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Digital Experiments in Learning the Concept of Gravitational Force in Classical Mechanics

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Abstract:

Gravitational force is one of the fundamental forces that plays an important role in understanding the interaction between massive objects in the universe. However, in physics education, this concept is often difficult to understand concretely due to the limitations of real experiments. This research purpose to analyse the relationship between mass, distance, and gravitational force using the PhET Gravity Force Lab: Basics interactive simulation, as well as to prove its conformity with Newton's Law of Gravity. The research method used was a virtual experiment with a quantitative descriptive approach. Data was obtained by conducting three stages of experiments, namely observing gravitational force on objects of the same and different masses, the relationship between force and mass at a fixed distance, and the relationship between force and distance at a fixed mass. The results showed that gravitational force increased as the mass of objects increased and decreased significantly when the distance between objects increased. The conclusion of this study was that it proved the theory that gravitational force is directly proportional to the product of the masses of the two objects and inversely proportional to the square of the distance between them, in accordance with Newton's Law of Gravity, and showed that the forces were opposite but equal in magnitude, as described in Newton's Third Law.

1. Introduction

Gravitational force is one of the fundamental forces in the universe which plays an important role in regulating the movement of celestial objects, from planets, stars, to galaxies [1]. This concept was first systematically explained by Sir Isaac Newton through the Law of Universal Gravitation, which states that all objects with mass attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them [2]. Understanding this law is the basis for various fields of science, especially physics, astronomy, and engineering.

In the context of physics learning, Newton's law of gravity is one of the fundamental concepts that is often difficult for students to understand because it involves the mathematical relationship between mass, distance, and force [3]. In addition, the limitations in conducting real gravity experiments make learning tend to be theoretical [4]. Therefore, an approach is needed that can provide a concrete and interactive learning experience so that students can understand the relationship between gravitational variables visually and conceptually.

Along with the development of technology, digital experiments has become an effective solution in helping the process of learning abstract physics concepts [5]. Sasmita, et al. (2023) have proven that digital experiments can improve students' ability to understand physics concepts with an average N-Gain of 0.68 which is in the moderate category and has an effect on students' ability to understand physics concepts with an effect size score reaching 0.83 which is in the large category [6]. Subeki et al. (2022) have also proven that the use of guided inquiry-based PhET digital experiments can improve science process skills [7]. Aina & Hariyono (2023) stated that the application of the Problem Based Learning model assisted by virtual labs in physics learning can improve the scientific literacy skills of class X high school students [8]. One of the digital experiment media that is widely used is PhET Interactive Simulations.

PhET Interactive simulations allow users to conduct virtual experiments without having to set up complex physical equipment and materials [9]. Through this simulation, the concept of gravitational force is not only explained verbally but also directly observed, facilitating students' understanding of the relationship between mass, distance, and gravitational force. Thus, this activity provides an opportunity for students and researchers to test Newton's law of gravity more effectively and efficiently.

Many previous studies have shown that the use of PhET simulations can improve students' understanding of physics concepts. Abdi et al. (2021) have proven that PhET simulations with a STEM approach can improve students' understanding of physics concepts [10]. Jullyantama et al. (2024) have proven that PhET simulations in Live Worksheets can improve understanding of physics concepts [11]. Sutaji et al. (2025) have conducted research demonstrating that understanding of physics concepts can be improved through the use of PhET

Simulation as an alternative learning medium [12]. Bui, et al (2025) stated that the application of PhET simulation-based discovery learning showed that students' understanding of physics concepts increased significantly, as indicated by an average N-Gain score of 0.79, which is included in the high category [13]. Rusnayati & Ariantara (2024) stated that PhET virtual simulations have positive potential in improving the understanding of physics concepts for physics education students [13]. In this research, the PhET Gravity Force Lab: Basics simulation focused on analyzing the relationship between three main variables: mass, distance, and gravitational force. By changing one of the variables, researchers can observe the magnitude of the gravitational force and verify its conformity with Newton's theory of gravity. The results of this simulation can provide empirical evidence through digital visualization of the relationship between these three variables.

This research also aims to foster students' scientific thinking skills through simulation-based exploratory activities. With a digital experimental approach, students are expected to understand the concept of gravitational force not only theoretically but also through directly observable empirical evidence. Furthermore, this activity strengthens the application of the scientific method in physics learning by systematically integrating observation, experimentation, and data analysis [14].

Based on this background, this research purpose to analyze the relationship between mass, distance, and gravitational force using the PhET Gravity Force Lab: Basics simulation, and to prove conceptually and mathematically that the magnitude of the gravitational force is directly proportional to the product of the masses of the two objects and inversely proportional to the square of the distance between them. This study is expected to strengthen the understanding of the concept of Newton's law of gravity through an interactive simulation-based experimental approach.

2. Theoretical Framework

2.1. The Universal Law of Gravity

From the time of Aristotle, the circular motion of heavenly bodies was regarded as natural. The ancients believed that the stars, the planets, and the Moon moved in divine circles. As far as the ancients were concerned, this circular motion required no explanation. According to popular legend, Isaac Newton was sitting under an apple tree when the idea struck him that what pulls apples from trees is the same force that keeps the Moon circling Earth. A force of gravity might account for the motions of planets. Others of his time, influenced by Aristotle, supposed that any force on a planet would be directed along its path. Newton, however, reasoned that the force on each planet would be directed toward a fixed central point-toward the Sun. Newton's stroke of intuition, that the force between Earth and an apple is the same force that pulls moons and planets and everything else in our universe, was a revolutionary break with the prevailing notion that there were two sets of natural laws: one for earthly events and another, altogether different, for motion in the heavens. This union of terrestrial laws and cosmic laws is called the Newtonian synthesis [15].

To test his hypothesis that Earth gravity reaches to the Moon, Newton compared the fall of an apple with the "fall" of the Moon. He realized that the Moon falls in the sense that it falls away from the straight line it would follow if there were no forces acting on it. Because of its tangential velocity, it "falls around" the round Earth (more about this in the next chapter). By simple geometry, the Moon's distance of fall per second could be compared with the distance that an apple or anything that far away would fall in 1 second. Newton's calculations didn't check. Disappointed, but recognizing that brute fact must always win over a beautiful hypothesis, he placed his papers in a drawer, where they remained for nearly 20 years. During this time, he founded and developed the field of optics, for which he first became famous.

Newton's interest in mechanics was rekindled with the appearance of a spectacular comet in 1680 and another 2 years later. He returned to the Moon problem at the prodding of his astronomer friend Edmund Halley, for whom the second comet was later named. Newton made corrections in the experimental data used in his earlier method and obtained excellent results. Only then did he publish what is one of the most farreaching generalizations of the human mind: the law of universal gravitation.

Everything pulls on everything else in a beautifully simple way that involves only mass and distance. According to Newton, every body attracts every other body with a force that, for any two bodies, is directly proportional to the product of their masses and inversely proportional to the square of the distance between them centers. This statement can be expressed as

$$\mathrm{Force} \sim \frac{\mathrm{mass_1 \ x \ mass_2}}{\mathrm{distance^2}}$$

or, in symbolic form,

$$\mathrm{F} \sim \frac{\mathrm{m_1 \ x \ m_2}}{\mathrm{d^2}}$$

where $\mathrm{m_1}$ and $\mathrm{m_2}$ are the masses of the bodies and d is the distance between their centers. Thus, the greater the masses $\mathrm{m_1}$ and $\mathrm{m_2}$, the greater the force of attraction between them, in direct proportion to the masses. The greater the distance of separation d, the weaker the force of attraction, in inverse proportion to the square of the distance between their centers of mass [16].

3. Method

This research uses a digital experimental method using PhET Colorado Simulations in the Gravity Force Lab: Basics simulation section to analyze the relationship between mass, distance, and gravitational force according to Newton's Law of Gravitation. This method was chosen to observe changes in gravitational force directly through digital visualization without the limitations of physical equipment.

3.1. Research Design

This research consists of three main experimental activities, namely 1) analysis of the magnitude and direction of the gravitational force between two objects of the same and different masses, 2) analysis of the relationship between the magnitude of the mass and the gravitational force at a constant distance, and 3) analysis of the relationship between the distance between objects and the gravitational force at a constant mass.

3.2. Research Procedures

The procedures in this research were: 1) running the PhET Colorado Simulations simulation, 2) changing the first and second mass values at a constant distance to observe changes in gravitational force, 3) setting a fixed mass and varying the distance between objects to observe the effect of distance on gravitational force, 4) recording the simulation results in the form of gravitational force values for each combination of mass and distance, and 5) presenting the results in the form of figures and tables for quantitative and conceptual analysis.

3.3. Data Analysis Techniques

The obtained data were analyzed using a quantitative descriptive approach, with graphs of the relationships between variables, namely mass-force and distance-force, used to strengthen the descriptive explanation. The simulation results were compared with the theory based on the universal gravitational equation in Equation 1.

$$F = G\frac{m_1 m_2}{d^2} \tag{1}$$

Analysis was carried out to see the suitability between the simulation results and theory [17]. The pattern of relationships between variables is analyzed to prove that the gravitational force increases with increasing mass and decreases with increasing distance between objects.

4. Result and Discussion

4.1. Magnitude and Direction of Force on Two Masses Objects

In the first experiment, two objects with mass are placed at a certain distance apart. The mass and distance can be varied. The researchers then observe the magnitude and direction of the force acting between the two objects. The force is represented by an arrow as shown in Figure 1.

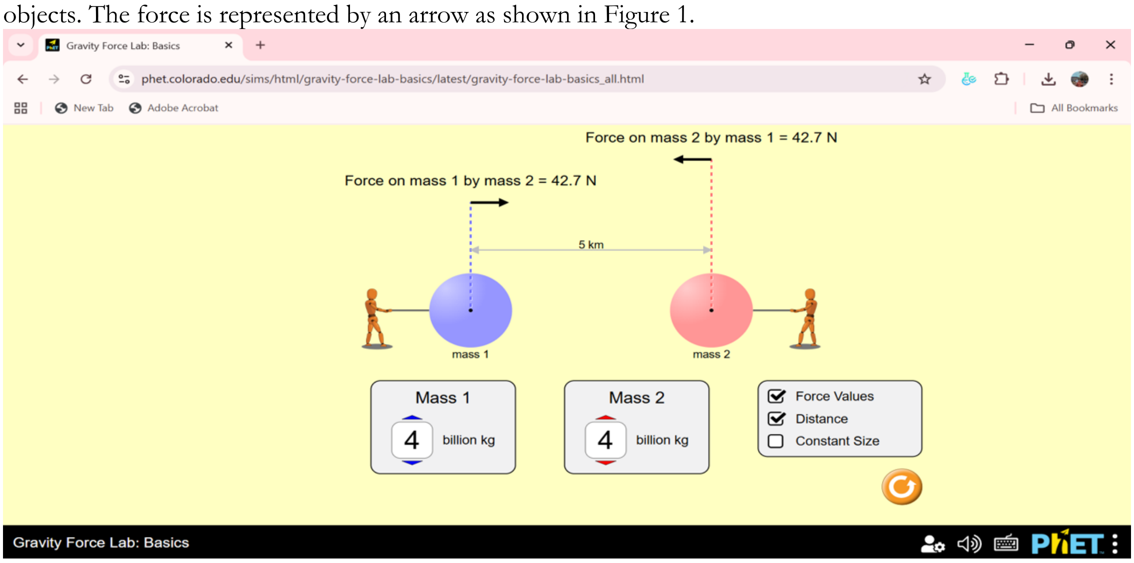

Figure 1. *Simulation of the interaction of gravitational forces between two objects of the same mass*

In Figure 1, the two objects each have a mass of 4 billion kg and are separated by a distance of 5 kilometers. Based on the simulation results, the gravitational force acting on each other is 42.7 N. The direction of the force indicates that the two objects with the same mass attract each other with the same magnitude but in opposite directions [2].

Figure 2 shows a simulation of the gravitational force between two objects of different masses. The first mass has a value of 10 billion kg, while the second mass is 4 billion kg, with a distance between them of 5 kilometers. The simulation results show that the two objects attract each other with a gravitational force of 106.8 N. Although the masses of the two objects are different, the gravitational force experienced by each object remains the same in magnitude but in opposite directions [2]. The magnitude of the gravitational force increases compared to Figure 1 because increasing one of the masses causes the gravitational pull to increase.

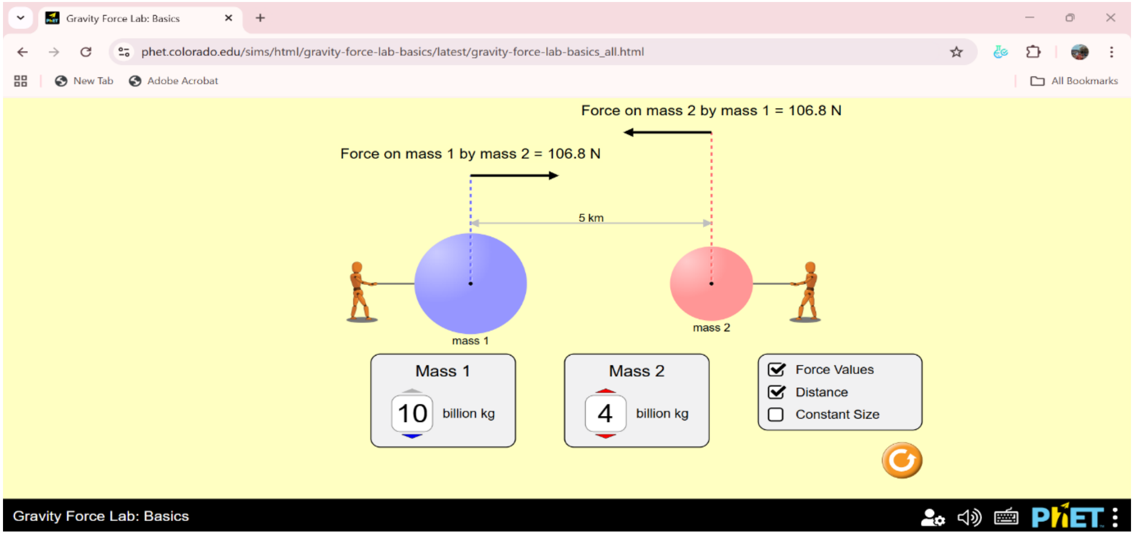

Figure 2. *Simulation of the interaction of gravitational forces between two objects of different masses*

4.2. The Relationship Between Gravitational Force and Mass

The second experimental activity analyzes the relationship between gravitational force and mass, where the magnitude and direction of the gravitational force are the dependent variables, the mass of the object is the independent variable, and the distance between the two objects is the control variable. The simulation data for the relationship between gravitational force and mass are shown in Table 1.

Table 1. *Simulation data results of the relationship between gravitational force and mass*

No	Mass		Distance	Gravitational Force
	Object 1	Object 2		
1	5 billion kg	8 billion kg	7 km	54,5 N
2	10 billion kg	2 billion kg	7 km	27,2 N
3	3 billion kg	6 billion kg	7 km	24,5 N
4	1 billion kg	2 billion kg	7 km	2,7 N
5	7 billion kg	4 billion kg	7 km	38,1 N

Based on the data in Table 1, it can be seen that the gravitational force between two objects is greatly influenced by the mass of each object. In an experiment with the same distance, namely 7 km, the gravitational force increases as the mass of one or both objects increases. For example, when the mass of object 1 is 5 billion kg and the mass of object 2 is 8 billion kg, the resulting gravitational force reaches 54.5 N, whereas when the mass of the objects is reduced to 1 billion kg and 2 billion kg, the gravitational force drops drastically to 2.7 N.

This phenomenon is in accordance with Newton's Law of Gravitation, which states that the gravitational force between two objects is proportional to the product of the masses of the two objects and inversely proportional to the square of the distance between them [18]. Since the distance in all experiments is kept constant, the change in force is solely due to the change in mass. Therefore, the greater the mass of one or both objects, the greater the gravitational attraction.

The simulation results also show that the relationship between mass and gravitational force is directly proportional. A doubling of mass tends to cause a nearly doubling of the gravitational force, depending on the total mass combination. Therefore, these results confirm experimentally through simulation that the gravitational force depends not only on distance but is primarily influenced by the masses of the interacting objects [19].

4.3. The Relationship Between Gravitational Force and Distance Between Mass Objects

The third experimental activity analyses the relationship between gravitational force and the distance between objects with mass, where gravitational force is the dependent variable, the distance between objects is the independent variable, and the mass of the objects is the control variable. The simulation data for the relationship between gravitational force and the distance between objects with mass are shown in Table 2.

Based on the data in Table 2, it can be seen that the gravitational force between two objects with the same mass, namely 5 billion kilograms, changes significantly when the distance between the two objects is changed.

When the distance between the two objects is only 3 km, the resulting gravitational force is 185.4 N, but when the distance is increased to 7 km, the gravitational force decreases to 34.1 N. This shows that the further the distance between two objects, the smaller the gravitational force that occurs between them.

Table 2. *Simulation data on the relationship between gravitational force and distance between objects with mass*

No	Mass		Distance	Gravitational Force
	Object 1	Object 2		
1	5 billion kg	5 billion kg	3 km	185,4 N
2	5 billion kg	5 billion kg	4 km	104,3 N
3	5 billion kg	5 billion kg	5 km	66,7 N
4	5 billion kg	5 billion kg	6 km	46,3 N
5	5 billion kg	5 billion kg	7 km	34,1 N

This phenomenon is in line with Newton's Law of Gravity, which states that the gravitational force is inversely proportional to the square of the distance between two objects [18]. This means that if the distance between two objects is doubled, the gravitational force will decrease to a quarter of its original value. With the masses of both objects remaining constant, the only factor affecting the magnitude of the gravitational force in this experiment is the distance between the objects.

The results of this simulation quantitatively demonstrate that distance has a significant impact on gravitational force. The greater the distance, the weaker the gravitational field experienced by each object. Therefore, this table reinforces the concept that gravitational force decreases sharply with increasing distance.

4.4. Conceptual Development Practice

The equation for universal gravitation is as in equation 1.

$$F = G\frac{m_1 m_2}{d^2} \quad (1)$$

where F is the attractive force between objects with masses m_1 and m_2 separated by a distance of d. G is the universal gravitational constant [20] By changing one variable in this equation, researchers can predict changes in the other variable. For example, we can see changes in the gravitational force if we know the change in the mass of the objects or the distance between them.

For example, if the mass of object 1 is made 2 times larger than the initial mass, then substitute the value $2m_1$ into m_1 in the equation 1, then Equation 2 will be obtained.

$$F_{final} = G\frac{2m_1 m_2}{d^2} = 2\left(G\frac{2m_1 m_2}{d^2}\right) = 2\,F_{initial} \quad (2)$$

The results show that the gravitational force is twice as large as the initial gravitational force. The mathematical relationship in Equation 2 can help students understand the concept of the relationship between physical variables. Students can understand that the gravitational force is directly proportional to the mass of the object. This experimental process trains students' ability to interpret mathematical symbols and operations in the context of real physics, not just calculating, but understanding the physical meaning of changes in variables. Thus, students learn that physics equations are not just formulas, but representations of cause-and-effect relationships in natural phenomena that can be explained quantitatively.

If the distance is made twice as large as the initial distance, then substitute the value of 2d into d in equation 1, then equation 3 will be obtained.

$$F_{final} = G\frac{m_1 m_2}{(2d)^2} = G\frac{m_1 m_2}{4d^2} = \frac{1}{4}\left(G\frac{m_1 m_2}{d^2}\right) = \frac{1}{4}F_{initial} \quad (3)$$

The results show that the gravitational force is only 1/4 of the initial gravitational force. The mathematical relationship in Equation 3 can help students understand the concept of the inverse square relationship between gravitational force and distance. This understanding strengthens students' ability to reason proportionally and think quantitatively, and recognizes that small changes in distance can result in large changes in force. Thus, students learn that mathematical operations represent real relationships between physical quantities, thereby enhancing their conceptual understanding.

5. Conclusion

Based on the results of the experiments and analyses conducted, it can be concluded that the magnitude of the gravitational force is influenced by the mass of the two objects and the distance between them. The greater the mass of one or both objects, the greater the gravitational force generated. Conversely, the further the distance between two objects, the smaller the gravitational force produced. The results of this experiment are in accordance with Newton's Law of Gravitation, which states that the gravitational force is directly proportional to the product of the masses of the two objects and inversely proportional to the square of the distance between the objects. In addition, the direction of the gravitational force on the two objects is always opposite but equal in magnitude, in accordance with Newton's Third Law of action and reaction. The digital experiment conducted ignores air resistance. Overall, this experiment proves conceptually that gravitational interactions can be explained and predicted mathematically through the universal equation of gravitation. The researcher suggests that future research focus on the effectiveness of using digital experiments in an effort to improve students' conceptual understanding and mathematical thinking skills on the concept of gravitational force.

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