Required Practical 3:
Determination of g by Free Fall

AS and A LEVEL (Year 1 content)

Name: _____ Date: _____

Aim: to determine the acceleration due to gravity g by timing a steel ball falling from rest through different heights, and to compare the result with the accepted value on Earth of 9.81 m s^{-2}.

Background

- An object in **free fall** has only its weight acting on it. On Earth it accelerates downwards at g = 9.81 m s^{-2} (the same as the gravitational field strength, 9.81 N/kg).
- A small, dense steel ball falling a short distance has very little air resistance compared with its weight, so its acceleration is very close to g.
- The ball starts **from rest**, so u = 0. Using $s = u\,t + \frac{1}{2}\,a\,t^2$ with a = g gives $s = \frac{1}{2}\,g\,t^2$.
- Rearranged as y = m x + c: $s = (g \div 2) \times t^2 + 0$. So a graph of **s (y-axis) against t^2 (x-axis)** is a straight line through the origin with **gradient g ÷ 2**. (Plotting 2s against t^2 gives a gradient of g.)
- A **systematic error** shifts every reading the same way. Here, **residual magnetism** holds the ball for a short time after the current is switched off, so every measured time is slightly too long. This moves every point to the right, so the line no longer passes through the origin.

$s = u\,t + \frac{1}{2}\,a\,t^2$ with u = 0: $s = \frac{1}{2}\,g\,t^2$ $g = 2 \times$ gradient

Quantity	Symbol	Unit
height fallen (bottom of ball to trapdoor)	s	Metres (m)
time to fall	t	Seconds (s)
acceleration due to gravity	g	Metres per second squared (m s^{-2})
initial velocity	u	Metres per second (m s^{-1})

In plain English
Drop a hammer and a feather on the Moon (the Apollo 15 astronauts did this) and they land together: with no air, everything falls with the same acceleration. On Earth a small steel ball is the next best thing, because air resistance hardly affects it.

Equipment

Electromagnet and low-voltage power supply, steel ball bearing, trapdoor and electronic timer (resolution 0.001 s), clamp stand with heavy base, 2 m rule (or a tape measure, as s goes above 1 m), set square, box to catch the ball. Two light gates and a data logger can be used instead of the trapdoor.

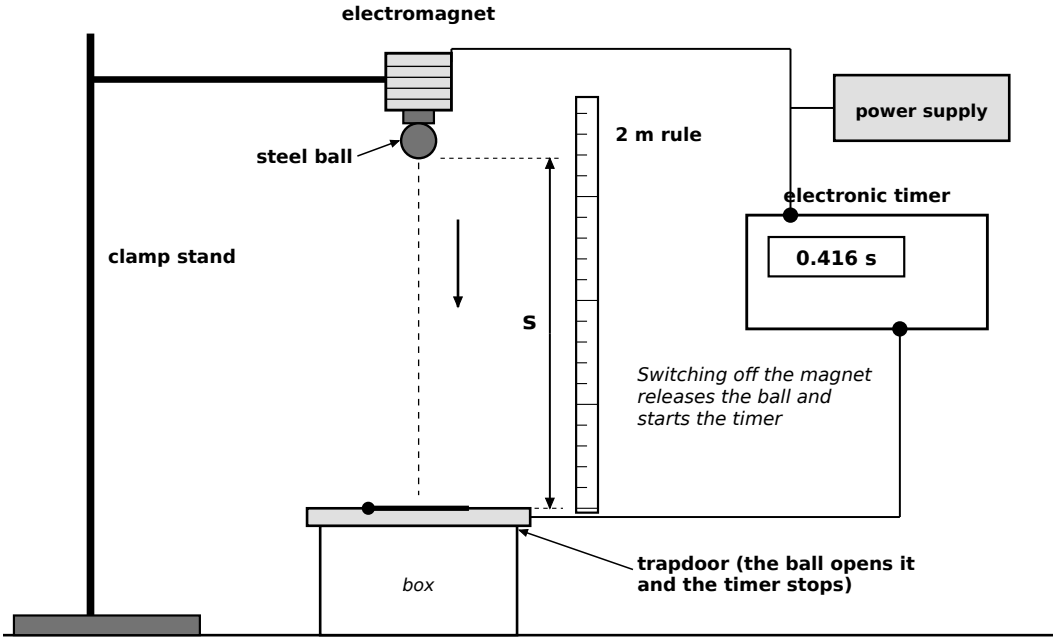


Figure 1: Timing a falling steel ball with an electromagnet and trapdoor

Variables

Independent (you change)	Dependent (you measure)	Control (keep the same)
height s (from the bottom of the ball to the trapdoor)	time t to fall	same ball, same electromagnet current, release from rest each time

Method

1. Set up the apparatus as in Figure 1 on the floor or a low, stable bench, with the clamp stand's base clamped or weighted so it cannot topple. Check the ball will land on the trapdoor.
2. Switch on the electromagnet and hang the ball from it. Use the **smallest current** that just holds the ball, so that it releases quickly (less residual magnetism).
3. Measure s from the **bottom of the ball** to the top of the trapdoor with the rule held vertical. Use a set square to read the rule at the bottom of the ball, with your eye level with the mark (no parallax). Start with s = 0.200 m.
4. Reset the timer to zero and close the trapdoor. Switch off the electromagnet: this releases the ball and starts the timer; the ball opens the trapdoor and stops it. Record t.
5. Repeat to get **three** readings of t for each height. Check the timer is reset and the trapdoor is properly closed each time.
6. Increase s in steps of 0.200 m up to 1.200 m. Calculate the mean t (ignoring anomalies) and t^2.

With **two light gates** a measured height h apart, the data logger records the speed of the ball at each gate (ball diameter ÷ time to pass through it) and the time t between the gates. The ball is not at rest at the first gate, so $s = \frac{1}{2} g t^2$ does not apply: use $g = (v_2 - v_1) \div t$, or $v_2^2 = v_1^2 + 2 g h$.

Hazards and getting good results

Problem	Why it matters	What to do
Falling steel ball	It can hit hands or feet, or roll away.	Keep feet and hands clear of the drop. Catch the ball in a box under the trapdoor.
Clamp stand toppling; trip hazards	Tall stand and trailing leads can be knocked over.	Clamp or weight the base. Keep leads tidy and bags clear of the floor area.
Electromagnet gets hot	Burns if left on for a long time.	Switch it off between runs. Use a low current.
Residual magnetism	The ball is released late, so every t is too long (systematic error).	Use the smallest current that holds the ball. Use the graph: it shows up as an intercept.
Measuring s	Parallax, or measuring to the wrong part of the ball.	Measure from the bottom of the ball; use a set square; eye level with the mark.
Timing by hand	Reaction time (about 0.2 s) is as long as the fall.	Use an electronic timer or light gates (resolution 0.001 s).
Short heights	% uncertainty in s and t is bigger.	Use a wide range of heights, up to 1.2 m or more, and repeat.

Analysis

- Calculate mean t and t^2 for each height. Plot **s against t^2**. Draw the line of best fit and find the gradient with a large triangle: **g = 2 × gradient**.
- **Absolute uncertainty** is the ± amount, in the **same unit** as the quantity. **Percentage uncertainty** = absolute uncertainty ÷ value × 100%. Example: at s = 0.400 m, t = 0.296 s ± 0.0015 s (absolute), so 0.0015 ÷ 0.296 × 100 = 0.51% (percentage).
- **Uncertainty in t:** the absolute uncertainty is half the range of the repeats. Percentage uncertainty in t^2 = 2 × percentage uncertainty in t (a squared quantity doubles the % uncertainty). Show these as horizontal error bars on t^2.
- **Gradient uncertainty:** draw the steepest and least steep lines through all the error bars. Uncertainty = half the difference between their gradients. Then %g = %gradient.
- **For one reading:** $g = 2s \div t^2$, so %g = %s + 2 × %t.
- **Intercept:** if the line cuts the t^2 axis at a positive value (or the s axis at a negative value), the times are too long: a systematic error such as the electromagnet delay t_0.
- **Graph of t against √s:** $s = \frac{1}{2} g t^2$ rearranges to $t = \sqrt{(2 \div g)} \times \sqrt{s}$. With a delay t_0 added to every time: **$t = \sqrt{(2 \div g)} \times \sqrt{s} + t_0$**. This is y = m x + c, so the gradient = $\sqrt{(2 \div g)}$ and the **intercept = t_0**. Square the gradient: gradient$^2 = 2 \div g$, so **$g = 2 \div \text{gradient}^2$**. A constant delay only moves the intercept, so it does not affect this value of g.
- Compare with 9.81 m s^{-2}: % difference = (experimental − accepted) ÷ accepted × 100.

In plain English
Fall for twice as long and you fall four times as far, because you are speeding up the whole time. That is why s goes with t^2, and why plotting s against t^2 (not t) gives a straight line.

In plain English
The electromagnet is like a sticky starting block: the clock starts, but the ball hangs on for about a hundredth of a second. Every time is a little too long, so all the points slide sideways and the line misses the origin. Repeating does not fix this; only changing the method or the graph can.

Sample results

A student used a steel ball bearing, an electromagnet and a trapdoor. The timer read to 0.001 s and s was measured to ± 1 mm.

height s / m	time t reading 1 / s	time t reading 2 / s	time t reading 3 / s	mean t / s	uncertainty (half range) / s	t^2 / s^2
0.200	0.213	0.211	0.214			
0.400	0.294	0.297	0.296			
0.600	0.361	0.359	0.391			
0.800	0.414	0.416	0.413			
1.000	0.461	0.463	0.462			
1.200	0.507	0.504	0.505			

Table 1: Time to fall through different heights

Your results

Record your own readings here. If your practical doesn't work, use the sample results instead.

height s / m	time t reading 1 / s	time t reading 2 / s	time t reading 3 / s	mean t / s	uncertainty (half range) / s	t^2 / s^2

Your results: time to fall through different heights

Questions

Questions 5 to 16 use the sample results. You will need your own graph paper for question 8.

1. Show that $s = \frac{1}{2} g t^2$ for an object dropped from rest, and state one assumption you have made. **[2]**

2. Explain why a graph of s against t^2 should be a straight line, and state what its gradient represents. **[2]**

3. Give one hazard in this experiment and how to reduce the risk. **[2]**

4. Describe how the student should measure s as accurately as possible. **[2]**

5. Identify the anomalous reading in Table 1 and suggest a cause. **[2]**

6. Complete the last three columns of Table 1. **[3]**

7. Calculate the percentage uncertainty in the mean t at s = 0.200 m. Hence find the percentage uncertainty in t^2. **[2]**

8. Plot a graph of s against t^2. Draw a line of best fit. **[4]**

9. Use the gradient of your graph to determine g. **[2]**

10. Calculate the percentage difference between your value and 9.81 m s^{-2}. **[1]**

11. Your line does not pass through the origin. Explain how residual magnetism in the electromagnet causes this and where the line cuts the axes. **[3]**

12. Explain the difference between a random error and a systematic error, using an example of each from this experiment. **[2]**

13. Suggest a different graph from which g can be found without being affected by a constant time delay. State how g and the delay are found from it. **[3]**

14. Explain why the student used an electronic timer rather than a stopwatch. **[2]**

15. Explain why a small steel ball is used rather than a table tennis ball of the same size. **[2]**

16. At s = 1.200 m, calculate $g = 2s \div t^2$ from the mean reading, its percentage uncertainty and its absolute uncertainty. **[3]**

17. Suggest one improvement to the method, other than the graph, and explain how it improves the result. **[2]**

Total: 39 marks

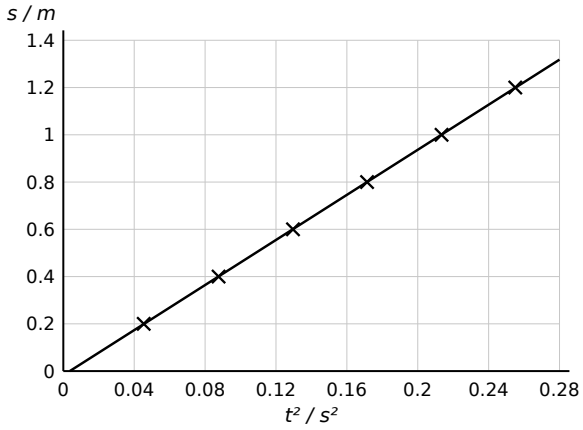
Required Practical 3: Determination of g by Free Fall: Answers

Completed results (Table 1)

height s / m	time t reading 1 / s	time t reading 2 / s	time t reading 3 / s	mean t / s	uncertainty (half range) / s	t^2 / s^2
0.200	0.213	0.211	0.214	0.213	0.0015	0.0454
0.400	0.294	0.297	0.296	0.296	0.0015	0.0876
0.600	0.361	0.359	0.391	0.360	0.0010	0.1296
0.800	0.414	0.416	0.413	0.414	0.0015	0.1714
1.000	0.461	0.463	0.462	0.462	0.0010	0.2134
1.200	0.507	0.504	0.505	0.505	0.0015	0.2550

The anomalous reading (0.391 s at 0.600 m) is left out of the mean and the half range.

Expected graph



A straight line with gradient 4.77 m s^{-2}, so g = 9.54 m s^{-2} (−2.8% from 9.81). The line cuts the t^2 axis at about 0.0037 s^2 (s intercept −0.017 m) because of the electromagnet delay. A graph of t against √s gives g = 9.85 m s^{-2} and a delay of 0.011 s.

Questions

1	$s = u\,t + \frac{1}{2}\,a\,t^2$ with u = 0 (dropped from rest) and a = g gives $s = \frac{1}{2}\,g\,t^2$ (1). Assumption: air resistance is negligible / acceleration is constant / ball released from rest (1).
2	$s = (g \div 2)\,t^2 + 0$ is in the form y = m x + c with y = s and $x = t^2$, so a straight line through the origin (1); gradient = g ÷ 2 (1).
3	Falling ball hits feet / hands, or stand topples, or hot electromagnet (1); keep feet clear, catch the ball in a box / clamp the base / switch off between runs (1).
4	Measure from the bottom of the ball to the top of the trapdoor (1); use a set square / eye level with the mark to avoid parallax, rule held vertical (1).
5	s = 0.600 m, reading 3 (0.391 s) (1). It is much longer than the others; e.g. the trapdoor was not closed properly / the timer was not reset / the ball was released late (1).
6	Mean t: 0.213, 0.296, 0.360, 0.414, 0.462, 0.505 s, ignoring 0.391 s (1). Half range: 0.0015, 0.0015, 0.0010, 0.0015, 0.0010, 0.0015 s (1). t^2: 0.0454, 0.0876, 0.1296, 0.1714, 0.2134, 0.2550 s^2 (1). Accept t^2 worked out from either the rounded (3 d.p.) or the unrounded means, e.g. 0.0452, 0.0874, 0.1296, 0.1717, 0.2134, 0.2554 s^2.
7	0.0015 ÷ 0.213 × 100 = 0.7% (1); % in t^2 = 2 × 0.7 = 1.4% (1).
8	s on the y-axis, t^2 on the x-axis, labelled with units (1); sensible scales using more than half the grid (1); points plotted correctly (1); straight line of best fit (1).

9	Gradient ≈ 4.77 m s^{-2} (allow 4.70–4.85) (1); g = 2 × gradient ≈ 9.54 m s^{-2} (1).
10	(9.54 − 9.81) ÷ 9.81 × 100 = −2.8% (1).
11	The ball is held briefly after the current is switched off, so every measured time is too long (1). Every point moves to the right / t^2 is too big (1), so the line cuts the t^2 axis at a positive value (the s axis at a negative value, about −0.017 m) (1).
12	Random errors scatter readings either side of the true value and are reduced by repeating and averaging, e.g. the spread in t (1); systematic errors shift every reading the same way and are not reduced by repeating, e.g. the electromagnet delay / zero error on the rule (1).
13	t against √s (1). t = √(2 ÷ g) × √s + delay, so gradient = √(2 ÷ g) and g = 2 ÷ gradient² (1); the intercept on the t axis = the delay (about 0.011 s here, giving g ≈ 9.85 m s^{-2}) (1).
14	Human reaction time is about 0.2 s, similar to the times being measured (1); an electronic timer starts and stops automatically with a resolution of 0.001 s / removes reaction time (1).
15	Air resistance is much smaller than the weight of a dense steel ball (1), so its acceleration is very close to g; the light table tennis ball is slowed significantly / reaches terminal velocity sooner (1).
16	%s = 0.001 ÷ 1.200 × 100 = 0.08%; %t = 0.0015 ÷ 0.505 × 100 = 0.3% (1); %g = 0.08 + 2 × 0.3 ≈ 0.7% (1); g = 2 × 1.200 ÷ 0.505^2 = 9.41 m s^{-2}, so absolute uncertainty = 0.7% of 9.41 = ± 0.06 m s^{-2} (1).
17	One improvement (1) with its matching reason (1): smallest electromagnet current / less residual magnetism, so the release delay is smaller; light gates instead of the electromagnet start, so no release delay; larger heights, so % uncertainties in s and t are smaller; more repeats, to reduce the effect of random error.

Total: 39 marks

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