

Measuring g by free fall • Required Practical 3 — solutions

Matching worked solutions and teaching prompts | 36 marks

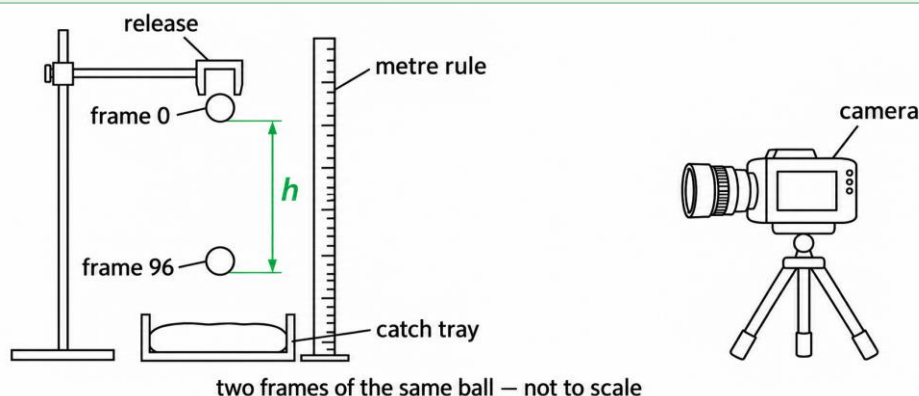
AQA AS Physics 7407 • First-year A Level 7408

Specification points covered

AQA AS 7407 / first-year A Level 7408: 3.4.1.3 — uniformly accelerated motion, acceleration due to gravity and Required Practical 3: determining g by free fall, including graphical analysis and random/systematic errors. Supporting: 3.1.2 — absolute, percentage and combined uncertainties; 3.4.1.4 and 3.4.1.5 — air resistance, resultant force and acceleration.

A drop-test rig for protective packaging

A conservation workshop designs protective packaging for ceramic artefacts. Before testing an empty carrier, it checks its vertical drop rig with a dense steel reference ball and slow-motion video. The team must validate the measurements, then choose a drop height for a specified impact speed.



Take downward as positive. Use $h = ut + \frac{1}{2}at^2$ and $v^2 = u^2 + 2ah$. For the reference ball, assume release from rest and negligible air resistance unless stated otherwise. The camera captures 240 frames per second at a constant, exactly known rate. Use worst-case uncertainties. Apparatus diagrams are not to scale.

1. Define the free-fall model [2 marks]

The steel ball provides a reference before the workshop tests a larger packaging carrier.

(a) State what is meant by free fall. [1 mark]

Motion under the action of gravity alone. [1] “Falling downwards” alone is insufficient: an object can move downwards while other forces act. A small dense ball in air can approximate free fall when drag is negligible.

(b) An ideal drop from rest gives $h = 0.600$ m and $t = 0.350$ s. Calculate an estimate of g. [1 mark]

$h = \frac{1}{2}gt^2$, so $g = 2h/t^2 = (2 \times 0.600)/(0.350)^2 = 9.80 \text{ m s}^{-2}$. [1] Acceleration is not h/t ; h/t would give average speed.

Teaching prompt: Free fall identifies the force model, not a direction of motion or a requirement that velocity is zero throughout the fall.

Continue your physics journey

Videos, practice and support for your next step

www.physicsuk.co.uk



2. Use the video measurement [7 marks]

In the diagram, frame 0 is the instant of release from rest. At frame 96, before impact, the bottom of the ball is 0.780 m below its position in frame 0. The labels identify two frames of the same ball, not two balls released together.

(a) Determine the elapsed time and use this run to calculate g . [2 marks]

Elapsed time = $(96 - 0)/240 = 0.400$ s. [1] $g = 2h/t^2 = (2 \times 0.780)/(0.400)^2 = 9.75$ m s⁻². [1] There are 96 frame intervals between frames 0 and 96, not 97 intervals.

(b) Explain why the team measures between the same point on the ball in both frames, and why the metre rule should be in the plane of the fall with the camera viewing that plane perpendicularly. [2 marks]

Tracking the same point (for example the bottom edge) gives the ball's displacement without adding or subtracting a radius/diameter. [1] Keeping the scale in the plane of motion and viewing it perpendicularly reduces parallax/perspective scale errors. [1] A ruler well behind the ball can give a different image scale even when both appear sharp.

(c) In a separate run the release gives the ball an initial downward speed u . The team still uses $g_{\text{est}} = 2h/t^2$. Use $h = ut + \frac{1}{2}gt^2$ to obtain an expression for $g_{\text{est}} - g$. Evaluate this bias for $u = 0.050$ m s⁻¹ and $t = 0.400$ s. [2 marks]

$g_{\text{est}} = 2(ut + \frac{1}{2}gt^2)/t^2 = g + 2u/t$, hence $g_{\text{est}} - g = 2u/t$. [1] Bias = $(2 \times 0.050)/0.400 = +0.250$ m s⁻²: g is overestimated. [1] These values describe the separate pushed-release run; the zero-initial-speed model no longer applies.

(d) Give one reason why timing the fall from recorded frames is preferable to starting and stopping a handheld stopwatch. [1 mark]

It avoids the operator's start/stop reaction-time error for the short fall. [1] Video still has uncertainty in choosing the release and end frames; "video has no error" is not acceptable.

Teaching prompt: Use capture rate, not playback speed. Repeats do not correct a release mechanism that consistently gives an initial push.



3. Determine g from a graph [7 marks]

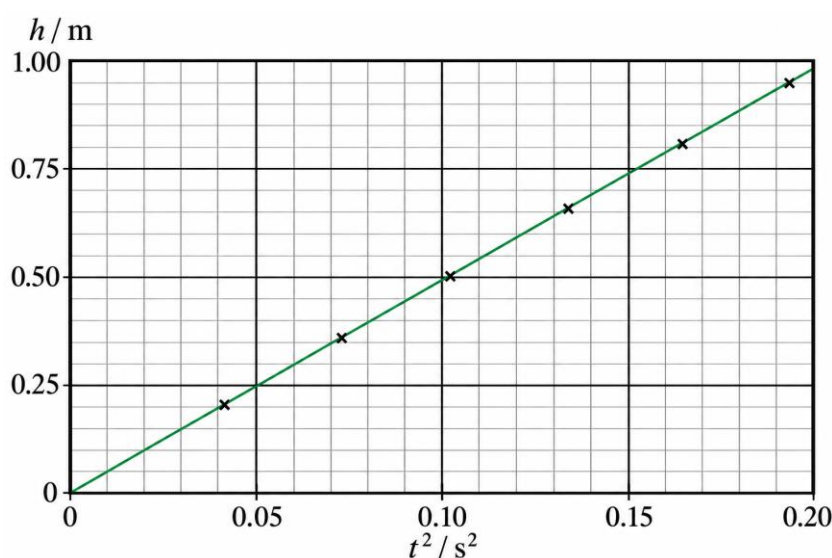
At $h = 0.500$ m the three fall times are 0.317 s, 0.319 s and 0.321 s. The other rows give mean times and their squares, rounded to four decimal places.

Height h / m	Mean time t / s	Square of mean t^2 / s^2
0.200	0.202	0.0408
0.350	0.267	0.0713
0.500	0.319	0.1018
0.650	0.364	0.1325
0.800	0.404	0.1632
0.950	0.440	0.1936

(a) Complete the missing mean time and its square in the table. [1 mark]

Mean $t = (0.317 + 0.319 + 0.321)/3 = 0.319$ s; square of the mean $= (0.319)^2 = 0.101761$ $s^2 \approx 0.1018$ s^2 . Both entries correct. [1] Square the stated mean time for this table.

(b) Plot all six points of h against t^2 on the grid. Draw one straight line of best fit, rather than joining successive points. [3 marks]



Use the completed table coordinates, as shown above. Three to five points within half a small grid division. [1] All six correctly plotted. [1] One straight best-fit line balancing the scatter and passing close to the origin. [1] Reference: $h \approx 4.90t^2$. Do not demand an exactly zero experimental intercept.

(c) Use a large triangle on your line to calculate its gradient, including the unit. Show the coordinates you use. [2 marks]

For example, use line coordinates $(0.040$ s^2 , 0.196 m) and $(0.180$ s^2 , 0.882 m): gradient $= (0.882 - 0.196)/(0.180 - 0.040)$. [1] Gradient ≈ 4.90 m s^{-2} . [1] Accept approximately 4.75 – 5.05 m s^{-2} from a reasonable line. Use a triangle spanning at least half the occupied horizontal range, not two adjacent data points.

(d) Use $h = \frac{1}{2}gt^2$ to obtain g from your gradient. [1 mark]

The gradient of h against t^2 is $g/2$, so $g = 2 \times \text{gradient} \approx 2 \times 4.90 = 9.80$ m s^{-2} . [1] Accept a consistent value from the candidate's gradient. If the vertical axis were $2h$, its gradient would instead be g .

Teaching prompt: The axes matter: h against t^2 has gradient $g/2$. The graph does not show h against t , and the gradient is not a speed.

Continue your physics journey

Videos, practice and support for your next step

www.physicsuk.co.uk



4. Quantify the uncertainty [6 marks]

Return to the 0.780 m camera run. Each selected frame number has uncertainty ± 1 frame. The two endpoint contributions are added in the stated worst-case approach. Use $g = 9.75 \text{ m s}^{-2}$ in part (b), regardless of earlier answers.

(a) Calculate the absolute uncertainty in the elapsed time, then its percentage uncertainty for $t = 0.400 \text{ s}$. [2 marks]

Uncertainty in elapsed frame count = $1 + 1 = 2$ frames, so $\Delta t = 2/240 = 0.00833 \text{ s}$. [1] Percentage uncertainty = $(0.00833/0.400) \times 100 = 2.08\% \approx 2.1\%$. [1] The two frame-number uncertainties belong to the same time difference; do not use only one endpoint.

(b) The measured height is $(0.780 \pm 0.004) \text{ m}$. Use $g = 2h/t^2$ and your answer to (a) to calculate the worst-case percentage uncertainty in g and its absolute uncertainty. [2 marks]

Percentage uncertainty in $g = (0.004/0.780) \times 100 + 2 \times (2/96) \times 100 = 0.513 + 4.167 = 4.68\% \approx 4.7\%$. Correct power-weighted combination. [1] Absolute uncertainty = $9.75 \times 0.0467949 = 0.456 \text{ m s}^{-2} \approx 0.46 \text{ m s}^{-2}$. [1] The factor 2 is exact; the percentage time uncertainty is doubled because t is squared.

(c) For the graph, the minimum and maximum acceptable gradients are 4.76 m s^{-2} and 5.00 m s^{-2} . Use their midpoint as the gradient estimate and half their range as its uncertainty. Obtain g with its absolute uncertainty, then judge whether it is consistent with 9.81 m s^{-2} . [2 marks]

Midpoint gradient = $(4.76 + 5.00)/2 = 4.88 \text{ m s}^{-2}$ and $\Delta_{\text{gradient}} = (5.00 - 4.76)/2 = 0.12 \text{ m s}^{-2}$. Hence $g = (9.76 \pm 0.24) \text{ m s}^{-2}$. [1] Yes: 9.81 m s^{-2} lies in the interval $9.52\text{--}10.00 \text{ m s}^{-2}$. [1] Both the value and its absolute uncertainty are multiplied by two. The full gradient range is not the uncertainty.

Teaching prompt: Separate absolute and percentage uncertainties. Multiplying a measured gradient by two doubles its absolute uncertainty, but leaves its percentage uncertainty unchanged.



5. Plan a repeatable free-fall investigation [7 marks]

Parts (a)–(c) scaffold a six-mark-style practical method using the camera and reference ball. Include operational details, not only a list of equipment.

(a) Describe the release arrangement and how you would measure the vertical displacement without a systematic geometry error. [2 marks]

Use a stable stand and a release that lets the small dense ball fall vertically from rest without a push, with a padded catch tray below and clear of the measured fall. [1] Place a vertical metre rule in the plane of motion, view it perpendicularly with a fixed camera and measure the displacement of the same point on the ball in the start and end frames. [1] Check the ruler scale/calibration; do not measure from the release clamp to the final ball centre.

(b) Describe how to obtain the fall time from the recording and limit timing uncertainty. [2 marks]

Use the known capture frame rate f and identify the release frame and the frame at the chosen end position; count the intervals N between them and use $t = N/f$. [1] Use a high capture rate with clear, well-lit frames/short exposure to reduce motion blur and repeated checking of the selected frames, or increase the safe fall distance to increase N . [1] Use the capture rate, not the slow playback rate. Repeating a frame selection does not validate an incorrect capture-rate calibration.

(c) Describe the measurements and analysis you would use to obtain a defensible value of g , rather than relying on one drop. [2 marks]

Repeat drops at each of several well-spaced measured heights, inspect anomalous readings and calculate a mean time for each height before squaring it. [1] Plot h against t^2 , draw a best-fit line and use $g = \text{twice its gradient}$; estimate an uncertainty, for example from acceptable limiting gradients, and compare with a reference value using that uncertainty. [1] Repeats help with random variation but do not remove an initial push or a ruler/frame-rate calibration error.

(d) State one specific precaution against injury or damage from the falling ball. [1 mark]

Place a padded catch tray beneath the drop to stop the ball bouncing or rolling into someone. [1] Accept securing the stand/release, keeping hands and feet out of the falling path, or another relevant specific precaution. The tray must not support the ball during the measured fall.

Teaching prompt: A useful method explains how each measured quantity is obtained and how errors are reduced. “Repeat and average” is not a remedy for every systematic error.



6. Set the packaging drop test [7 marks]

Use $g = 9.76 \text{ m s}^{-2}$ for the empty carrier, which is released from rest with negligible air resistance in parts (a)–(c). A separate light-gate check uses the speeds stated; do not assume the carrier is at rest when it reaches the upper gate.

(a) The required impact speed is 3.00 m s^{-1} . Calculate the drop height and the time from release to impact. [2 marks]

From $v^2 = 2gh$, $h = (3.00)^2/(2 \times 9.76) = 0.461 \text{ m}$. [1] From $v = gt$, $t = 3.00/9.76 = 0.307 \text{ s}$. [1] Measure the drop displacement of the same point on the carrier; the release-clamp height is not necessarily that displacement.

(b) A timer is started only when the falling carrier reaches an upper light gate below the release point. Explain why $h = \frac{1}{2}gt^2$ cannot be applied to the distance and time between two lower light gates. [1 mark]

The carrier already has a nonzero downward speed when the timed interval begins, so the displacement includes an initial-speed term ut . [1] Gravity has not stopped acting at the upper gate; $u = 0$ applies at release, not at every measuring point.

(c) Two gates are 0.400 m apart vertically. The instantaneous speeds are 1.50 m s^{-1} at the upper gate and 3.17 m s^{-1} at the lower gate. Calculate the acceleration between the gates. [2 marks]

Use $v^2 = u^2 + 2ah$, giving $a = (v^2 - u^2)/(2h)$. [1] $a = ((3.17)^2 - (1.50)^2)/(2 \times 0.400) = 9.75 \text{ m s}^{-2}$. [1] This is consistent with 9.76 m s^{-2} after rounding of the given speeds. The speed difference divided by distance is not an acceleration.

(d) A lightweight dummy carrier fitted with a wide card panel takes longer to fall from the same height than the reference steel ball. Explain why this does not show that the local g has decreased, and what happens to the value calculated using $2h/t^2$. [2 marks]

The larger upward air resistance reduces the resultant downward force and acceleration; local gravitational acceleration g has not changed. [1] The longer time makes $2h/t^2$ smaller, so this method underestimates g when drag is significant and the free-fall model is used incorrectly. [1] As drag grows, acceleration can vary; the carrier is no longer falling under gravity alone.

Teaching prompt: Distinguish gravitational acceleration from the actual acceleration when drag acts. Say that downward velocity increases, not that “velocity is accelerating”.

