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Comparing The Acceleration Due to Gravity using Traditional Method Versus Tracker Video Analysis: Experiments in A Simple Pendulum

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Abstract

This study used a simple pendulum to compare the accuracy and precision of the traditional method and Tracker video analysis in determining the acceleration due to gravity (g). The experiment involved two groups of participants: science teachers in the Philippines, who used the traditional method, and high school students in Uzbekistan, who employed video analysis. Both groups conducted multiple trials by measuring the period of the swinging pendulum. Data were collected by manually recording the pendulum's motion with a stopwatch or through video analysis software, and the resulting periods were used to calculate *g*. The data were analyzed by comparing the measured values of *g* from both methods and assessing the precision and accuracy of each. The results indicated that the traditional method provided more accurate g measurements than the video analysis method, though both methods yielded results close to the accepted average value of 9.81 ms^{-2}. The study suggests that both methods are feasible, but user experience and familiarity with the tools significantly impact the results.

Keywords: comparative experiment, physics education, physics teaching, simple pendulum, tracker video analysis

INTRODUCTION

Gravity is a fundamental force in the universe that governs how objects interact with each other. Determining the acceleration due to gravity is crucial in physics as it helps us understand the physical world and develop new technologies. Measuring the acceleration due to gravity has been a subject of interest for scientists since Galileo's time. Several methods have been developed over the years to measure the acceleration due to gravity, including the traditional method of calculating the period of a simple pendulum and video analysis. The Institute of Physics of the United Kingdom confirms that a computed *g* value of around 10 ms^{-1} is acceptable. This indicates that when an object is in free fall, its velocity increases by 9.8 meters per second for every second it falls. (Pacala & Pili, 2023).

The traditional method of measuring the acceleration due to gravity involves using a simple pendulum consisting of a weight suspended from a fixed point by a string. (Parks & Faller, 2014). The pendulum's period is measured by timing how long the weight will swing back and forth through its arc. The relationship between the pendulum's period and the string's length can be used to calculate the acceleration due to gravity. (Kuhn & Vogt, 2012). This method has been used for centuries to determine the acceleration due to gravity.

Video analysis is a more modern method of measuring the acceleration due to gravity. It involves recording the motion of an object using a video camera and analyzing the data using software. Video analysis provides more accurate measurements than the traditional method, as it eliminates human error in measuring the pendulum's period. (Humeniuk, Bezvesilna Bogdanovskyi, & Yanchuk, 2020). Video analysis can also provide additional data, such as velocity and displacement, which can be used to calculate the acceleration due to gravity.

Several studies have compared the traditional method of measuring the acceleration due to gravity with video analysis. One study conducted by Suwanpayak et al. (2018) The traditional method of using a physical pendulum is better than Atwood's machine and the simple pendulum for determining the acceleration due to gravity. Very few research studies have been conducted and performed to compare acceleration due to gravity using two or more methods using a simple pendulum. Hence, this research paper adds to this gray area.

The importance of determining the acceleration due to gravity extends beyond physics. Measuring the acceleration due to gravity is essential in various fields, including geology, satellite navigation, and aerospace engineering. For example, Humeniuk et al. (2020) explained that the acceleration due to gravity is used to calculate a satellite's altitude and monitor changes in the Earth's gravitational field. Measuring acceleration due to gravity is important for students because it helps them to understand and apply fundamental principles of physics, such as Newton's laws of motion and gravitational force (Sanjoy Mahajan, 2020). It also gives them a practical understanding of how gravity affects objects on Earth (Brown & Bryce, 2013).

The traditional method of measuring the acceleration due to gravity has limitations, including human error in timing the pendulum's period and constraints on measurement precision. Video analysis enhances the traditional method by eliminating human error and providing additional data. However, video analysis necessitates more advanced technology and software than the traditional method, making it less accessible to some teachers and students.

Another important factor when comparing the traditional method with video analysis is the cost involved. The traditional method only requires a simple pendulum, a stopwatch, and a ruler, making it relatively inexpensive. In contrast, video analysis requires a video camera, computer, and analysis software, which can be costly.

This experiment compares the traditional method of measuring the acceleration due to gravity with video analysis in different countries, specifically in the Philippines and Uzbekistan. Measuring g in different countries highlights Earth's slight gravitational variations due to latitude, altitude, and local factors. This study compares traditional methods and Tracker video analysis to explore their accuracy and practical applications in detecting these variations. This paper measured the period of a simple pendulum using both methods and compared the results to determine which method provides more accurate measurements. This experiment contributed to the existing knowledge of the accuracy and limitations of each method and provided insights into the use of these methods in research and industry—theoretical *Background***.** The motion of a simple pendulum is one example of simple harmonic motion. In simple harmonic motion, the restoring force on an object is proportional to its displacement from its equilibrium position (Alrasheed, 2019). For a simple pendulum, this force is due to the weight of the bob pulling it downward and the tension in the string pulling it upward.

Through mathematical analysis, it can be shown that the period of a simple pendulum (the time it takes for one complete oscillation) is directly proportional to the square root of its length and inversely proportional to the square root of the acceleration due to gravity.

By measuring the time it takes for a simple pendulum to complete one full swing and knowing the length of the pendulum, we can use this relationship to calculate the acceleration due to gravity (g). This can be done using the equation:

$$T = 2\pi\sqrt{\frac{L}{g}} \quad (1)$$

and finding the equation for g led to

$$g = (4\pi^2 L) \div T^2 \quad (2)$$

where g is the acceleration due to gravity, L is the pendulum's length, and T is the period of one complete oscillation.

If the length versus period squared is plotted, the gradient (G) of the graph is L/T^2. By using this gradient of the line of best fit, we can calculate the g by

$$g = 4\pi^2 G \quad (3)$$

Therefore, by measuring the period and length of the pendulum, we can easily calculate the acceleration due to gravity.

METHOD

Research Design: This research is a comparative experimental method used to figure out the acceleration of gravity using a simple pendulum. A comparative experimental method is a particular kind of research study that involves selecting a group of participants and assigning them to various situations for a specific period, then analyzing the variations between them. (Wang, Lu, Liu, Zhu, & Liu, 2023). The research compares two experimental methods – the traditional approach and video analysis. This comparison offers a valuable perspective on the advantages and disadvantages of each method, thereby helping to develop a more complete understanding of experimental physics.

The research involved comparing two methods and analyzing and interpreting the data obtained from both methods. The participants calculated the acceleration of gravity using the results from each approach to assess the reliability and accuracy of the measurements. The traditional and video analysis methods showed some differences, which led to discussions on potential sources of error and the importance of refining experimental techniques.

Materials: This experiment used three retort stands, a 55-gram load, rug yarn, a boss, a clamped, two protractors, a mobile phone camera from an iPhone 13, a laptop with tracker video analysis, and two stopwatches. Figure 1 shows the setup for the traditional method of measuring the acceleration due to gravity in a pendulum. Figure 2 shows the setup for the video analysis.

Figure 1. The setup is for a traditional method of measuring acceleration due to gravity.

A 60 cm retort stand was set up. A boss was connected to the retort stand, and the C-clamp was attached to the boss. The 38 cm rug yarn was connected vertically from the C-clamp. Finally, the 55-gram load was attached to the rug yarn.

The same setup was used as seen in Figure 2; however, another retort stood with the boss, and a clamping assembly was assembled. The iPhone 13 was clamped facing with a wide view of the opposite side. The two stands were 1.5 meters apart. The Tracker Video Analysis and Modelling Tool was downloaded from the internet.

Participants: Two groups of students conducted this experiment, one using the conventional way and one using the tracker. The traditional method was performed at Samar State University, Philippines; the other was held at the Presidential School in Qarshi, Uzbekistan. Traditionally, the period was measured using a stopwatch. A group of prospective science teachers enrolled in a master's program and participating in a CPD training measured acceleration due to gravity using the traditional method. Meanwhile, a group of high school students, facilitated by the researcher, measured g using the tracker video analysis. To ensure fairness, both groups received comparable training and facilitation on each method before experimenting. Both groups were given a worksheet to experiment with and were facilitated by the researchers. In this experiment, the level of educational outcomes does not matter because the measurement of g is the study's objective, and data collection focused on measuring the value of *g* following the same procedures outlined by the researcher.

Experimental Procedures: The length of the rug yarn was the independent variable of this experiment, while the dependent variable was the period. Other variables, such as the area and type of yarn, the environmental conditions, the mass of the load, and the angle of oscillation, remained constant throughout the experiment.

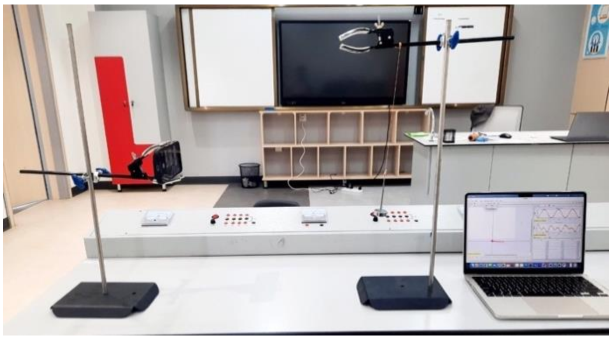

Figure 2. The setup for measuring the acceleration due to gravity using Tracker Video Analysis and Modelling.

The length of the yarn was measured using a meter ruler. The mass of the load was measured using a mass balance. The angle of oscillation was measured using a protractor, and this angle was maintained at 15 degrees throughout the entire experiment to maintain simple harmonic oscillation.

The period of a simple pendulum was measured as the time it takes for the pendulum to complete one full swing or oscillation. Typically, this is calculated from the point of maximum displacement on one side to the same point on the opposite side. There were six measurements of the period, and so there were also six different lengths of the rug yarn.

The Tracker software generated a time displacement-time graph, as shown in Figure 3. To determine the period from a displacement-time graph of a pendulum, it was necessary to identify one complete oscillation of the pendulum on the graph. Once this was done, the time it took for the pendulum to complete one oscillation was measured by calculating the time interval between two consecutive points on the graph where the pendulum was at the same position and moving in the same direction. This time interval represented the time for one complete oscillation, equal to the pendulum period. Thus, for Figure 3, the period can be calculated by subtracting the period of the amplitude, which equals 1.29 seconds, from the period of the second amplitude. A similar approach was followed to determine the period of other measurements. This group of students had their rug yarn cut into six different lengths corresponding to the six measurements of the period. All of these vibrations were captured on an iPhone 13's high-speed camera.

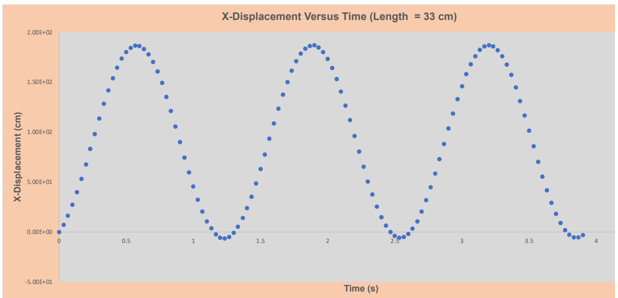

Figure 3. The period of this oscillation is 1.29s

After gathering all the recordings, the videos were analyzed using Tracker Video Analysis and Modelling Software, a copyrighted software created by Brown, Christian, and Hanson (2023). This software is an open-source video analysis tool that allows users to track objects in videos, examine their motion, and produce dynamic models (Kanga, Astro, & Ika, 2021).

The tracker was used to upload a video, which was rotated 180 degrees based on its alignment in an experiment. The boss's clamped length was used to input a calibration stick; in this case, the boss was 11.5 cm long. Moreover, the coordinate axis was shifted towards the load or mass, and the purple crossed line represents this axis. At the same time, the calibration stick is indicated as the blue line parallel to the boss, as shown in Figure 4. The center of mass was selected by clicking on the tracked button, and the auto-tracking began when the shift plus command key combination was pressed on a MacBook. The auto tracker was paused after collecting the necessary data.

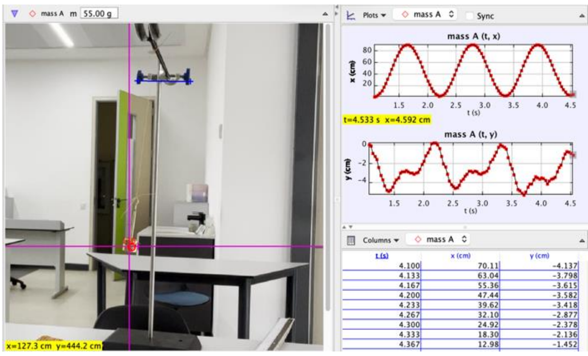

Figure 4. The Tracker Video Analysis and Modelling Software has an interface with a graph showing the x-displacement over time created by the software on the right-hand side.

During the implementation, each group conducted the pendulum experiment, measured the length of the pendulum string, recorded the swing time, and calculated *g* using Equation 2. The traditional group used stopwatches to time the period manually, while the tracker group used video frames. Then, each group submitted their output to their teachers.

For data analysis, students' data were compared to the average value of *g*, 9.81 ms^{-2}. The percent error was calculated for each group's data. This discrepancy was discussed with the respective students to analyze potential data sources and enhance students' understanding of sources of error and the calculation of data uncertainty.

RESULT AND DISCUSSION

The results of this experiment were obtained from two groups of practicum students. One uses traditional data collection and measurement, and the other uses tracker video analysis. Each group was able to compute by following the worksheet and receiving facilitation from the teachers.

Traditional Method: The group consisted of five students, each given a stopwatch. Another pair of students was tasked with oscillating the load at a 15-degree angle. The average period from these five students was taken to reduce the random error. They did this six times at various lengths of yarn.

The period of the different lengths of yarn in a pendulum using the traditional method. The data gathered by the first group of students follows the theory in Equation 1. The length is proportional to the period. Table 1 also showcased the period squared because the plot was length versus period. These data were plotted using Microsoft Excel. The students generated a scatter plot diagram and used the line of best fit, as shown in Figure 5.

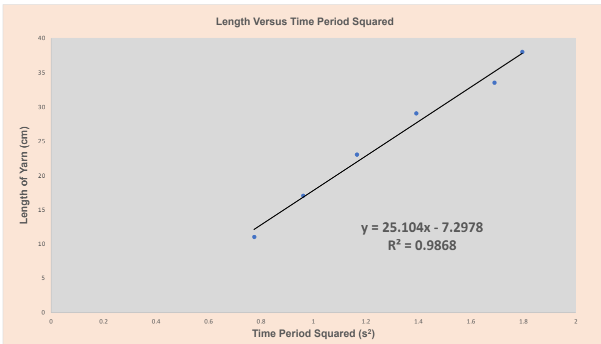

Figure 5. The data formed a straight line of best fit with a gradient of 25.104 cms-2.

The line gradient in Figure 5 is 25.104 cms^{-2} or 0.251 ms^{-2}. To evaluate the g, the value of this gradient was substituted in equation 3 to find the acceleration value due to gravity. The acceleration due to gravity is 9.91 ms^{-2}, which is very close to the average value of *g*, which is 9.81 ms^{-2}. The percent error was computed to be 1.02 percent. Also, SensorsOne, an online gravity calculator, reports g in Catbalogan City, Samar to be 9.87 ms^{-2}. The article by Dessouki (2022) used traditional apparatus (e.g., stopwatch, metal sphere) to measure the value of *g* in a simple pendulum. He discovered that its value is 10.5 ms^{-2} with a 7.03% error. Azahra et al. (2024) have conducted a study using a mathematical pendulum to find the value of *g*. They discovered that *g* in there is an average of 8.81 ms^{-2}.

Using Tracker Video Analysis: Another group of students was tasked to conduct the same experiment using tracker video analysis. They captured six different oscillations and uploaded them to the tracker software. The period was measured by generating a graph, as shown in Figure 3.

Equation 3 suggests that the data for length and period must increase. It indicates a linear relationship between length and period where the pendulum's length increases with the period, but not at a proportional rate. Table 2 displays this slower increase in the period as the pendulum length increases. On the other hand, observing the period squared versus time is directly proportional to the pendulum's length. As the pendulum's length increases, so does the period squared, creating a direct proportion.

Table 1. The period of Varying Lengths of the Yarn in a Pendulum using Tracker Video Analysis

Length (cm)	Period (s)	Period Squared (s^2)
33.2	1.29	1.67
29.5	1.21	1.46
24.5	1.13	1.28
20.0	1.05	1.1
15.5	0.97	0.94
10.5	0.87	0.76

The data were again plotted in Microsoft Excel. The plot in Figure 6 indicates a positive linear relationship between the length of the pendulum wire and the period squared. This linear relationship has a slope equal to g/4π2 or the equation 3, where *g* represents the local acceleration due to gravity. A straight line of best fit can be observed, indicating that the theory under equation 1 is correct. This conclusion implies that the correct data has been obtained from the experiment.

The line of best fit with a gradient of 25.431 cms-2 or 0.25431 ms-2 is displayed in Figure 6. This particular gradient is used in Equation 3 to determine the acceleration due to gravity. The outcome of this calculation is a value "g" equal to 1003 cms-2 or 10.03 ms-2. This value is relatively close to the average value of "g," which is 9.81 ms-2. Using the formula for percent error, it is found that the difference between the experimental value and the accepted value of "g" is only 2.24%. The value of g in Uzbekistan is almost the same as that computed by Pacala & Pili (2023), which has a value of 9.78 ms-2. The calculated value of g is practically similar to that of Suwanpayak et al. (2018), who recorded 9.55 ms-2 and 9.64 ms-2 with a percent error of 1.41%. In addition, the study by Castellanos et al. (2020) found that using a physical pendulum would increase the value of g by 5% because of faulty and uncalibrated instruments. Martin et al. (2020) found a value for g with a 19.7% error, but their procedure was not as rigorous as the current experiment. The percentage of error in Wabeto's experiment in 2018, which utilized tools such as Adobe Photoshop and MATLAB programming algorithms to track a pendulum's movement, was lower compared to the experiment conducted by Fatmala et al. (2019), who used a phyphox mobile application. Wabeto's experiment calculated g with a value of 9.79 ms^{-2} and had a percent error of 0.20%.

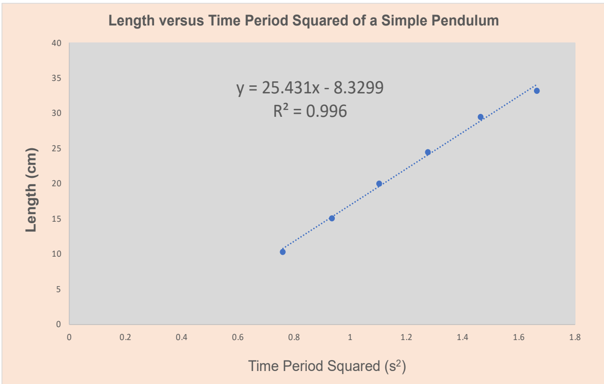

Figure 6. The Tracker Video Analysis data showed a straight line of best fit.

Uncertainty on the Computed g. For the traditional method of measuring acceleration due to gravity in a simple pendulum, the uncertainty of a meter ruler is 0.1cm (Davis, 2015). The uncertainty of a stopwatch is 0.1s (Pan & Zhang, 2023). The uncertainty in *g* (Δg) can be calculated using the error propagation on division and power. Using equation 2, the Δg can be calculated using

$$\Delta g = g\left(\frac{\Delta L}{L} + 2\frac{\Delta T}{T}\right)$$

where Δg is the absolute uncertainty in *g*, ΔL is the fractional uncertainty on the length, and ΔT is the fractional uncertainty the periodiod.

Table 2. The error propagation data sheet for the conventional method of uncertainty in g.

L(m)	ΔL(m)	T(s)	ΔT(s)	Δg(ms^{-2})
0.38	0.0026	1.34	0.075	1.5
0.335	0.0030	1.3	0.077	1.6
0.29	0.0034	1.18	0.085	1.7
0.23	0.0043	1.08	0.093	1.9
0.17	0.0059	0.98	0.102	2.1
0.11	0.0091	0.88	0.114	2.3
Average Absolute Uncertainty in g				1.8

Therefore, the final value of the acceleration due to gravity using the traditional method is (9.9 ± 1.8) ms^{-2}. In Uzbekistan, SensorsOne has determined that the accepted value of g is 9.80 ms^{-2}. To use this SensorsOne calculator, the user must input the latitude and elevation of the location where the experiment is being conducted.

Moreover, the video analysis's uncertainty regarding the period relied on related literature. Martin et al. (2020) stated that the uncertainty was 0.3 ms^{-2}, while Anni (2021) reported it as 0.08 ms^{-2}. An average of the uncertainties from these sources was taken to determine the uncertainty for this experiment on the period, resulting in an uncertainty of 0.3s.

Table 3 shows that the average uncertainty of *g* using the tracker video analysis is ±0.9 ms^{-2}. Therefore, this paper reported that the acceleration due to gravity using video analysis is (10.0 ± 0.9) ms^{-2}.

This experiment was successful for the students. They have calculated the acceleration due to gravity with values very near the average. The traditional method has obtained a more accurate g than the tracker video analysis. However, based on conversations with the groups, they were more fascinated and hooked on video analysis. This idea is supported by Hockicko (2014), who cited that video analysis is a sound substitute for conventional course-related activities in fundamental physics that are educational, inspiring, and reasonably priced. In addition, Vera et al. (2013) claimed that using video analysis as an instructional medium can significantly enhance students' understanding and retention.

Table 3. The error propagation data sheet for the Video Analysis Method of uncertainty in g.

T(s)	ΔT(s)	L(m)	△L(m)	Δg(ms^{-2})
1.29	0.0233	0.332	0.00301	0.453259
1.21	0.0248	0.295	0.00339	0.526407
1.13	0.0265	0.245	0.00408	0.637464
1.05	0.0286	0.2	0.00500	0.797146
0.967	0.0310	0.155	0.00645	1.060459
0.872	0.0344	0.105	0.00952	1.700744
Average Uncertainty in g				0.86258

The traditional method's result was more accurate than the tracker video analysis. High school students reported that while they are potentially familiar with the software, they still need to gain experience to optimize its use fully or troubleshoot issues that arise during the analysis, leading to less accurate results. Student A clarified, *"I believe we need more experience dealing with the tracker to gather accurate data."* This is supported by Student C, *"We were careful and followed the worksheet by our teacher; anyway, our value is near the average g."*

Meanwhile, prospective science teachers, who likely have extensive experience with manual measurements and traditional experimental techniques, can execute the method with high precision and consistency. These teachers reported that the ease of use of the apparatus contributed to the success. Propective teacher D suggests, *"The* *experiment is easy to follow, although it was my first time conducting it."* A study by Kittiravechote and Sujarittham (2021) found no significant difference between the value of *g* obtained by experts and novices in Thailand. Both groups used Phyphox as an intervention. The literature (e.g., Kittiravechote & Sujarittham, 2021) often involves participants with significant training in video analysis tools, while in this study, the high school students had limited exposure to troubleshooting software challenges, such as calibration and noise reduction, which likely affected their results. Finally, Traditional methods involve straightforward data collection, minimizing errors during measurement and calculation. On the other hand, video analysis requires precise digitization and frame selection, which, if not optimized, can introduce systematic errors, leading to discrepancies. The experiment highlighted the advantages and disadvantages of traditional and modern methods, highlighting their complementary nature.

CONCLUSION

This study aims to compare the traditional method of measuring the acceleration due to gravity with video analysis in different countries, specifically in the Philippines and Uzbekistan. The final value of the acceleration due to gravity using the traditional method is (9.9 ± 1.8) ms^{-2}. This paper reported that the acceleration due to gravity using video analysis is (10.0 ± 0.9) ms^{-2}. Both groups measured g near the accepted value, demonstrating that despite differences in accuracy and precision, both methods can reasonably approximate Earth's gravitational acceleration. This aim is achieved, and this paper concludes that both methods can calculate the acceleration due to gravity with a minimal percentage error. Both methods have their sources of error, and reducing these errors is the main point of experience for the students and their teacher because all experiments could have their uncertainties and mistakes. Spotting these is vital to come up with more accurate data. As the author observed the students, the flaws in this experiment were the technical aspects of using the tracker video analysis. The students incorrectly set the calibration stick and calculated the period based on the displacement-time graph due to errors in the minor decimal points. Indeed, the tracker video analysis requires more practice to perfect since some keys and pins must be considered. The use of the traditional method was also linked to more errors, most especially random errors, due to the reaction time of the stopwatch. The teachers could adapt this experiment and learn from its defects. They could use longer yarn and longer stands because it was observed that longer wire has lower uncertainty on g. They could also use more data points, which is more than six values. They could try conducting this experiment outside or in the field to check the effect of air resistance on acceleration due to gravity.

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