Research Question: What is the acceleration[ms^-2] due to gravitational force measured for a plastic ball during free fall dropping from a height of 1.00m during the time interval of 0.00s to 0.40s.

Hypothesis:

It is hypothesized that the measured acceleration of the plastic ball dropped at the height of 1 metre during its free fall will be close to 9.81ms^-2, the universal gravitational constant on Earth. Because during its motion, only gravity is in effect, and according to F_g=mg and g=F_g/m, gravity is the only source of acceleration. Since gravity is a constant force, acceleration will be consistent throughout the experiment. Thus, the measured acceleration during freefall would be 9.81ms^-1 during the motion.

Results and Analysis

Raw data table

Trial one:

Time[s]	Position[m] [±0.0001m]	y-velocity/ms^-11 [±0.001ms^-1]	y-acceleration/ms^-2 [±0.01ms^-2]
0.00	0.01		
0.02	0.00	-0.17	
0.03	0.00	-0.09	-19.44
0.05	0.00	-0.70	26.91
0.07	-0.02	0.35	2.99
0.08	0.01	0.26	-25.42
0.10	-0.01	-1.31	-55.32
0.12	-0.03	-1.22	11.96
0.13	-0.06	-1.05	2.99
0.15	-0.07	-0.96	-4.49
0.17	-0.09	-1.31	-13.46
0.18	-0.11	-1.40	-11.38
0.20	-0.13	-1.58	-9.96
0.22	-0.17	-1.74	-9.96
0.24	-0.19	-1.92	-14.23
0.25	-0.23	-2.35	-4.49
0.27	-0.27	-2.18	-4.49
0.29	-0.30	-2.27	-5.98
0.30	-0.35	-2.62	-17.94
0.32	-0.39	-2.70	-16.45
0.34	-0.44	-3.23	-22.43
0.35	-0.50	-3.49	-14.95
0.37	-0.56	-3.66	-11.96
0.39	-0.62	-3.92	
0.40	-0.69		

Table 1: The position in m, velocity in ms^-1 and acceleration in ms^-2 of a ball dropped that undergoes freefall from 0.00s to 0.40s every 1/60th a second for the first trial.

Trial 2:

Trial 2			
time[s]	Position/m [±0.0001]	y-velocity/ms^-1 [±0.001]	y-acceleration/ms^-2 [±0.01]
0.00	-0.01		
0.02	-0.03	-1.01	
0.03	-0.04	-0.81	1.73
0.05	-0.06	-1.01	-6.93
0.07	-0.08	-1.06	-4.33
0.08	-0.09	-1.11	-13.85
0.10	-0.11	-1.52	-15.58
0.12	-0.15	-1.72	-6.93
0.13	-0.17	-1.67	-4.33
0.15	-0.20	-1.87	-9.52
0.17	-0.23	-2.02	-13.85
0.18	-0.27	-2.27	-14.13
0.20	-0.31	-2.63	-8.66
0.22	-0.36	-2.58	-4.33
0.24	-0.40	-2.68	-4.33
0.25	-0.44	-2.83	-19.05
0.27	-0.49	-3.18	-19.91
0.29	-0.55	-3.64	-13.85
0.30	-0.61	-3.59	-2.60
0.32	-0.67	-3.69	-12.99
0.34	-0.73	-4.04	-24.24
0.35	-0.81	-4.49	-16.45
0.37	-0.88	-4.65	17.31
0.39	-0.96	-3.94	
0.40	-1.02		

Table 2: The position in m, velocity in ms^-1 and acceleration in ms^-2 of a ball dropped that undergoes freefall from 0.00s to 0.40s measured every 1/60th a second for the second trial. The highlighted part is the outliers.

Trial 3:

Trial 3			
Time[s]	Position/m [±0.0001]	Y-velocity/ms^-1 [±0.001]	Y-acceleration ms^-2 [±0.01]
0.00	-0.01		
0.02	-0.01	-0.48	
0.03	-0.03	-0.67	1.64
0.05	-0.04	-0.40	4.91
0.07	-0.04	-0.45	-7.73
0.08	-0.05	-0.75	-18.04
0.10	-0.06	-1.00	-18.90
0.12	-0.08	-1.40	-10.31
0.13	-0.11	-1.40	0.00
0.15	-0.13	-1.30	-6.87
0.17	-0.15	-1.65	-7.73
0.18	-0.19	-1.65	-9.45
0.20	-0.21	-1.80	-13.75
0.22	-0.25	-2.26	-14.61
0.24	-0.28	-2.26	-9.45
0.25	-0.32	-2.51	-10.31
0.27	-0.37	-2.71	-12.03
0.29	-0.41	-2.81	5.16
0.30	-0.46	-2.66	-11.17
0.32	-0.50	-2.96	-21.48
0.34	-0.56	-3.61	-24.06
0.35	-0.62	-3.66	-4.30
0.37	-0.68	-3.76	-0.86
0.39	-0.75	-3.71	
0.40	-0.81		

Table 3: The position in m, velocity in ms^-1 and acceleration in ms^-2 of a ball dropped that undergoes freefall from 0.00s to 0.40 every 1/60th a second for the third trial. The highlighted part is the outliers.

Processed data table:

Time[s]	Position [m]	Uncertainty [m]	y-velocity [ms^-1]	Uncertainty [ms^-1]	y-acceleration [ms^-2]	Uncertainty [ms^-2]
0.00	-0.01	0.00				
0.02	-0.01	0.02	-0.48	0.00		
0.03	-0.02	0.02	-0.52	0.36		0.00
0.05	-0.03	0.03	-0.70	0.30	-6.93	0.00
0.07	-0.05	0.03	-0.76	0.30	-6.03	1.70
0.08	-0.04	0.05	-0.93	0.18	-13.85	0.00
0.10	-0.06	0.05	-1.28	0.26	-15.58	0.00
0.12	-0.09	0.06	-1.45	0.25	-8.62	1.69
0.13	-0.11	0.06	-1.37	0.31	-4.33	0.00
0.15	-0.13	0.07	-1.38	0.45	-6.96	2.52
0.17	-0.16	0.07	-1.66	0.36	-11.68	3.06
0.18	-0.19	0.08	-1.77	0.44	-11.66	2.34
0.20	-0.22	0.09	-2.00	0.52	-10.79	2.55
0.22	-0.26	0.09	-2.19	0.42	-9.63	5.14
0.24	-0.29	0.10	-2.28	0.38	-9.34	4.95
0.25	-0.33	0.11	-2.56	0.24	-7.40	2.91
0.27	-0.38	0.11	-2.69	0.50	-8.26	3.77
0.29	-0.42	0.12	-2.90	0.68	-9.92	3.93
0.30	-0.47	0.13	-2.95	0.48	-11.17	0.00
0.32	-0.52	0.14	-3.12	0.49	-12.99	0.00
0.34	-0.58	0.15	-3.63	0.41		
0.35	-0.64	0.15	-3.88	0.50	-9.63	5.33
0.37	-0.71	0.16	-4.02	0.49	-11.96	0.00
0.39	-0.77	0.17	-3.86	0.12		
0.40	-0.84	0.16				

Table 4: The average position[m] and its uncertainty[m] and average vertical velocity and its uncertainty[ms^-1] and average acceleration and its uncertainty[ms^-2] of three trials from 0.00s to 0.40s. The blank blocks are outliers and will not be considered in the calculator.

Sample calculations:

1. Position:
   Data used for sample calculations:
   First data value of position for all three trials (0.02s)

Trial	time/s	Position/m (±0.0001)
Trial 1	0.02	0.00
Trial 2	0.02	-0.03
Trial 3	0.02	-0.01

$\overline{position} = (position_1 + position_2 + position_3) \div 3 =$
$\frac{0.00-0.03-0.01}{3} \approx -0.01$

Position uncertainty
Data used for sample calculations
Data value of all three trials(0.02s)

Trial	time/s	Position/m (±0.0001)
Trial 1	0.02	0.00
Trial 2	0.02	-0.03
Trial 3	0.02	-0.01

$position\ uncertainty = (position_{max} - position_{min}) \div 2$
$position\ uncertainty = \frac{0.00-(-0.03)}{2} \approx 0.02$

2. y-velocity:
   Data used for sample calculations:
   Data value of velocity for all three trials (0.02s)

Trial	time/s	Velocity/m (±0.001)
Trial 1	0.03	-0.09
Trial 2	0.03	-0.81
Trial 3	0.03	-0.67

$\overline{velocity} = (velocity_1 + velocity_2 + velocity_3) \div 3 =$
$\frac{-0.09-0.81-0.67}{3} \approx -0.52$

Velocity uncertainty

Data used for sample calculations
Data value of all three trials (0.03s)

Trial	time/s	Velocity/m (±0.001)
Trial 1	0.03	-0.09
Trial 2	0.03	-0.81
Trial 3	0.03	-0.67

$$velocity\ \ uncertainty\ = (velocity_{max}\ - velocity_{min})) \div 2$$

$$velocity\ uncertainty\ = \frac{-0.09-(-0.81)}{2} = 0.36$$

3. y-acceleration
   Data used for sample calculations:
   First data value of velocity for all three trials (0.15s)

Trial	time/s	Acceleration/m (±0.01)
Trial 1	0.15	-4.49
Trial 2	0.15	-9.52
Trial 3	0.15	-6.87

$$\overline{acceleration} = (acceleration_1 + acceleration_2 + acceleration_3) \div 3 = \frac{-4.49-9.52-0.87}{3} \approx -6.96$$

Acceleration uncertainty
Data used for sample calculations
First data value of all three trials (0.15s)

Trial	time/s	Acceleration/m (±0.01)
Trial 1	0.15	-4.49
Trial 2	0.15	-9.52
Trial 3	0.15	-6.87

$$acceleration\ uncertainty\ = (acceleration_{max}\ - acceleration_{min})) \div 2$$

$$acceleration\ \ uncertainty\ = \frac{-4.49-(-9.52)}{2} = 2.52$$

4. Average position uncertainty and its percentage uncertainty

Data used for sample calculations:
Processed data table, second column, Uncertainty(m)
Processed data table, first column, Position(m)

Position (m)	Uncertainty (m)
-0.01	0.00
-0.01	0.02
…	
-0.71	0.16
-0.77	0.17
-0.84	0.16

$Average\ position\ uncertainty(APH)\ = (APU_1 + APU_2 + ... + APU_n) \div n$

$APU = \frac{0.00+0.02+0.02+...+0.16}{25} = 0.09$

$Average\ position(AP) = (AP_1 + AP_2 + ... + AP_n) \div n$

$AP = \frac{-0.01-0.01-...-0.84}{25} = -0.293$

$Average\ position\ percentage\ uncertainty(APPU) = APU \div |AP| \times 100\%$

$APPU = \frac{0.09}{0.293} \times 100\% = 30.37\%$

5. Average velocity uncertainty and its percentage uncertainty
Data used for sample calculations:
Processed data table, third column, velocity(ms^-1)
Processed data table, fourth column, Uncertainty(ms^-1)

Velocity (ms^-1)	Uncertainty (ms^-1)
-0.48	0.00
-0.52	0.36
…	
-3.88	0.50
-4.02	0.49
-3.86	0.12

$Average\ velocity\ uncertainty(AVH)\ = (AVU_1 + AVU_2 + ... + AVU_n) \div n$

$AVU = \frac{0.00+0.36.+...+0.12}{23} = 0.37$

$Average\ velocity(AV) = (AV_1 + AV_2 + ... + AV_n) \div n$

$AV = \frac{-0.48-0.52-...-3.86}{23} = -2.1$

$Average\ velocity\ percentage\ uncertainty(AVPU) = AVU \div |AV| \times 100\%$

$AVPU = \frac{0.37}{2.1} \times 100\% = 17.45\%$

6. Average acceleration uncertainty and its percentage uncertainty
   Data used for sample calculations:
   Processed data table, fifth column, acceleration(ms^-2)
   Processed data table, sixth column, Uncertainty(ms^-2)

Acceleration (ms^-2)	Uncertainty (ms^-2)
-6.93	0.00
-6.03	1.70
…	
-9.63	5.33
-11.96	0.00

$Average\ acceleration\ \ uncertainty(AAH) = (AAU_1 + AAU_2 + ... + AAU_n) \div n$

$AAU = \frac{0.00+1.70+...+0.00}{19} = 2.10$

$Average\ acceleration(AA) = (AA_1 + AA_2 + ... + AA_n) \div n$

$AA = \frac{-6.93-6.30+...-11.96}{19} = -9.83$

$Average\ acceleration\ percentage\ uncertainty(AAPU) = AAU \div |AA| \times 100\%$

$AAPU = \frac{2.10}{9.83} \times 100\% = 21.36\%$

7. Uncertainty for velocity-time graph
   Data used for sample calculations:
   Slope of Max line: -9.629
   Slope of Min line: -8.793
   $Uncertainty\ for\ velocity - time\ graph(UVT) = |(k_{max} - k_{min}) \div 2|$
   $UVT = |-9.629 - (-8.793)/2| \approx 0.42$

Graphs

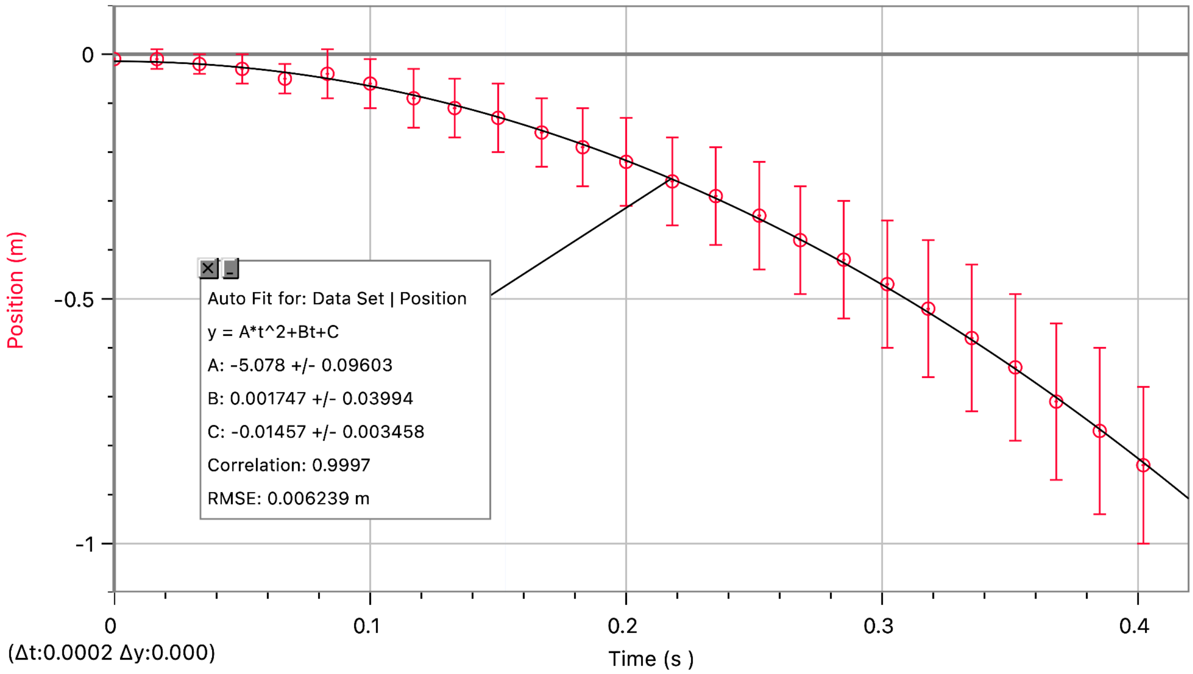

Figure 1- The graph shows the position(m) of the ball relative to time of the motion from 0.00 to 0.40s. The graph reveals a strong negative quadratic correlation between position and time suggested by the downward trendline, concave down function characteristics and coefficient of correlation.

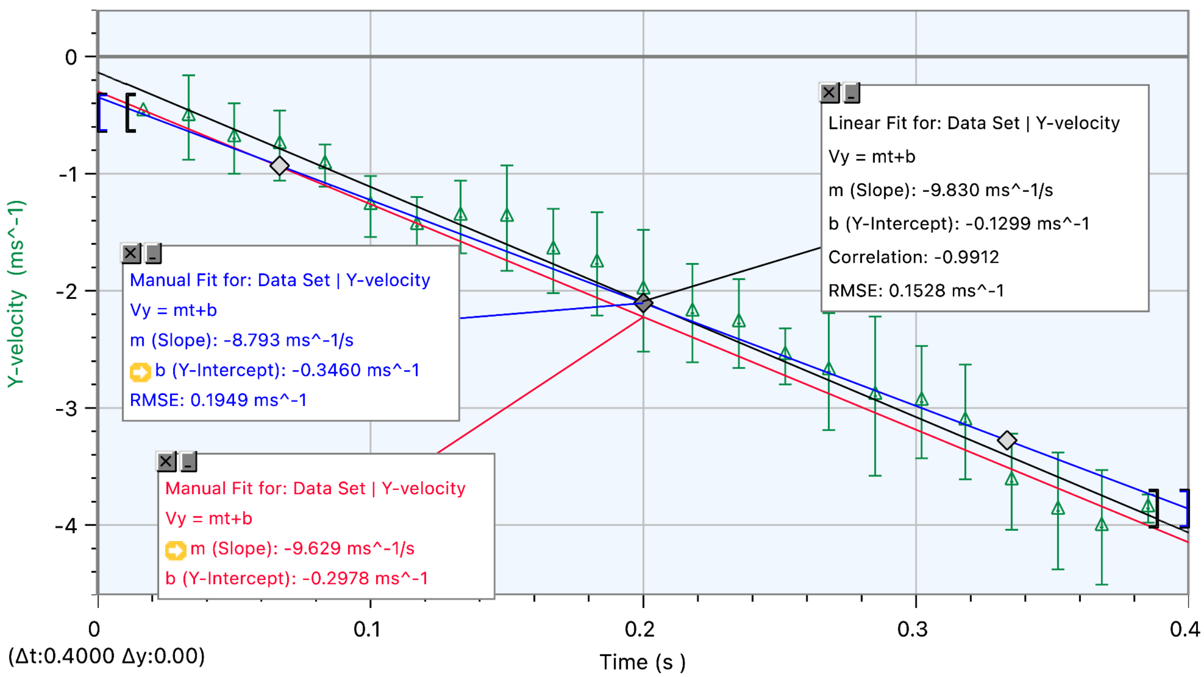

Figure 2: The graph shows the velocity(ms^-1) of the ball relative to time of the motion from 0.00 to 0.40s. The graph reveals a strong negative linear correlation between velocity and time suggested by the downward trendline, negative first degree derivative of the function and coefficient of correlation.

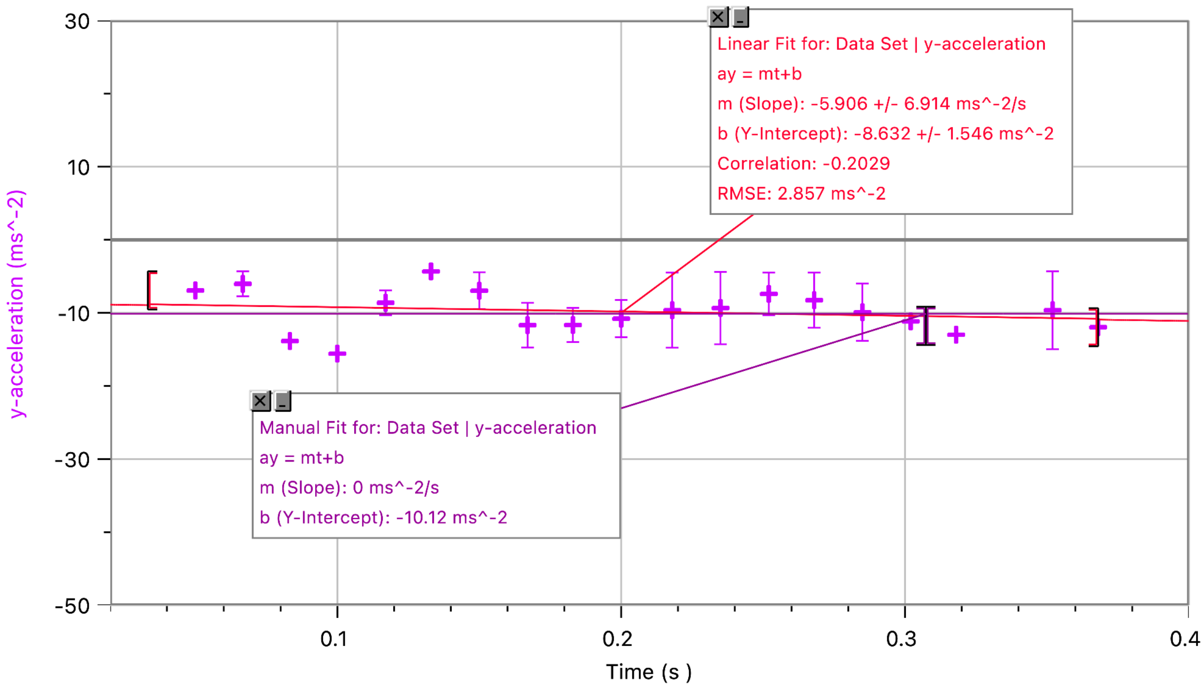

Figure 3: The graph shows the acceleration(ms^-2) of the ball relative to time of the motion from 0.00 to 0.40s. The graph reveals a weak negative correlation between acceleration and time suggested by the slightly downward trendline, negative first derivative of the function and small coefficient of correlation. However, in theory, the relationship should fit a constant function.

Qualitative observation table:

Type of qualitative observation	Qualitative observations
Speed of falling	After the ball was dropped, it seems like the velocity of the ball increased slightly during its entire motion.
Time travelled	There is no quantitative measurement of time but it seems like the time it took to perform the 1m motion was under 1 second.
Path of the ball	The ball travelled directly vertically downward.

Analysis

According to figure-1, which displays the relationship between the change in position(m) and time(s) measured during its free fall motion from 0.00 to 0.40s, there is a negative quadratic correlation between the change in position and time. $At^2 + Bt + C$ models the plotted graph, a second-degree polynomial with $A =- 5.078 \pm 0.096$, $B = 0.0017 \pm 0.0399$ $C =- 0.0146 \pm 0.0035$, meaning as time increases, the magnitude(absolute value) of the change in position would increase in a manner to the square of time. This quadratic model fits the theory because in free fall motion with no initial velocity, the change in position would be modelled by $x = \frac{1}{2}gt^2$, in which a quadratic polynomial models the change in position. The velocity of the ball and its graph can be derived from the data in the position time graph which could eventually lead to the answer to the research question, which is the value of acceleration. The slope of the graph, represented by $\frac{dx}{dt}$(as the first derivative of $y =- 5.078t^2 + 0.0017t - 0.0146$) represents the ball's velocity when falling because $v = \frac{dx}{dt}$. The absolute value of the slope increases as time increases because velocity is also getting greater. The correlation coefficient, with a value of 0.9997, suggests a strong relationship between the graphed quadratic polynomial and the input data, as it is very close to 1.

According to figure 2 which displays the relationship between velocity(ms^-1) and time(s) measured during its free fall from 0.00s to 0.40s, there is a negative linear correlation between velocity and time. The negative linear correlation suggests that as time increases, the velocity increases its magnitude in the downward direction. The linear fit for the data points is modelled by $mt + b$, in which m and b are constants equal to -9.83ms^-1/s and -0.13ms^-1 respectively. This linear model is valid and fits the theory because the velocity in freefall motion with no initial velocity would be modelled by vy=gt, representing a negative linear relationship between velocity and time if the positive direction is upward. The slope of the graph, which is -10.12, can be obtained by taking the function's first derivative as $\frac{d(-9.83t-0.13)}{dt}$. It represents the acceleration in this case because according to theories in kinematics, a=dv/dt, so the slope, -9.83, would be the ball's acceleration during its freefall. In this way, the acceleration(ms^-2) due to gravitational force measured for a plastic ball during free fall dropping from a height of 1m during the time interval of 0.00s to 0.40s is derived as -9.83ms^-2.
The correlation coefficient, which is -0.9912, suggests a strong negative correlation between y-velocity and time, as the absolute value of -0.9912 is close to one.

According to figure 3, the acceleration-time graph, there is a weak negative correlation between acceleration and time modelled by $a_y =- 5.906t - 8.632$. The graph suggests that as time increases, the magnitude of acceleration increases during free fall motion. However, this would be incorrect because according to kinematics theory, acceleration due to gravity in free fall motion should be constant as $g = \frac{d\frac{1}{2}gt^2}{dt}$. Thus, the linear fit for this graph is incorrect. It's better to use the first derivative of the velocity-time graph to determine the acceleration due to the discrepancies of the acceleration-time graph.

To examine the accuracy of the acceleration tested and how it compares to the actual value of the gravitational constant, the uncertainty of acceleration should be considered. According to figure 2, the uncertainty for the slope of the velocity-time graph is ±0.42ms^-2. Since the experimentally obtained value of acceleration is -9.83ms^-2, as stated in the previous paragraph, any values in the range of $-\ 9.83 \pm 0.42ms^{-1}$ can be considered accurate. Because -9.81ms^-2, the actual value of the gravitational constant, is in the range of $-\ 9.83 \pm 0.42ms^{-1}$, so the measurement is accurate.

Conclusion:

In conclusion, the experimentally determined value(magnitude) for acceleration($-\ 9.83 \pm 0.42ms^{-1}$) by taking the first derivative of the velocity-time graph is accurate compared to the theoretical value(9.81ms^-2) of the gravitational constant because 9.81 is in the range. During the entire motion, acceleration exhibits a quadratic growth. Velocity exhibits linear growth. Acceleration is constant.

Evaluations:

The average error bars(uncertainty)for the measurement of displacement are insignificant, which is 0.09. The average percentage uncertainty is 30.37%, greater than 10.00%. Thus, the data collected for acceleration is not reliable because the percentage uncertainty is greater than 10%.

The error bars for the measurement of velocity are more significant. The average velocity uncertainty is 0.37. The average percentage uncertainty is 17.45%, greater than 10.00%. Thus, the data collected to determine velocity is not reliable.

The error bars for acceleration time graphs are significant, with an average of 2.10, relative to the average acceleration of -9.83 ms^-2, so the percent uncertainty is approximately 21.36%. The considerable uncertainty suggests the unreliability of the collected data in the acceleration-time graph in determining the value of acceleration.

Overall, for all three quantities, the measurements are imprecise, suggested by their huge percent uncertainty value.

Errors in the experiment.

There are three sources of uncertainty in this experiment. Each will be indicated and their impacts on the experiment will be presented below.

Firstly, during the free fall motion of the ball, in normal classroom conditions, the ball will experience both a downward gravity and an upward air resistance. According to dynamic rules, the net force exerted on the ball would be F_g-f, in which F_g represents gravity and f represents the force exerted by air resistance. Then, according to Newton's 2nd law, $F = ma$, acceleration in this circumstance will be $\frac{(F\_g-f)}{m}$. However, the correct expression should be G/m. Thus, the measured acceleration should be slightly smaller than the theoretical value. This is a systematic error because air resistance would exist whenever and wherever the experiment is performed. Nevertheless, this error is insignificant as air resistance is not great enough to affect net force profoundly.

Secondly, when dropping the ball, the dropping hand might unconsciously apply an initial acceleration and force by pushing the ball down. If such a force is applied, initial acceleration will increase the value of measured acceleration. The impact can be insignificant as not much initial acceleration is applied. This is a systematic error because this will happen every time the experiment is performed.

Thirdly, when using the tracker app to obtain the displacement from the video of the freefall motion, the image of the ball is not clear. In this experiment, the reference point is chosen to be the bottom of the ball. However, the unclear image of the ball at each frame made it hard to determine the exact bottom point. This error can be significant depending how much deviations are carried out. It might both over-exaggerate the value of position and underestimate it. This is a systematic error because of discrepancies caused by technical difficulties of the tracker app.

Improvements:

During the experiment, to avoid the uncertainties and errors listed above, the following improvements and extensions can be added to ensure the accuracy of the measurements.

To avoid the influence caused by air resistance that hinders the ball's movement, investigators must perform the experiment in a vacuum. During the freefall motion in a vacuum, the ball would only be affected by gravity with no air resistance. The measurement would be more accurate that way. However, there will be few access to vacuum channels in high school. Thus, this error is temporarily unavoidable.

To avoid any force, initial velocity, and acceleration caused by hand movement when dropping the ball from 1 meter, it's better to hold and release the ball using a mechanical hand or similar apparatus. In this way, there will be no initial velocity of the ball which would fit the requirements of testing the acceleration during the freefall motion.

Experimenters should use the motion mapper to measure the parameters to avoid any "misclicks", unclear image and inaccurate measurements caused by tracker software. The motion mapper would detect the ball's motion more accurately by sending electrical signals to the object and letting it rebound off from the object's surface back to the detector. It then draws the graphs on the logger-pro app accordingly.

Extensions:

In this experiment, a ball of the same mass was dropped thrice from 1m to test its acceleration due to gravity. An extension to the experiment can be employing balls of different masses and comparing their acceleration values. This experiment will be a reperformance of Galileo's demonstration to verify that acceleration is consistent for all objects on Earth. Another extension can be testing the experiment in different parts of the world, where the value of the gravitational constant varies slightly based on their latitude. This experiment allows the further exploration of factors influencing the gravitational constant caused by Earth's autorotation and centripetal force. If possible, conditions mentioned in the improvement part should be achieved to ensure the accuracy of results.