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Reconstructing Galileo’s Inclined Plane Experiments: Problems of Time Measurements

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***Abstract* – In this paper, we describe the recreate Galileo’s experimental setup to explore the dynamics of motion along an inclined plane. We not only replicate the physical measurements of distance and velocity but also emphasize the critical role of accurate time measurement, as used by Galileo to decipher the laws governing natural motion. In addition to reproducing the experiment using instruments available in Galileo’s time, this article presents a comparative analysis of the motion using modern tools: a video analysis application (Tracker) and an audio analysis application (Audacity).**

I. INTRODUCTION

Galileo’s groundbreaking experiments forever changed our understanding of motion. Among his most influential explorations was the inclined plane experiment—a simple yet profound demonstration of the principles of acceleration. By allowing a ball to roll down a gently sloping surface, Galileo was able to slow down motion enough to measure time intervals with the ingenuity of early timekeeping techniques, such as water clocks and pendulum approximations. His careful observation and quantification revealed that the acceleration of objects under gravity was uniform, laying the foundation for classical mechanics.

In this paper, we describe the recreate Galileo’s experimental setup to explore the dynamics of motion along an inclined plane. We not only replicate the physical measurements of distance and velocity but also emphasize the critical role of accurate time measurement, as used by Galileo to decipher the laws governing natural motion. By bridging historical methodology with modern experimental practices, we aim to provide readers a hands-on understanding of the principles underlying acceleration. This approach invites us to appreciate both the experimental creativity of the past and its enduring relevance in today’s scientific inquiry.

Building on Galileo’s legacy, our discussion will delve into the geometric and kinematic aspects of motion while highlighting how precision in timing—whether with rudimentary instruments or modern digital devices—remains central to all scientific pursuits.

II. EXPERIMENT IN GALILEO’S BOOK

Galileo aimed to demonstrate that every object experiences the same free-fall acceleration, irrespective of its mass. Because free-falling objects accelerate too rapidly to be measured directly, he devised an ingenious method to effectively reduce gravitational acceleration: he employed an inclined plane with a very shallow angle. This approach enabled the ball, during its descent, to attain a speed that could be measured with precision.

To overcome this difficulty, Galileo conceived the ingenious idea of using an inclined plane. By rolling a ball down a gently sloped surface, the effective gravitational acceleration was reduced, thereby slowing the motion. This modification allowed the duration of the ball’s descent to be extended to a time scale more suitable for measurement, rendering the phenomenon accessible for quantitative analysis. Despite the limitations of his timekeeping instruments, Galileo’s experimental innovation laid the groundwork for the systematic study of dynamics, ultimately paving the way for the development of more precise timing methods in later centuries.

Galileo explained his well-known inclined-plane experiment as follows [1-3]:

"A piece of wooden moulding or scantling, about 12 cubits long, half a cubit wide, and three finger-breadths thick, was taken; on its edge was cut a channel a little more than one finger in breadth; having made this groove very straight, smooth, and polished, and having lined it with parchment, also as smooth and polished as possible, we rolled along it a hard, smooth, and very round bronze ball. Having placed this board in a sloping position, by lifting one end some one or two cubits above the other, we rolled the ball, as I was just saying, along the channel, noting, in a manner presently to be described the time required to make the descent. We repeated this experiment more than once in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse-beat. Having performed this operation and having assured ourselves of its reliability, we now rolled the ball only one-quarter the length of the channel; and having measured the time of its descent, we found it precisely one-half' of the former. Next we tried other distances, comparing the time for the whole length with that for the half, or with that for two-thirds, or three-fourths, or indeed for any fraction; in such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times, and this was true for all inclinations of the plane, i.e., of the channel; along which we rolled the ball. We also observed that the times of descent, for various inclinations of the plane, bore to one another precisely that ratio which, as we shall see later, the Author had predicted and demonstrated for them. For the measurement of time, we employed a large vessel of water placed in an elevated position; to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent, whether for the whole length of the channel or for a part of its length; the water thus collected was weighed, after each descent, on a very accurate balance; the differences and ratios of these weights gave us the differences and ratios of the times, and this with such accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results."

Galileo provides a detailed description of one of the most celebrated experiments in the history of science, which is featured in most physics' textbooks. Galileo's account is simple and detailed enough to permit replication of the experiment without significant difficulty. Interestingly, it is reported that the experiment was repeated multiple times. In our view, it is reasonable to hypothesize that some form of averaging was applied and that, although not formalized as it is today, an early notion of the standard deviation of the experimental data may have been considered. The experiment is also depicted in a fresco by Giuseppe Bezzuoli (1784–1855), located in the Tribuna di Galileo in Florence, Italy (see Figure 1).

Fig. 1. Galileo Galilei (1564–1642) demonstrating the law of gravity in the presence of Giovanni de' Medici (1543–1562), fresco by Giuseppe Bezzuoli (1784–1855), Tribuna di Galileo (Florence-Italy).

Doubts persist among historians of science as to whether the experiment was ever actually conducted, at least in the manner described by Galileo [4-6]. In particular, it is widely doubted whether Galileo possessed the ability to measure time with an accuracy of one-tenth of a second. Galileo, for measuring time, refers to the heartbeat and the water clock. For most scientists, these methods are incapable of measuring time with precision on the order of a tenth of a second; we add without repeated measurements and without statistical analysis of the spectral data.

Regardless of the method Galileo used to measure time, his background from a family of musicians may have led him to employ rhythmic patterns to determine when two very short time intervals were equal—a possible explanation for the presence of "bells" on his inclinometer. By adjusting the position of these bells, he could identify points at which sounds occurred within equal time intervals [7].

The motion of a body down an inclined plane encompasses various aspects, including measurement techniques, accuracy, the communication of experimental results, and the inductive reasoning underlying the experiment. These elements make it a crucial topic for teaching physical measurements. Additionally, efforts to reconstruct Galileo's experiments, particularly those involving the inclined plane, aim to enhance our understanding of historiographical and epistemological issues [8-10].

In this paper, we aim to recreate Galileo's experiment involving the fall of a heavy object on an inclined plane. We will attempt to reconstruct the experiment based on the description provided by Galileo himself [1-3]. Specifically, we will focus on the feasibility of accurately measuring time to the nearest tenth of a second using a water clock similar to the one Galileo is believed to have used.

III. GALILEO'S INCLINED PLANE

The study of the inclined plane in university courses fosters a mindset that values systematic inquiry, precision in measurement, and the constant evolution of scientific knowledge. It prepares future scientists and engineers to approach more advanced topics with a robust foundation in both experimental and theoretical physics [11].

When a sphere rolls down an inclined plane without slipping, its motion is a beautifully coordinated interplay between translation and rotation. Gravity propels the sphere downwards, but rather than simply sliding, static friction at the point of contact ensures that the sphere rotates as it moves. This friction is crucial because it provides the necessary torque for rotation without allowing the sphere to skid. The gravitational force is resolved into two components: one perpendicular to the plane, which is balanced by the normal force, and one parallel to the plane, which drives the motion downwards. If we consider a solid sphere of radius R and moment of inertia $I = (2/5)mR^2$ that rolls without slipping along an inclined plane with an angle of inclination θ, its acceleration is:

$$a = (5/7) \cdot g \cdot \sin\theta \, . \quad (1)$$

In other words, the sphere descends along the inclined plane with constant acceleration.

This allows the use of a sphere that rolls without slipping to study uniformly accelerated motion; experimentally it is not feasible with the “material point”; it is a mathematical abstraction. Generally, in educational laboratories, "sophisticated" inclined planes are used to verify the law of uniformly accelerated motion and that acceleration is independent of the mass of the object.

That is, demonstrate that the space travelled is squared by the time:

$$\Delta s \propto t^2. \qquad (1)$$

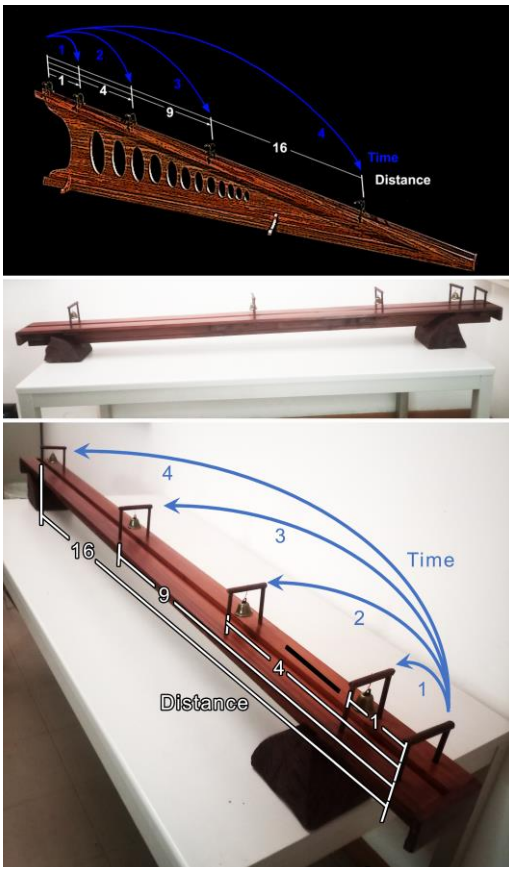

Fig. 2. Reconstruction of Galileo's inclined plane.

In 1604, Galileo conducted his famous inclined plane experiment. Through this experiment, he provided empirical support for Eq. 1. By using an inclined plane, Galileo effectively "slowed down" the motion of falling bodies, allowing for more precise observation and measurement. He marked reference points along the plane at distances corresponding to the sequence of odd numbers: 1, 3, 5, 7, 9, and so on. This sequence forms an arithmetic progression in which each successive spatial interval increases by two units. By showing that these increasingly larger intervals were traversed in equal time intervals, Galileo demonstrated that the motion exhibited uniform acceleration. In doing so, he laid both the conceptual and experimental groundwork for what would later be formalized as the law of falling bodies—namely, that the distance traveled under constant acceleration is proportional to the square of the elapsed time.

We reconstructed Galileo's inclined plane by selecting spatial intervals of 11 cm, 33 cm, 55 cm, and 77 cm, resulting in a total distance of 176 cm. The constructed inclined plane is shown in Figure 2.

In his inclined plane experiment, Galileo employed his musical expertise to measure time, relying on the rhythmic sound of bells. By placing bells at increasing distances along the plane, he could identify equal time intervals based on the regularity of their sound. Lacking Galileo’s musical acuity, we verified the timing by recording the bell sounds and analyzing the resulting audio waveform using Audacity software [12]. Figure 3 shows the audio track obtained from our replication of the experiment using an inclined plane.

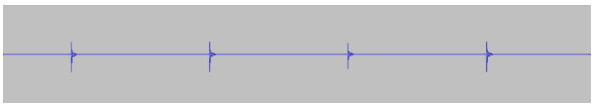

Fig. 3. Audio waveform recorded during the inclined plane experiment, showing sound events occurring at regular time intervals.

However, in Galileo’s time, using sound rhythms to measure equal time intervals was not an objective or standardized method.

IV. GALILEO'S WATER CLOCK TIME MEASUREMENT

In Galileo's time, objectively measuring time was a very complex thing; there were no clocks, much less chronometers. Galileo was faced with the challenge of accurately measuring very short intervals of time, particularly those involved in the study of accelerated motion. His winning idea was to use an instrument that was extremely precise and accurate at the time, the balance, to measure time. In Galileo’s time, it was assumed that the balance could measure masses with an accuracy of up to half a gram. To evaluate this assumption, we employed the double-pan balance depicted in Fig. 4. Using our balance and the double-weighing technique, we were able to achieve measurements with an accuracy greater than 0.3 g.

In his inclined plane experiments, Galileo, rather than relying on imprecise time-measuring methods, utilized the constant and continuous flow of water. He allowed water to flow from a calibrated container through a small orifice and measured the flow rate using a precision balance. With this technique Galileo claimed to be able to obtain time measurements with an accuracy of one tenth of a second.

This apparatus was not simply a device for recording time; it embodied Galileo's broader commitment to experimental precision and innovation. His water hourglass allowed him to transform rapid, transitory phenomena, such as the motion of a ball rolling down an inclined plane, into quantifiable data. In doing so, he laid the foundation for the rigorous, measurement-based approach that is the hallmark of modern science.

Fig. 4. Balance used to assess the accuracy of mass measurements achievable in Galileo's time.

Galileo's water clock functioned similarly to a stopwatch. To start the timing process, he allowed water to flow into a container; to stop it, he halted the water flow; and to reset the device, he emptied the container. By weighing the water collected, he could correlate the water mass with time intervals. For example, if the container held twice as much water by weight, he inferred that twice as much time had elapsed.

The accuracy of the measurements primarily depended on the manual procedures used to start and stop the clock, which inherently introduced uncertainty.

V. EXPERIMENTAL APPARATUS

To assess Galileo's capability to measure time with an accuracy of 0.1 seconds, we constructed a system analogous to the one described by Galileo [1-3].

To replicate the time measurements made by Galileo using the water clock, we not only recreated the experimental apparatus but also implemented a data collection system involving two "independent" operators. The experimental setup consists of a glass barrel equipped with a flow-regulating tap, graduated cylinders for collecting water, and a balance for measuring mass. The objective is to verify the proportionality between the mass of collected water and the time interval. Assuming an approximately constant water flow, the mass of water dm passing through a small orifice is proportional to the elapsed time dt, according to the relation:

$$dm = \rho \cdot Q \cdot dt. \quad (2)$$

where Q is the flow rate and ρ is the density of the liquid, which in the case of water is equal to 1 g/cm^3.

This approach allows the use of the collected water mass as an indirect but reliable measure of time, due to the constancy of the flow. The barrel was initially filled completely, after which the lower tap was opened to produce a continuous and approximately constant stream of water. To maintain a constant water level inside the barrel and ensure flow stability, the barrel was placed beneath a second tap that continuously feeds the reservoir. The constancy of the flow is in fact closely related to the water level in the barrel, according to Torricelli's law, which states that the outflow speed v of a liquid through an orifice is given by:

$$v = \sqrt{2gh}. \quad (3)$$

where g is the acceleration due to gravity and h is the height of the liquid column above the orifice. Consequently, keeping the height h constant ensures a steady outflow rate. A few seconds after opening the tap, the system reaches a steady-state regime, in which the outflow and inflow rates of water balance each other, maintaining a constant water level. Under these conditions, the flow rate can be considered time-invariant, allowing for an indirect yet precise measurement of time through the collected water mass. Fig. 5 shows the implemented water clock.

Fig. 5. Experimental hydraulic setup used for measuring the collected water mass over time.

Water was collected by two different operators in separate trials, using a graduated cylinder for time intervals of 5, 10, and 15 seconds, measured with a digital stopwatch. For each interval, 50 independent measurements were performed. The collected water was subsequently weighed using a precision balance, and for each time interval, the mean of the measured masses and the standard deviation were calculated. The results are reported in Table 1.

Table 1. Mean values and standard deviations of collected water masses for different time intervals.

Time [s]	Mass [g]	σ (%)	$\sigma/\sqrt{N}$ (%)
2.5	16.5	5.4	0.8
4.9	31.1	3.6	0.5
10.0	56.5	1.9	0.3
14.9	93.7	1.7	0,2

The data obtained show a linear dependence between the collected water mass and time, of the form:

$$v = \sqrt{2gh}\,. \tag{4}$$

The data obtained show a linear dependence between the collected water mass and time, of the form:

$$m(t) = \dot{m} \cdot t\,, \tag{5}$$

where $\dot{m}$ is the mass flow rate, measured in g/s. The resulting regression line has the form;

$$m(t) = \alpha \cdot t + \beta, \tag{6}$$

where α represents the mass flow rate and β is a constant related to the initial conditions. The coefficient of determination, $R^2 = 0.99$, confirms the goodness of fit and the validity of the model. Fig. 6 shows the graph of collected mass as a function of time, with the linear regression line superimposed.

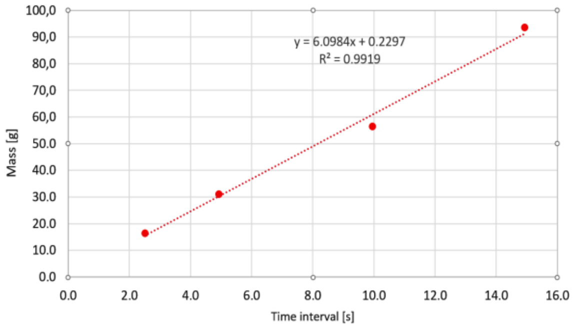

Fig. 6. Linear correlation between collected water mass and elapsed time. The regression line exhibits a coefficient of determination $R^2 = 0.99$.

In a second set of measurements, the 10-second interval was repeated while intentionally varying the outflow rate of the tap, in order to assess the influence of the flow rate on the proportionality between collected mass and time. The standard deviation was determined for each group of measurements, ranging between 0.2% and 0.3% relative to the mean value, confirming the high repeatability and precision of the experimental system. The results obtained are reported in Table 2. The collected data indicate that the adopted method provides sufficient precision for the experimental measurement of time. The measurements showed high repeatability, with a relative uncertainty between 0.2% and 0.3%.

Table 2. Measurements at 10-second intervals with varied flow rates.

Flow rate	Mass [g]	σ (%)	$\sigma/\sqrt{N}$ (%)
1	27.7	1.8	0.2
2	51.8	1.7	0.2
3	56.5	1.9	0.3
4	153.6	1.9	0.3

The flow rate remained constant within the limits of experimental uncertainties, demonstrating that the constructed hydraulic system was well calibrated and maintained near-ideal conditions. These results confirm the reliability of the method for use in subsequent experiments, particularly to demonstrate the quadratic relationship between displacement and time during the descent of an object along an inclined plane, according to the uniformly accelerated motion model.

VI. VERIFICATION OF $\Delta s \propto t^2$ BY VIDEO ANALYSIS

For educational purposes, our inclined plane can be used to experimentally study the dynamics of motion along an incline by analyzing video recordings of spheres rolling without slipping. For this purpose, we used the Tracker software [13]. Tracker is a software tool used to monitor the motion of an object. It is specifically designed for educational applications in physics, particularly in the areas of kinematics and dynamics [14]. In particular, Tracker is a video analysis and modeling tool built on the Open Source Physics (OSP) Java framework.

By capturing videos of spheres of varying sizes and masses as they descend, it is possible, for educational purposes, to verify whether their motion along the inclined plane conforms to Galileo's laws. Figure 7 presents an example of a space-time graph obtained using Tracker software. The resulting equation of motion is:

$$s(t) = \frac{5}{7} \cdot g \cdot \sin{(0{,}81°)} \tag{7}$$

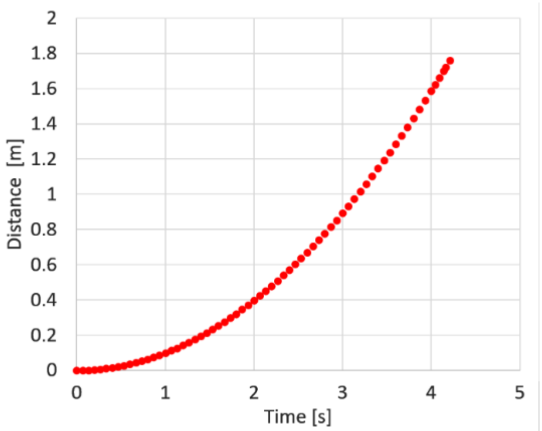

Fig. 7. Linear correlation between collected water mass and elapsed time. The regression line exhibits a coefficient of determination $R^2 = 0.99$.

VII. CONCLUSION

We constructed an inclined plane similar to the one used by Galileo to investigate the equation of motion for bodies under constant acceleration. To measure time, we employed a water clock and a two-pan balance. All tests indicated that Galileo was capable of measuring time intervals with an accuracy of approximately one-tenth of a second. However, we observed that such accuracy can only be achieved through repeated measurements and statistical analysis of the data. Therefore, although the concept had not yet been formalized in Galileo's time, it is likely that he applied a rudimentary form of what we now refer to as standard deviation to assess the consistency of his experimental results.

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