instead.

In 1589, Galileo became the Chair of Mathematics at the University of Pisa where he established theorems on centers of gravity. However, it was these times when he began his interest in studying the science of motion. He started discovering that the speed of fall of an object is not proportional to its weight as Aristotle told. His paper "On Motion" contained contradictions with the Aristotelian beliefs which ended his career in the University of Pisa.

Meanwhile, with the invention of the telescope in 1609, Galileo's focus transferred to heavenly objects after figuring out and designing a far better telescope which could magnify heavenly bodies up to twenty times [13] and [20]. However, his discoveries proved that the Aristotelian philosophy about the geocentric belief is wrong. He converted to the Copernican philosophy which highlights the heliocentric orientation [18] and [20]. With more discoveries and writings using mathematical experiment as the scientific method of his investigation came a satirical manuscript of Galileo. This pushed the case filed against him by the Inquisition.

Despite being in a house arrest for the rest of his remaining years, he summarized his mathematical experiments on motion especially the law of falling bodies and the parabolic path of projectiles given constant speed and uniform acceleration [15]. He was blind when he wrote these and was accompanied by his student Vincenzo Viviani until he died in January 8, 1642.

Laying the foundations of the science of motion

Galileo was indulged in measuring the motion of a swinging pendulum [21] and [12] of falling objects [22] and of projectiles [23] even before he discovered the motion of heavenly bodies. As he was most interested in investigating motions and gravity, his works, though they spanned in different fields, all contributed to the advancement of the science of motion. Even his famous telescopic discoveries which proved the Copernican belief about heliocentric philosophy were all about motion—the motion of heavenly bodies with the Sun in the center of the solar system. These discoveries went unplanned and the scientific method that Galileo utilized ushered unintentional findings and conclusions that introduced a new philosophy on the science of motion [7] and [8]. Unexpectedly, his telescope revealed among others the moons revolving a planet and the phases of planets which were strong proofs that there has to be more than one center of motion [13], [14] and [17].

In 1632, Galileo published his "Dialogue Concerning the Two World Systems." This involves a discussion involving three men—Salviati, Sagredo, and Simplicio. While Salviati stands for Galileo and presents in the discussion his astronomical discoveries, Simplicio is the person who holds the Aristotelian beliefs especially on geocentric philosophy. Meanwhile, Sagredo is a layman. Satirically presented in the book were the two philosophies which shaped science education as it shifted from the ancient times to the modern era—the Aristotelian geocentric philosophy and the Copernican heliocentric philosophy [14] and [17].

On the other hand, the weight of the findings of Galileo put his reputation at stake. Not only was Galileo's revelations contrary to Aristotle's beliefs, but these revelations also contradicted the belief of the Catholic Church about heavenly bodies in the first place [20] and [19]. The latter strongly believed that the Earth is the center of the universe with the Sun and the moon moving around it. Literally interpreting it, the church used the Biblical verse Joshua 10:12 which says:

"…Sun, stand thou still upon Gibeon; and thou, Moon, in the valley of Ajalon.
And the sun stool still, and the moon stayed, until the people had avenged themselves upon their enemies." [24]

The Catholic Church leaders also plainly understood Ecclesiastes 1:5 as it was used as basis of this geocentric belief. The verse says:

"The sun also ariseth, and the sun goeth down, and hasteth to his place where he arose." [24]

Little did the church leaders realize that they might have misinterpreted these biblical accounts. It would be easier for Israelites that time to understand that it was God who delivered them in the battle against Amorrhites if it would be directly pronounced that the sun and moon stayed. It does not necessarily mean that these bodies are revolving around the Earth in ordinary days. In like manner, it does not literally mean that the sun rises and sets. Part of Galileo's study on motions tells us that the Earth rotates around its axis from west to east, and so it just seems that the sun rises in the east and sets in the west. One fact stands still, the Bible is written for human beings according to their level of understanding.

In 1633, the Catholic Church leaders accused Galileo of heresy and he was put on trial at the Inquisition [19]. Had the society realized that Galileo has laid the foundations of the embodiment of a matured science education with his heliocentric philosophy, scientific knowledge should have flourished sooner.

Advancing science education through experimental scientific method

The search for observable objects both on and out of the Earth, and documenting his observations of them at different times were key features of Galileo's scientific method. He coupled these with repeated experimentation primarily through measurement of dependent variables like distance, and period of pendulum. He analyzed their relationships with corresponding independent variables like time and length of pendulum, respectively [7] and [8]. In 1610, Galileo published the synthesis of his observations through "Starry Messenger".

Galileo compared the distance travelled by rolling bronze balls in an inclined plane within the time it took for the pendulum to oscillate called the period of pendulum [21], [12], [25] and [26]. He compared the relationship between time and distance by continuously increasing the length of the pendulum, and found that the time elapsed is proportional to the distance travelled.

In 1633, under house arrest, Galileo resumed his investigation on the speed of falling objects, pendulum, and projectiles. These were embodied in his book "Dialogues Concerning Two New Sciences" where equations were first represented by text versions [14], [17], [27], [15] and [26].

He was able to conclude that given constant speed and uniform acceleration, the velocity of a moving object is proportional to the time elapsed until the object reaches the ground. He was able to establish the law of falling bodies through the equation $v = gt$ where *v* is the velocity, *g* is the acceleration due to gravity, and *t* is the time elapsed [28] and [25]. He was able to find that *g* or the acceleration due to gravity is 9.81 m/s^2. Moreover, Galileo was able to establish that the distance travelled by the falling object is proportional to the square of time elapsed through the equation $d = \frac{1}{2}gt^2$ where *d* is the distance travelled in meters, *g* is the acceleration due to gravity, and *t* is the time elapsed in seconds [28] and [25].

In addition, Galileo was able to describe the period of a pendulum in terms of mathematics. He did this by comparing the movement of the swinging lamp in a cathedral in Pisa and his pulse rate [21] and [12]. He was able to find that regardless of the mass of the object suspended in a pendulum, the period of its oscillation is defined by the equation $T = 2\pi\sqrt{\frac{L}{g}}$ where *T* is the period of the pendulum, π = 3.14, *L* is the length of the pendulum and *g* is the acceleration due to gravity [29], [16], [21] and [15]. From this mathematical law, Galileo deduced that the period *T* can be made longer by increasing the length *L*. This is expressed through explanation of Salviati in the fourth day of Galileo's "Two New Sciences" where he likened the relationship between the length of the pendulum and its period to the motions of the Earth's moon to the moons of Jupiter. According to him, moons that move in the larger circles take more time in passing through them. Hence, the period of the pendulum is directly proportional to the square root of the length of the pendulum [14], [17], [27], [15] and [26]. However, it is noted that Galileo considered small angle pendulums only in his experiments. With science being constantly advancing, this formula for period *T* is enhanced [22].

Galileo's studies extended to projectile motion [22]. He rolled inked bronze ball across a horizontal table and off the edge as well. He varied the horizontal velocity and the vertical height of the table. He was able to discover that projectiles observe a parabolic trajectory [22], [27], [23], [15] and [26].

Galileo's law of falling bodies and parabolic trajectories paved way for modernizing the science of motion [14] and [25]. Through painstaking observations and measurements, Galileo performed empirical experiments. In "The Assayer", he highlighted that the language of the universe is mathematics, he made a shift from a qualitative account to a mathematical one where performing experiments was being recognized as a scientific method in discovering knowledge of nature [14] and [17].

Conclusion

The experimental scientific method was proven to be an effective way of understanding the laws of nature especially through the use of the language of mathematics [7]. Galileo had proven that mathematics is the language of the universe and that the scientific method should make use of it through empirical experiment. By saying so, scientific method should allow replication where experiment may be conducted repeatedly which may lead to either discovery, contradiction or improvement of a theory or a mathematical equation [7] and [8]. Thus, the scientific method in the truest sense supports that science is continuously changing in pursuit of the knowledge of the truth.

Proving the heliocentric belief in contrast with the geocentric idea, and the discovery of concepts behind the science of motion are great contributions of Galileo to the advancement of science using the experimental scientific method. Through this, Galileo had proven that science does not contradict the Bible. His unwavering faith in God through the wonderful creation his telescope revealed had empowered him to go further with more discoveries knowing that He was the same God who inspired the writing of the Holy Scripture. In 1992, the Catholic Church has reinvestigated the heresy case which Galileo was accused of and made a public apology. Science will not deny the Bible. True science is first and foremost biblical.

The milestones in science which the human race has achieved through Galileo are truly meaningful paving way for more advances. The scientific method that is grounded on trial-and-error or experimental method should be inculcated in science and mathematics education [30], [12], [5], [11] and [3] like writing a journal [32] and [33], and derivation of formulas [12] and [34]. It is indispensable that they learn through this process that a scientific concept is developed from a series of trial-and-error endeavors. Truly, HPS lessons in both subjects should be part of the curriculum and lesson plans so that conceptual understanding will be honed [1], [9], [10], [26] and [35].

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