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The Contribution of Archimedes in Greek Mathematics After Euclid to the Advancement of Modern Mathematics: Implications for Student Understanding

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Abstract
This study examines Archimedes' contributions to the development of Greek mathematics after Euclid and its impact on the advancement of modern mathematics, as well as its implications for students. Although his contributions have been widely discussed, a deep understanding of the relevance of Archimedes' principles to modern mathematics is still limited. The purpose of this study is to analyze Archimedes' contributions and their implications across various fields of mathematics and their contemporary applications. The research method used is descriptive qualitative with a literature review approach to understand Archimedes' contributions within the historical context and modern relevance. The instruments used are relevant scholarly literature, including books and journals. The literature review includes previous works that highlight Archimedes' contributions to mechanics and mathematics, particularly in areas such as geometry, calculus, and the understanding of volume and surface area. The data analysis technique applied is descriptive qualitative analysis to identify patterns and themes in Archimedes' contributions, such as his development of methods for calculating areas and volumes of geometric bodies, as well as his innovative work in fluid mechanics. The results of this study emphasize the importance of historical understanding of Archimedes' contributions to mathematics and their implications for students. This study encourages students to explore the historical roots of modern mathematical concepts, fostering a deeper appreciation for the evolution of mathematical thought. The implications and benefits of this study motivate students to develop critical thinking and innovative problem-solving skills, applying mathematical concepts in real-world contexts.

INTRODUCTION

Greek mathematics reached its peak during the time of Euclid, who had a great influence on the development of mathematical science [1], [2] . Euclid was a very influential person in the teaching of geometry for several centuries since 300 BC. Euclid is famous for his magnum opus, *The Elements*, which became the foundation of modern geometry by outlining postulates and theorems that are still used today [2]. In *The Elements,* Euclid lays out five postulates that became the foundation for theorems, axioms, and postulates in geometry and the development of mathematics [1], [3].

The development of mathematics did not stop at the time of Euclid. One of the figures who also contributed greatly to mathematics was Archimedes. Archimedes was a Greek mathematician, astronomer, philosopher, and physicist [4], [5]. Archimedes was a great mathematician of ancient times who was born in *Syracuse*, Sicily, and was once an advisor to King Hieron [6]. Archimedes

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managed to discover the mathematical theory of levers, pulley systems, ulil penak, and many other works[5] . From his experimental works, Archimedes was later dubbed the Father of Experimental Science [7], [8].

In the development of mathematical sciences, Archimedes is considered to be a reference figure because Archimedes provided one of the earliest and accurate approaches to the value ofπ (*pi*) [9]. In addition, Archimedes also contributed to the measurement of volume, surface area, and integral calculus [10], [11]. These discoveries were not only important to the advancement of mathematics, but also impacted physics and engineering, such as in the design of machinery and building structures [4], [5]. Thus, Archimedes' discoveries have significant contributions in various fields of science and technology.

By studying Archimedes' contributions, students are expected to appreciate and understand the importance of his works and discoveries in the development of modern science and mathematics. The knowledge gained from the history of mathematics will be very beneficial in future scientific and educational progress [5], [7], [8]. In addition, it is hoped that students will not only understand the origins of Archimedes' theory and contributions, but also gain a broader perspective on the process of scientific development.

Research on Archimedes' contribution to mathematics and science continues to be conducted by academics or other previous researchers. Gunawan (2015) in his research entitled "Archimedes and Estimation of Numbersπ " reviews that Archimedes' contribution in estimating the value ofπ through geometric methods is one of the major contributions to the development of mathematics. In addition, Chondros (2010) in his research entitled *"Archimedes life works and machines"* discusses Archimedes' contribution in the field of mechanics, especially in creating machines and tools that facilitate human work. These two studies provide a strong basis for digging deeper into Archimedes' contributions, as well as their implications for mathematics and science [13].

While Archimedes' contributions to mathematics have been widely discussed in the literature, there is a lack of in-depth understanding of how the principles he introduced influenced the development of modern mathematics and their relevance in higher education. Most of the literature tends to focus on aspects of mechanics or geometry without exploring the broader implications of Archimedes' work for mathematics learning today.

On the other hand, based on research by Efendi *et al.*, (2021), many students do not understand the history of mathematics well, as many as 53% of the current generation still have a low interest in the history of mathematics, and as many as 63% of the current generation feel that the history of mathematics does not change their impression that mathematics is scary. This gap suggests the need for a more integrative approach to the history of mathematics, particularly by highlighting Archimedes' contributions and explaining the application of his principles in the context of modern mathematics, in order to improve students' understanding of more complex mathematical concepts.

This research aims to analyze Archimedes' contribution to the development of Greek mathematics after Euclid and explain how his thought influenced different areas of mathematics. In addition, this study aims to explore the implications of the principles introduced by Archimedes for the advancement of modern mathematics and their application in today's scientific context. Thus, this research is expected to enhance students' understanding of the importance of Archimedes' mathematical legacy and its relevance in understanding broader mathematical

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concepts. This study also aims to encourage readers, especially students, to conduct further research on the role of Archimedes and his influence in the history of mathematics.

This research seeks to connect Archimedes' contributions to the development of modern mathematics and in the context of higher education. While many studies have addressed Archimedes' contributions to classical mathematics, this research highlights the implications of his principles to modern mathematics and the understanding of today's university students. By integrating historical analysis and contemporary relevance, this research can offer a more applicable approach for students to understand and apply complex mathematical concepts. In addition, this study serves as an introduction to encourage further research on the role of Archimedes in the context of mathematics education, which is rarely discussed in depth in the existing literature.

METHODS

This research uses a qualitative descriptive method with a literature study approach (*library research*). The qualitative descriptive method is research that is intended to describe in full about existing events by describing data related to current situations, behaviors, and perspectives in society [15], [16]. The literature study approach is an activity to review or review various sources of literature that have been published by academics or other researchers related to the topic to be studied [17], [18].

This method aims to deeply analyze Archimedes' contribution to the development of Greek mathematics after the Euclid era towards the advancement of modern mathematics, as well as its implications for students. Through literature study, this research will examine various relevant sources, such as books, scientific journals, and previous research works that discuss similar topics. This approach allows for a more comprehensive understanding of Archimedes' contribution in the context of mathematical development.

The source of this research is scientific literature that discusses Archimedes and his contributions in the field of mathematics, both in the Ancient Greek era and its impact on the development of modern mathematics. The literature was selected based on its relevance to the research topic, particularly with regard to the influence of Archimedes after Euclid's time and its application in modern mathematical theory. The selected literature includes research from scientific journals, books, and published research reports.

The data analysis technique used is qualitative descriptive analysis. Data collected from various literatures will be organized and described narratively to identify patterns, themes, and relationships relevant to Archimedes' contribution to modern mathematics. Each piece of information will be analyzed based on historical and theoretical contexts, focusing on how Archimedes' thought translates in the advancement of mathematics, as well as its influence on current students' understanding.

This method also allows researchers to evaluate the various perspectives that exist in the related literature. With this approach, researchers can identify debates, gaps or differences in interpretation in understanding Archimedes' contributions. In addition, this method provides flexibility in linking the main ideas raised by Archimedes with practical implications in the field of mathematics education and modern science. This analysis is designed to explain how Archimedes' mathematical concepts are not only the basis of theory, but also applied in various technological innovations that can inspire the learning of the younger generation.

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RESULTS AND DISCUSSION

Short Biography of Archimedes

Archimedes, as seen in Figure 1, was a mathematician, astronomer, and physicist born in *Syracuse*, *Sicily* [6], [19]. Archimedes began his studies by going to *Alexendria* and returned to *Syracuse to* continue his work in mathematics [19], [20] . Archimedes is not only famous for his contributions in the field of mechanical instruments, Archimedes made great strides in the field of mathematics that paralleled Euclid's advances in geometry [20], [21], [22].

Image1 . Archimedes

Archimedes is known for the discovery of Archimedes' Law in hydrostatics and the calculation methodπ (*pi*) [6], [23]. His work in math and physics had a huge impact that is still felt today. Archimedes died in 212 BC while doing mathematical calculations on the ground [24]. A Roman soldier, who had been assigned to kill him, approached Archimedes. Before his death, Archimedes asked the soldier to be given time to complete his calculations first [6].

The discovery of Archimedes

1. Archimedes Principle

Archimedes' principle is one of the most famous findings in physical science. Many of Archimedes' famous achievements are based on this principle [4], [24]. This principle states that any object that is partially or completely immersed in a fluid, will gain a buoyant force proportional to the weight of the fluid displaced by the object [25].

The discovery of the hydrostatic principle came about when he was asked by King Hiero II to prove the authenticity of a gold crown made by craftsmen [19]. The king suspected that the gold had been mixed with other cheaper metals, such as silver. The king wanted Archimedes to find a way to determine whether the crown was made of pure gold without damaging it [24].

Archimedes thought of a way to solve this problem and found the answer while bathing in a tub full of water [4]. As he stepped into the tub, he noticed that the water spilling out of the tub was equal to the volume of his submerged body. The more he stepped into the tub, the more water was wasted out of the tub [19]. From this observation, Archimedes realized that he could measure the volume of an object by seeing how much water it displaced [20]. Using this method, he was able to calculate the density of the crown and compare it to the density of pure gold.

When he found the solution, Archimedes was overjoyed. Archimedes ran out of the bathroom shouting *"Eureka! Eureka!"* which in Greek means "I have found it!" [19], [26].

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Archimedes proved that the king's crown was not of pure gold, so the crown maker was punished for cheating.

2. Law of Lever

Although Archimedes was not the inventor of the lever, he provided a mathematical proof of the lever principle in his work entitled *"On the Equilibrium of Planes"* [27]. He was the first person to explain the working principle of the lever [5]. This law began when Archimedes observed a group of children playing by the sea using a seesaw. This interest prompted him to make a model of the seesaw. He conducted various experiments with variations in load, load arm length, power, and power arm length [28], [29].

After conducting experiments, Archimedes managed to find the relationship between power, power arm length, load, and load arm length [5], [28]. He formulated, "Effort times arm length equals load times load arm length". Archimedes summed up the law of the lever with the famous statement: "Give me a lever long enough and a fulcrum on which to rest it, and I will move the world" [2], [28], [29].

3. Archimedes screw

An Archimedes screw is a hollow tube that has a spiral or helix coiled upwards inside a cylinder [19], [27] . The lower end of the tube is placed in a water source, then the tube is rotated. As the screw rotates, it picks up some of the water, as shown in Figure 2. Further rotation will lift the water through the pockets of the helix gradually until it reaches the top of the tube [26], [30].

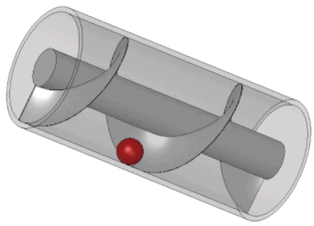

Image2 . Archimedes screw

The earliest recorded use of the Archimedes screw was for irrigation in ancient Egypt [31]. According to other experts, the screw was also used to remove water from ships in Ancient Greece [31]. The use of this machine allowed people to move water from lower to higher areas, especially for irrigation purposes.

Archimedes' Contribution to Mathematics

1. Estimating the Number π and Proving the Area of a Circle

The estimation of the numberπ (*pi*) by Archimedes in the 3rd century BC, is one of the important contributions to the history of mathematics. At that time, the understanding ofπ was still limited, and there was no systematic method to calculate it [12], [23]. In his work, Archimedes used a geometric approach to approach the value of π. He utilized the concept of regular polygons inscribed and arranged outside a circle to estimate the circumference of a circle, which was then used to calculate the value of π [32].

Archimedes started with a hexagon polygon, then increased the number of sides until he reached a polygon with 96 sides [12]. By calculating the perimeter of the polygon, he was able to establish a lower and upper limit forπ , from which he concluded that 3.1408 and 3.1429 were the

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limits of the value of π, which equates to an approximate value of 3.1413. This estimate is very close to the actual value of π that we know today, which is around 3.1415 [12], [32].

In addition, Archimedes discovered a method for calculating the area of a circle, namely by using the formula: $L = \pi r^2$ where L is the area of the circle and r is the radius of the circle [12], [32]. He proved that the area of a circle is equal to half its circumference times its radius. He estimated that ifπ is the ratio of the circumference to the diameter of the circle, then the area of the circle is equal toπ times the radius squared [12], [33]. The proof of the area of a circle by Archimedes is to arrange the pieces of the circle as shown in Figure 3 below. It appears that the area of the circle will be equal to half the circumference of the circle [12], [32].

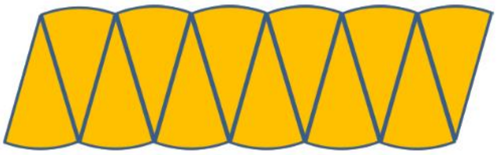

Image3 . Circle Pieces

2. Archimedes' Theorem on Volume and Area

Archimedes made important contributions in calculating the area and volume of various geometric figures, such as spheres, cylinders, cones, and paraboloids [3], [25]. One of his most famous achievements is the theorem that states that the volume of a sphere is two-thirds of the volume of the cylinder surrounding it, as seen in Figure 4 [12], [24].

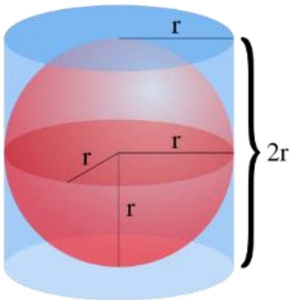

Image4 . A sphere and a cylinder surrounding it.

He discovered this theorem during his research on geometric shapes. One of his most famous works, *"On the Sphere and Cylinder"*, explains this theorem [34]. The book consists of two parts, and in them, Archimedes provides proofs of theorems regarding the volume and surface area of spheres and cylinders [25]. This discovery was very important as it became the basis for future calculations of three-dimensional geometry and integral methods.

3. Initial Calculus and Integral Calculus

Archimedes was one of the pioneers in the development of early calculus, although calculus was later in the 17th century developed by Isaac Newton and Gottfried Leibniz [4], [11]. Archimedes′ contribution to calculus was based on the *method of exhaustion,* which was the forerunner of the concept of the integral [34], [35]. This method allowed Archimedes to calculate the area, volume and perimeter of various complex geometric shapes by dividing the object into smaller parts [25].

Archimedes developed a method for calculating the volumes of various geometric shapes, such as spheres and cylinders, which became the basis for the principles of integral calculus [11], [19]. This invention demonstrates Archimedes' abstract thinking ability and how he applied

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geometric concepts in a practical context. For example, Archimedes' method for calculating the volume of a sphere using a constraint and rigor approach is the basis of differential calculus [19], [25].

Archimedes' Influence on the Advancement of Modern Mathematics

1. Basic Geometry and Calculus

Archimedes established a solid foundation for calculating the volume and surface area of various geometric figures [3], [25]. His theorem that the volume of a sphere is equal to two-thirds of the volume of the cylinder surrounding it became an important reference in teaching geometry [19], [24]. His systematic approach of using the method of exhaustion to calculate areas and volumes not only demonstrated his mathematical expertise, but also introduced the concept of limits that became the foundation for modern calculus [34]. In works such as *"On the Sphere and Cylinder",* Archimedes explained geometric principles that remain relevant in the study of geometry today [19], [34], [36]. These methods are not only used to calculate geometric values but also teach students the importance of rigor in mathematical analysis. Therefore, Archimedes' works can be a source of inspiration for later generations of mathematicians and play an important role in the development of geometry and calculus theory.

2. Algebraic Approach

Although Archimedes did not use modern algebraic notation, his mathematical approach in solving complex problems paved the way for the development of algebra [3], [27]. His approach to geometric problems, especially in calculating the value of π and performing numerical estimations, shows how algebraic concepts can be applied in the context of geometry. For example, by using a numerical approach to calculate π, Archimedes utilized estimates and bounds that were close to the true value, a method that is very important in algebraic analysis [10]. His work gave a sense of how the relationship between numbers and shapes could be used to solve problems, encouraging the later development of algebraic theory [12], [27].

3. Innovation in Mathematics

The invention of tools such as Archimedes' screw and the development of the lever principle demonstrate the practical application of mathematical theory [31]. The Archimedes screw, used to move water, is a clear example of the application of mathematics in engineering [13], [27]. This innovation not only makes man's job of moving water easier but also shows how mathematical theory can be applied in everyday life and industry. The lever principle, described by Archimedes, underlies many of the heavy machinery and simple machines used today [31]. Thus, Archimedes' contribution was not only limited to the theoretical field but also penetrated into practice, encouraging the integration between mathematical theory and technology [4], [19]. This was highly influential in the development of measuring instruments and machines that became the basis for many innovations in engineering and industry.

4. Development for Future Mathematicians

Archimedes' work became a key reference for many later mathematicians and scientists. His work was not only studied, but also further developed by figures such as Isaac Newton and Gottfried Leibniz in the context of calculus and mathematical analysis [4], [11]. Archimedes set the standard for rigor and systematic methods in mathematical analysis, which set an example for

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subsequent generations. For example, the concept of the method of exhaustion that he used in calculating area and volume was eventually adopted in modern calculus, allowing for more complex and abstract calculations [34], [35]. In addition, Archimedes' works also provided valuable insights in the field of physics, particularly in understanding force and motion, which became the foundation for Newton's development of physical theory [11], [29]. Thus, Archimedes' influence is not only seen in the development of mathematics, but also in the advancement of science as a whole, shaping the way we understand and study the world around us.

Implications of Archimedes' Discovery for Students

1. Application of Geometry and Calculus Theory in Studies

Students studying math and science will often encounter problems in geometry and calculus, two fields to which Archimedes made major contributions. Concepts such as volume and surface area of spheres, cylinders, and other geometric shapes taught in calculus or analytical geometry have their roots in the work of Archimedes [4], [25] . As a student, understanding how Archimedes used the method of exhaustion to calculate area and volume provides deep insight into the origins of integral calculus which is so important in modern science and engineering [34], [35]. This allows students to better appreciate the relationship between classical mathematical theories and their applications in real problem solving.

2. Development of Critical and Logical Thinking Skills

Archimedes' systematic approach to solving problems and performing numerical estimations, such as in the calculation of π, provides an excellent role model for students in terms of critical and logical thinking [3]. His work teaches the importance of using the scientific method and deductive logic to reach accurate conclusions [3]. For students, especially in Science, Technology, Engineering, and Mathematics, emulating Archimedes' way of approaching complex problems can enhance their analytical skills in solving academic and practical challenges faced in their studies.

3. Inspiration for Innovation and Scientific Research

As an inventor and innovator, Archimedes showed how math can be applied in technology and everyday life. Discoveries such as Archimedes' screw and the lever principle show that mathematics is not only theoretical, but also has far-reaching practical implications [19], [27]. Students in engineering or science can be inspired by these discoveries to develop innovations that utilize mathematical principles in solving modern technical or scientific problems. It also motivates students to think creatively in scientific research and exploration of new technologies.

Archimedes' discoveries, such as the Archimedes screw and lever principle, have been the basis for subsequent research in various fields of science. For example, the study by Villacrés et al., (2023) explores the efficiency of modern designs of the Archimedes screw for irrigation systems, showing that this ancient concept remains relevant in sustainable agricultural technology. In addition, the study by Karin, (2014) reviews how the lever principle discovered by Archimedes has become the foundation in the development of mechanical technology, including heavy machinery and modern lever systems. This indicates that Archimedes' intellectual legacy continues to contribute to technological development, driving innovations that link basic science with practical applications.

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CONCLUSIONS AND SUGGESTIONS

Archimedes' contributions to the development of Greek mathematics after the era of Euclid were significant and had far-reaching impacts and implications on the progress of modern mathematics and students. Through discoveries such as methods for calculating the value of π, measurement of volume and surface area, and the principle of hydrostatics, Archimedes not only enriched mathematical science but also created the basis for the development of modern calculus and mechanics. The works and ideas generated by Archimedes provide important insights that enable students to understand the interrelationship between theory and practice in various disciplines.

Understanding Archimedes' contributions also has important implications in the context of higher education. By studying the history of mathematics and the contributions of mathematicians such as Archimedes, students can develop the critical and analytical thinking needed to solve complex problems. In addition, the integration of historical studies into the curriculum can motivate students to apply innovative approaches in their research and studies.

Therefore, delving deeper into Archimedes' contributions not only enriches students' academic horizons but also better prepares them to face challenges in the professional world. This research confirms that an understanding of the mathematical legacy of Archimedes remains relevant and important for the future development of science and education. As a suggestion, educational institutions should further explore and integrate Archimedes' works in the mathematics curriculum, so that students not only learn the theory but also understand the underlying scientific thought process. With this approach, students will be better able to connect mathematical concepts with their applications in real life and the development of modern science.

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