REAL-LIFE PHYSICS

Our Dynamic Universe

Teacher guide

For the Higher Physics workbook



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Blewis LEARNING

Using the workbooks

The Higher Physics workbook for **Our Dynamic Universe** has six topics. Every topic has learning pages, a practical the learner plans and evaluates (with uncertainties), a brain break and an exam-style check-up.

PRACTICALS

Learners plan each investigation (variables, prediction, kit, risk, method), take repeat readings, work out averages, draw graphs with their own scales, and write conclusions and evaluations.

PRACTICAL SAFETY

Every practical has a Stay safe table and a teacher note with hazards, adapted versions and common problems. The Stay safe tables and these notes are a starting point, not a complete risk assessment: the teacher or school must risk assess every practical for their own learners, room and kit before use, following their employer's policies and national guidance (in Scotland, SSERC). Always check learners' care plans and medical information. High-voltage supplies and tubes are teacher-only; radioactive sources and nuclear processes are covered by data or simulations; lasers are class 2 only and never looked into.

NO LAB, NO KIT, OR A LEARNER ABSENT

Each practical includes example results so learners can still complete the results, graph, conclusion and evaluation.

EVIDENCE

The practicals develop the skills needed for the assignment and for questions on experimental work in the exam; the learn pages and check-ups build knowledge and problem solving. The skills tracker at the back of each workbook can be signed off as you go. Always check the latest course documents and your centre's arrangements.

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TEACHER NOTES

Practical 1: Measuring g with a light gate

Time	One 55-minute period in pairs or threes: about 30 minutes of measurements (five heights, three repeats) and the graph for homework.
Kit per group	Light gate and timer or data logger reading to 0.1 ms, a 5.00 cm card weighted with a small mass (or a 5.00 cm interrupt card on a 100 g mass), clamp stand clamped to the bench, metre stick, padded catch box.
Prep	Check the card blocks the beam fully and falls flat. Mark heights on the metre stick. A heavier mass reduces the effect of air resistance.
Expected results	v^2 against h gives a straight line close to the origin with gradient about 19 m/s^2 (sample data: 19.6), so g between about 9.6 and 9.9 m/s^2.
Level	H plans the test, finds means, random and scale-reading uncertainties and the largest percentage uncertainty, draws a best-fit line and finds g from the gradient.

Safety and inclusion

- Drop into a padded box on the floor; nobody puts hands or feet under the card. The clamp stand is clamped to the bench, never held at height on a chair.
- All roles can be done seated: releasing from a lower height, reading the timer or recording.
- Risk assess for your own class and follow your employer's policies and SSERC guidance.

Common problems

- **Air resistance:** slows the card and gives a low g; a heavier mass on the card reduces it. Keep the card vertical so it passes squarely through the beam.
- **Height measured to the wrong point:** measure from the bottom of the card at release to the beam.
- **Card length in cm:** convert to metres before dividing.

No lab, no time, or a learner absent?

The sample results let learners complete the analysis, graph, uncertainty and evaluation without the practical.

Assessment link

Good practice for the assignment: uncertainties, a graph with a gradient, comparison with a published value and a reference.

Answers: Topic 1

Topic 1: Motion: equations and graphs (Higher)

1 The equations of motion

1 a = (v − u) ÷ t = (0 − 6.0) ÷ 40 = −0.15 m/s² (a deceleration of 0.15 m/s²). s = ½ (u + v) t = ½ × 6.0 × 40 = 120 m.

2 s = u t + ½ a t² = 0 + ½ × 9.8 × 1.8² = 15.9 m, so about 16 m. v = u + a t = 9.8 × 1.8 = 17.6 m/s, so about 18 m/s.

3 v² = u² + 2 a s: 12.0² = 2.0² + 2 × a × 70, so 144 = 4 + 140 a and a = 140 ÷ 140 = 1.0 m/s².

2 Motion graphs

1 A horizontal line at −9.8 m/s² from A to D, with a short spike upwards (a large positive value) at the bounce B to C.

2 (a) a = 8 ÷ 4 = 2.0 m/s². (b) a = (0 − 8) ÷ 2 = −4.0 m/s². (c) area = 16 + 48 + 8 = 72 m upwards.

3 The velocity changes all the time (the ball slows on the way up and speeds up on the way down), so the gradient of the displacement–time graph changes and the line curves.

3 Up, down and measuring acceleration

1 t = (0 − 24.5) ÷ (−9.8) = 2.5 s. s = (0 − 24.5²) ÷ (2 × −9.8) = 30.6 m, so about 31 m.

2 u = 0.020 ÷ 0.040 = 0.50 m/s; v = 0.020 ÷ 0.025 = 0.80 m/s; a = (0.80 − 0.50) ÷ 0.30 = 1.0 m/s².

3 Its weight still acts on it at the top, so its velocity is still changing (from up to down) at 9.8 m/s per second. Zero velocity does not mean zero acceleration.

Practical 1: Measuring g with a light gate

Variables: change the height the card falls before the gate; measure the time the card blocks the beam, then calculate v; keep the same: the card (length and mass), release method (from rest), light gate settings.

Theory: v² = 2 g h, so the graph of v² against h is a straight line through the origin with gradient 2g.

Equipment: light gate, timer or logger, card with mass, clamp stand, metre stick, catch box. Not needed: thermometer, stopwatch.

Hazards, e.g. clamp stand toppling (clamp to the bench or add a counterweight); trailing leads (tape them down).

Method key points: measure the height from the bottom of the card at release to the beam; release from rest without pushing; three repeats at each of five heights; v = card length ÷ mean time; plot v² against h.

Sample results: 0.200 m: 0.0254 s, 1.97 m/s, 3.88 m²/s²; 0.400 m: 0.0179 s, 2.79 m/s, 7.80 m²/s²; 0.600 m: 0.0146 s, 3.42 m/s, 11.73 m²/s²; 0.800 m: 0.0127 s, 3.94 m/s, 15.50 m²/s²; 1.000 m: 0.0113 s, 4.42 m/s, 19.58 m²/s².

Gradient of best-fit line ≈ 19.6 m/s², so g ≈ 9.78 m/s² (accept 9.6 to 9.9 m/s²).

(a) at 1.000 m: (0.0114 − 0.0113) ÷ 3 = ±0.00003 s, about ±0.00003 s; this is smaller than the scale-reading uncertainty of ±0.0001 s, which is about 0.9% of the mean, so quote ±0.0001 s (0.9%).

(b) percentage difference = (9.8 − 9.78) ÷ 9.8 × 100 ≈ 0.2%.

(c) Systematic: air resistance on the card slows it, so v and so g are too small. Precision: make sure the card falls vertically through the beam, use a longer drop range, more repeats, or a logger reading to 0.00001 s.

Check-up

1 (a) v = u + a t (1); v = 0 + 1.5 × 4.0 (1); v = 6.0 m/s (1). (b) s = u t + ½ a t² (1); s = 0 + ½ × 1.5 × 4.0² (1); s = 12 m (1).

2 s = u t + ½ a t² with down positive (1); s = 3.0 × 2.0 + ½ × 9.8 × 2.0² = 6.0 + 19.6 = 25.6 m, about 26 m (1).

3 Open-ended (3 marks: a full, clear explanation of the main physics.) Points could include: Zara is wrong; both balls have the same vertical motion (u = 0 vertically, a = 9.8 m/s² downwards), so they fall the same height in the same time and land together (ignoring air resistance); horizontal motion is independent of vertical motion; in practice air resistance could make a small difference.

4 Mean = 0.0221 s (1); random uncertainty = (0.0225 − 0.0218) ÷ 5 = ±0.00014, so ±0.0001 s (1); percentage = 0.0001 ÷ 0.0221 × 100 ≈ 0.5% (accept 0.5 to 0.7%) (1).

TEACHER NOTES

Practical 2: How does acceleration depend on force?

Time	One 55-minute period in pairs: about 30 minutes of measurements, then the graph.
Kit per group	Dynamics trolley, runway with a pulley clamped at the end, two light gates and logger (or one gate with a double-mask card), mass hanger with 10 g slotted masses, string, balance, sand tray or foam under the hanger.
Prep	Friction-compensate the runways beforehand if time is short. Total mass (trolley, masses, hanger) 1.00 kg.
Expected results	A straight line close to the origin; gradient about 0.97 kg^{-1}, so a mass about 1.03 kg, slightly more than 1.00 kg, e.g. because the mass of the string, pulley or hanger was not included, or the slotted masses are not exactly their stated values. Leftover friction would instead give an intercept on the force axis.
Level	H plans a fair test with a constant total mass, uses uncertainties, finds the mass from the gradient and evaluates.

Safety and inclusion

- Short drop for the hanger onto sand or foam; a stop at the end of the runway; feet clear.
- All roles can be done seated: logging, releasing at bench height, recording.
- Risk assess for your own class and follow your employer's policies and SSERC guidance.

Common problems

- **Total mass changing:** masses must be moved from trolley to hanger, not added.
- **Using hanging mass instead of weight** on the x-axis: multiply by 9.8.

No lab, no time, or a learner absent?

The sample results allow the whole analysis to be done without the practical.

Assessment link

Gradient analysis and uncertainties, as needed for the assignment and the exam.

Answers: Topic 2

Topic 2: Forces, energy and power (Higher)

1 Newton's second law

1 Resultant = 140 − 35 = 105 N; a = 105 ÷ 70 = 1.5 m/s².

2 R − m g = m a, so R = m (g + a) = 60 × (9.8 + 1.2) = 660 N.

3 a = 15 ÷ (2.0 + 3.0) = 3.0 m/s². The rope pulls only the rear 2.0 kg sledge: T = 2.0 × 3.0 = 6.0 N.

2 Components and slopes

1 Horizontal = 400 cos 30° = 346 N; vertical = 400 sin 30° = 200 N.

2 Down slope = 65 × 9.8 × sin 15° = 165 N; resultant = 165 − 80 = 85 N; a = 85 ÷ 65 = 1.3 m/s².

3 At first weight is bigger than air resistance, so she accelerates. As her speed rises, air resistance increases until it equals her weight. The forces are then balanced, so the resultant force is zero and she moves at a steady (terminal) velocity.

3 Energy and power

1 E_p = 80 × 9.8 × 15 = 11 760 J (1.2 × 10⁴ J). P = 11 760 ÷ 20 = 588 W, about 590 W.

2 m g h = ½ m v², so v = √(2 g h) = √(2 × 9.8 × 2.0) = 6.3 m/s.

3 E_p at top = 12 × 9.8 × 8.0 = 941 J; E_k at bottom = ½ × 12 × 10² = 600 J; energy transferred by friction = 341 J, about 3.4 × 10² J.

Practical 2: How does acceleration depend on force?

Variables: change the resultant force (the hanging weight); measure the acceleration; keep the same: the total mass of the system (by moving masses from the trolley to the hanger), the friction-compensated runway, the light-gate positions.

Theory: a = F ÷ m, so a against F is a straight line through the origin with gradient 1 ÷ m.

Equipment: trolley, runway, light gates, logger, slotted masses (and hanger), balance. Not needed: thermometer.

Hazards, e.g. trolley running off the end (fit a stop); trailing leads (tape down).

Method key points: tilt the runway until the trolley rolls at constant speed when pushed (friction compensated); keep total mass constant; release from rest at a mark; measure a with two light gates or a double-mask card; three repeats each.

Sample results: 0.010 kg: F = 0.098 N, mean a = 0.095 m/s²; 0.020 kg: F = 0.196 N, mean a = 0.190 m/s²; 0.030 kg: F = 0.294 N, mean a = 0.285 m/s²; 0.040 kg: F = 0.392 N, mean a = 0.381 m/s²; 0.050 kg: F = 0.490 N, mean a = 0.476 m/s².

Gradient ≈ 0.972 kg^{-1}, so mass = 1 ÷ gradient ≈ 1.03 kg (accept 0.98 to 1.06 kg).

(a) Random uncertainty = (0.481 − 0.471) ÷ 3 = ±0.0033 m/s², about ±0.003 m/s²; percentage = 0.7%.

(b) The acceleration is directly proportional to the resultant force (straight line through the origin). The mass from the graph is about 1.03 kg, close to 1.00 kg.

(c) Leftover friction (the runway not perfectly compensated) means a small force is needed before the trolley accelerates, giving an intercept on the force axis; the masses not being exactly their stated values also shifts the points.

Check-up

1 T − m g = m a (1); T = 900 × (9.8 + 0.40) (1); T = 9180 N, about 9.2 × 10³ N (1).

2 Component = 40 × 9.8 × sin 25° = 166 N (1); resultant = 166 − 60 = 106 N (1); a = 106 ÷ 40 = 2.6 m/s² (1).

3 E_p = 75 × 9.8 × 60 = 44 100 J (1); P = 44 100 ÷ 120 = 368 W, about 370 W (1).

4 Open-ended (3 marks: a full, clear explanation of the main physics.) Points could include: weight greater than air resistance, so she accelerates; air resistance increases with speed until balanced, giving terminal velocity; opening the parachute increases air resistance so the resultant force is upwards and she decelerates; air resistance falls as she slows until it again equals weight, giving a new, lower terminal velocity; the landing force from the ground brings her to rest.

5 E_k = ½ × 0.15 × 12² = 10.8 J (1); E_p = 0.15 × 9.8 × 6.5 = 9.55 J (1); energy to the air = 1.2 J (1).

TEACHER NOTES

Practical 3: Is momentum conserved?

Time	One 55-minute period in pairs: four masses with three runs each, about 30 minutes.
Kit per group	Two dynamics trolleys (Velcro pads or pin and cork), friction-compensated runway, two light gates and logger, a card on trolley A, slotted masses, balance, stop at the end.
Prep	Check both trolleys roll freely. Card heights must break both beams. Gate 2 should be close to the collision point.
Expected results	Momentum after about 1 to 4% lower than before (sample: 3%, 3%, 3%, 3%); kinetic energy clearly lost.
Level	H plans the test, uses percentage uncertainties, tests conservation within uncertainty and classifies the collision.

Safety and inclusion

- A stop at the end of the runway; masses taped on; push gently.
- All roles can be done seated at the bench.
- Risk assess for your own class and follow your employer's policies and SSERC guidance.

Common problems

- **Trolleys not sticking:** check the Velcro or the pin and cork.
- **Pushing through gate 1:** the push must have finished before the card reaches the gate.
- **Using the mass of A only after:** after the collision the mass is A + B.

No lab, no time, or a learner absent?

The sample results let learners do the whole analysis without the practical.

Assessment link

Percentage uncertainties and judging a result "within uncertainty", as the assignment and the exam expect.

Answers: Topic 3

Topic 3: Collisions, explosions and impulse (Higher)

1 Conservation of momentum

1 Before: 20 × 1.5 = 30 kg m/s. After: 20 × 0.30 + 20 v. So 20 v = 24 and v = 1.2 m/s in the original direction.

2 (60 × 4.0) + (40 × 1.0) = 280 kg m/s = 100 v, so v = 2.8 m/s east.

3 East positive: 1200 × 15 + 800 × (−10) = 18 000 − 8000 = 10 000 kg m/s = 2000 v, so v = 5.0 m/s east.

2 Elastic, inelastic and explosions

1 E_k before = ½ × 1200 × 15² + ½ × 800 × 10² = 175 000 J. After = ½ × 2000 × 5.0² = 25 000 J. Kinetic energy is lost, so it is inelastic.

2 Total momentum is zero: 0.40 × (−15) + 0.20 v = 0, so v = 30 m/s to the right.

3 Each skater pushes on the other with an equal and opposite force for the same time (Newton's third law), so they get equal and opposite impulses: their momenta are equal and opposite, adding to the zero they started with. Equal momentum with a smaller mass needs a bigger velocity.

3 Impulse

1 Impulse = area = ½ × 0.020 × 400 = 4.0 N s. v = 4.0 ÷ 0.16 = 25 m/s.

2 F = (m v − m u) ÷ t = (0 − 19 × 0.80) ÷ 0.050 = −304 N, so about 300 N against the motion.

3 The driver's change in momentum is the same, but the airbag makes the stopping time longer, so (F = Δp ÷ t) the average force on the driver is smaller.

Practical 3: Is momentum conserved?

Variables: change the mass of trolley A; measure u of A before and v of both after; keep the same: the mass of B, the friction-compensated runway, the card length, the gate positions.

Equipment: two trolleys (one with Velcro or a pin and cork), runway, light gates, logger, masses, balance. Not needed: stopwatch.

Hazards, e.g. masses falling off the trolley (secure with tape); trailing leads (tape down).

Method key points: friction-compensate; measure masses on a balance; push A gently through gate 1; time the joined trolleys through gate 2; three runs per mass; p = m v before and after.

Sample results: 0.50 kg: before 0.310, after 0.300 kg m/s (3.2% less); 1.00 kg: before 0.580, after 0.562 kg m/s (3.1% less); 1.50 kg: before 0.825, after 0.800 kg m/s (3.0% less); 2.00 kg: before 1.200, after 1.164 kg m/s (3.0% less).

(a) Mass: 0.01 ÷ 1.00 = 1%. Velocity: 0.01 ÷ 0.58 ≈ 1.7%. The velocity has the larger percentage uncertainty.

(b) E_k before = ½ × 1.00 × 0.58² = 0.168 J; after = ½ × 2.00 × 0.281² = 0.079 J. Kinetic energy is lost, so the collision is inelastic.

Conclusion: the momentum after is consistently about 3% less than before, more than the 1.7% uncertainty, so a systematic effect (friction, the trolleys slowing before gate 2) is acting. Momentum is conserved apart from this external force.

(c) Friction is not completely compensated, so a small external force acts during and after the collision; or the joined trolleys slow before gate 2.

(d) Use an air track, put gate 2 close to the collision, or take more repeats.

Check-up

1 0.17 × 2.0 = 0.17 v (1), so v = 2.0 m/s (1). E_k before = ½ × 0.17 × 2.0² = 0.34 J; after = ½ × 0.17 × 2.0² = 0.34 J (1). Kinetic energy is conserved, so it is elastic (1).

2 Total momentum zero: 0 = 2.0 × 30 + 50 v (1, 1); v = −1.2 m/s, so 1.2 m/s backwards (1).

3 Take the final direction as positive: change in momentum = 0.058 × 25 − 0.058 × (−20) (1) = 2.61 kg m/s (1); F = 2.61 ÷ 0.0040 (1) = 653 N, about 650 N (1).

4 Open-ended (3 marks: a full, clear explanation of the main physics.) Points could include: the climber's change in momentum is the same either way; a stretchy rope increases the stopping time; so the average force (F = Δp ÷ t) on the climber and the anchors is much smaller; a steel cable would stop her very quickly, giving a large force that could injure her or break the anchors.

TEACHER NOTES

Practical 4: Does range depend on launch speed?

Time	One 55-minute period in pairs: five speeds with three repeats, about 30 minutes.
Kit per group	Curved ramp or grooved track clamped at the bench edge, steel ball or marble, light gate and logger, carbon paper on white paper, metre stick, plumb line, sand tray beyond the landing area.
Prep	The end of the ramp must be horizontal at the bench edge. Mark release heights on the ramp to give a spread of speeds.
Expected results	A straight line through the origin; gradient about 0.42 s, close to $\sqrt{(2h/g)}$ = 0.43 s for a 0.900 m bench.
Level	H links the gradient to the time of flight, uses uncertainties and evaluates.

Safety and inclusion

- Balls on the floor are a slip hazard: collect them at once and use a sand tray. Keep the landing area clear of people.
- All roles can be done seated: releasing at bench height, logging, marking the landing point.
- Risk assess for your own class and follow your employer's policies and SSERC guidance.

Common problems

- **Range measured from the bench leg** rather than directly below the edge: use a plumb line.
- **Ramp end not horizontal:** the ball leaves at an angle and the line curves.

No lab, no time, or a learner absent?

The sample results allow the full analysis without the practical.

Assessment link

Gradient meaning, uncertainties and comparing two values, as in the assignment and the exam.

Answers: Topic 4

Topic 4: Projectiles and gravitation (Higher)

1 Horizontal projectiles

1 Vertical: $80 = ½ \times 9.8 \times t^2$, t = 4.04 s, about 4.0 s. Horizontal: d = 20 × 4.04 = 81 m.

2 Vertical v = 0 + 9.8 × 4.04 = 39.6 m/s. Resultant = $\sqrt{(20^2 + 39.6^2)}$ = 44 m/s at 63° below the horizontal.

3 Its horizontal velocity stays the same while its vertical velocity keeps increasing downwards, so the direction of motion changes all the time.

2 Launched at an angle

1 u_h = 30 cos 35° = 24.6 m/s; u_v = 30 sin 35° = 17.2 m/s. Max height: $0 = 17.2^2 - 2 \times 9.8 \times s$, s = 15.1 m.

2 Time to top = 17.2 ÷ 9.8 = 1.76 s, so flight = 3.5 s. Range = 24.6 × 3.51 = 86 m.

3 Air resistance acts against its motion, reducing the horizontal velocity (and the height), so it travels a shorter distance.

3 Newton's law of gravitation

1 $F = 6.67 \times 10^{-11} \times 5.0 \times 5.0 \div 0.20^2 = 4.2 \times 10^{-8}$ N.

2 $F = 6.67 \times 10^{-11} \times 6.0 \times 10^{24} \times 7.3 \times 10^{22} \div (3.84 \times 10^8)^2 = 2.0 \times 10^{20}$ N.

3 A quarter of the force, about 2.0×10^3 N, because F is inversely proportional to r^2: doubling r divides F by $2^2 = 4$.

Practical 4: Does range depend on launch speed?

Variables: change the launch speed (by releasing the ball from different heights on the ramp); measure the range; keep the same: the bench height, the ball, where the ramp ends.

Equipment: ramp, light gate, logger, metre stick, ruler, carbon paper on white paper. Not needed: thermometer.

Hazards, e.g. ramp falling off the bench (clamp it); someone walking into the landing area (mark it off).

Method key points: measure the speed with a light gate at the end of the ramp; tape carbon paper on white paper where the ball lands; measure the range from directly below the edge (use a plumb line); three repeats; plot range against speed.

Sample mean ranges: 0.80 m/s: 33.6 cm; 1.00 m/s: 42.1 cm; 1.20 m/s: 50.4 cm; 1.40 m/s: 58.9 cm; 1.60 m/s: 67.2 cm.

Gradient ≈ 0.420 s. (a) The gradient is the time of flight. From the bench, $t = \sqrt{(2 \times 0.900 \div 9.8)}$ = 0.429 s; the gradient is about 2% smaller.

(b) Random uncertainty = (68.0 − 66.5) ÷ 3 = ±0.5 cm; percentage = 0.7%.

Conclusion: the range is directly proportional to the launch speed (a straight line through the origin).

(c) Air resistance, or the ball not leaving the bench exactly horizontally, or the light gate measuring the speed slightly before the edge.

Check-up

1 (a) $45 = ½ \times 9.8 \times t^2$ (1); t = 3.0 s (1). (b) d = 8.0 × 3.03 (1) = 24 m (1).

2 u_v = 20 sin 30° = 10 m/s (1); time to top = 10 ÷ 9.8 = 1.02 s, so flight = 2 × 1.02 = 2.04 s, about 2.0 s (1).

3 $F = G m_1 m_2 / r^2$ (1); $F = 6.67 \times 10^{-11} \times 6.0 \times 10^{24} \times 70 \div (6.8 \times 10^6)^2$ (1); F = 606 N, about 6.1×10^2 N (1).

4 Open-ended (3 marks: a full, clear explanation of the main physics.) Points could include: gravity is still strong there (the force is about 600 N, not much less than on the surface); she feels weightless because she and the station are both falling towards the Earth at the same rate (free fall), so nothing pushes up on her; they move sideways fast enough to stay in orbit.

TEACHER NOTES

Data practical 5: Do muons prove time dilation?

Time	One 50-minute lesson, individually or in pairs. No apparatus.
What it is	A data-analysis practical modelled on a classic muon experiment. The counts are realistic but made up for the book.
Optional extras	If your department has a cosmic-ray (muon) detector, compare counts indoors and outdoors or at different floors. A short video of a cloud chamber shows tracks.
Expected results	Classical prediction about 38 per hour; relativistic prediction about 418; measured 410. $\gamma \approx 9.1$.
Level	H processes data, uses uncertainties in counts and evaluates a model against evidence.

Safety and inclusion

- No practical hazards in class. If you use a cloud chamber, follow local rules for dry ice (teacher handles it with gloves; ventilation).
- Calculator steps can be scaffolded with the worked example; pair learners for discussion of the conclusion.
- Risk assess for your own class and follow your employer's policies and SSERC guidance.

Common problems

- **Using 0.994 instead of 0.994^2** inside the square root.
- **Dividing instead of multiplying by γ:** the muons' own time is shorter.
- **Powers of a half:** show how to use the x^y key for 0.5^n.

Assessment link

Data handling, comparing predictions with measurements, and referencing a source, all useful for the assignment.

Answers: Topic 5

Topic 5: Special relativity (Higher)

1 Two big ideas

1 The laws of physics are the same for all observers moving at constant velocity relative to each other; the speed of light in a vacuum is the same for all observers.

2 3.00×10^8 m/s (c). The speed of light is the same for every observer, whatever the speed of the source.

3 Simple adding would give light faster than c, but every observer measures light at exactly c. Near the speed of light, time and length change instead, so speeds do not just add.

2 Time dilation

1 $t' = 2.2 \div \sqrt{(1 - 0.995^2)} = 22$ µs.

2 $t = t' \times \sqrt{(1 - 0.60^2)} = 25 \times 0.80 = 20$ hours.

3 $v \div c = 7.5 \times 10^3 \div 3.00 \times 10^8 = 2.5 \times 10^{-5}$; $\sqrt{(1 - (2.5 \times 10^{-5})^2)} = 0.999\ 999\ 9997$, which is greater than 0.999 999 999, so the effect is less than one part in a billion.

3 Length contraction

1 $l' = 10 \times \sqrt{(1 - 0.995^2)} = 1.00$ km, about 1.0 km.

2 $l' \div l = 0.60 = \sqrt{(1 - v^2/c^2)}$, so $v^2/c^2 = 1 - 0.36 = 0.64$ and $v = 0.80c$.

3 In the muons' frame the atmosphere is moving and is length-contracted to about 1 km, so the distance is short enough for many muons to cross it before decaying.

Data practical 5: Do muons prove time dilation?

Plan: changes: the height of the detector (summit or sea level); measured: number of muons detected per hour; kept the same: the detector and its settings, the counting time, similar weather and time of day.

Equipment: detector (scintillator or Geiger-type), counter, timer. Not needed: thermometer, balance.

Fieldwork safety, e.g. carrying heavy kit (share the load, use a trolley or vehicle).

(a) Summit mean 560 ± 6 per hour; sea level mean 410 ± 6 per hour.

(b) $t = 1800 \div (0.994 \times 3.00 \times 10^8) = 6.04$ µs.

(c) Half-lives = 6.04 ÷ 1.56 = 3.87; fraction left = 0.5^3.87 = 0.068; prediction ≈ 38 per hour.

(d) γ = 9.14; muon time = 6.04 ÷ 9.14 = 0.660 µs = 0.42 half-lives; fraction left 0.746; prediction ≈ 418 per hour.

Compare: measured 410 ± 6; without relativity about 38; with relativity about 418.

Conclusion: allowing for the counting uncertainty of about √410 ≈ 20 per hour, 410 agrees with 418. The data agree with the relativistic prediction and are about ten times the classical one, so the muons' clocks run slow (time dilation) as special relativity predicts.

(e) Random variation in counts; muons do not all travel at exactly 0.994c; some are absorbed or scattered by the air; the detector efficiency may differ slightly.

(f) Radioactive-type decays and cosmic-ray arrivals are random, so long, repeated counts reduce the random uncertainty and give a reliable mean.

Check-up

1 Every observer measures the same value for the speed of light in a vacuum, whatever their own speed or the speed of the source (1).

2 $t' = t / \sqrt{(1 - v^2/c^2)}$ (1); $t' = 5.0 \div \sqrt{(1 - 0.70^2)}$ (1); $t' = 7.0$ hours (1).

3 $l' = l \sqrt{(1 - v^2/c^2)}$ (1); $l' = 30 \times \sqrt{(1 - 0.85^2)}$ (1); $l' = 16$ m (1).

4 $1 \div \sqrt{(1 - 0.60^2)}$ (1) $= 1 \div \sqrt{0.64} = 1 \div 0.80 = 1.25$ (1).

5 Open-ended (3 marks: a full, clear explanation of the main physics.) Points could include: v/c is about 1.3×10^{-5}, so the factor is extremely close to 1 and each clock runs slow by only about a part in 10^{10}; but GPS needs timings to nanoseconds, because light travels 30 cm in a nanosecond, so tiny errors add up to large position errors over a day; so the correction does matter (general relativity effects also matter, beyond this course).

TEACHER NOTES

Data practical 6: How old is the Universe?

Time	One 50-minute lesson, individually or in pairs. No apparatus.
What it is	A data-analysis practical with realistic but made-up galaxy data. It mirrors how Hubble's law is used.
Optional extra	A Doppler demonstration: a buzzer in a soft foam ball swung on a short cord (teacher only, clear space, cord checked), or a phone app recording a passing sound source.
Expected results	A good straight line through the origin; $H_o \approx 2.3 \times 10^{-18}$ s^{-1}; age ≈ 14 billion years.
Level	H processes data, draws a line through the origin, uses percentage uncertainties and evaluates a model.

Safety and inclusion

- Stress never looking at the Sun through any optical device.
- If swinging a buzzer, only the teacher swings it, in a cleared area, with a checked cord.
- Risk assess for your own class and follow your employer's policies and SSERC guidance.

Common problems

- **Forgetting to subtract** the rest wavelength before dividing.
- **Mixing powers of ten** on the axes: label them clearly (× 10^{24} m, × 10^{6} m/s).
- **Converting seconds to years:** divide by 3.15 × 10^{7}.

Assessment link

Processing data, gradients, uncertainties and comparing with a referenced value, as in the assignment.

Answers: Topic 6

Topic 6: The expanding Universe (Higher)

1 The Doppler effect

1 Receding: $f_o = 900 \times 340 \div (340 + 30) = 827$ Hz.

2 $450 = 400 \times 340 \div (340 - v_s)$, so $340 - v_s = 302$ and $v_s = 38$ m/s.

3 As it approaches, the waves are squashed together (shorter wavelength, higher frequency). As it moves away they are spread out (longer wavelength, lower frequency), so the pitch drops as it passes.

2 Redshift and Hubble's law

1 $z = (503 - 486) \div 486 = 0.035$; $v = 0.035 \times 3.00 \times 10^8 = 1.05 \times 10^7$ m/s.

2 $d = v \div H_o = 1.05 \times 10^7 \div 2.3 \times 10^{-18} = 4.6 \times 10^{24}$ m.

3 $t = 1 \div 2.3 \times 10^{-18} = 4.35 \times 10^{17}$ s; $\div 3.15 \times 10^7 = 1.38 \times 10^{10}$ years, about 14 billion years.

3 Evidence and the dark Universe

1 The measured orbital speeds stay high far from the centre, but the visible matter predicts speeds that fall away. Extra unseen mass must be providing the extra gravity: dark matter.

2 Star Q, because hotter objects have a shorter peak wavelength.

3 The big bang model predicts the early Universe was very hot and gave out radiation; expansion has stretched that radiation to microwave wavelengths, matching a temperature of about 2.7 K, and it arrives evenly from every direction.

Data practical 6: How old is the Universe?

Plan: independent: distance; dependent: recession speed; calculated first: z from the wavelengths, then $v = z\,c$.

Equipment: telescope, spectrometer, computer. Not needed: thermometer, stopwatch.

Prediction: a straight line through the origin. Safety: never look at the Sun through a telescope or binoculars.

(a) 0.50: $z = 0.0038$, $v = 1.14 \times 10^6$ m/s; 1.00: $z = 0.0072$, $v = 2.15 \times 10^6$ m/s; 1.50: $z = 0.0114$, $v = 3.43 \times 10^6$ m/s; 2.00: $z = 0.0157$, $v = 4.71 \times 10^6$ m/s; 2.50: $z = 0.0181$, $v = 5.44 \times 10^6$ m/s; 3.00: $z = 0.0227$, $v = 6.81 \times 10^6$ m/s.

(b) Best-fit gradient $\approx 2.26 \times 10^{-18}$ s^{-1} (accept 2.1 to 2.4 $\times 10^{-18}$ s^{-1}).

(c) $t = 1 \div 2.26 \times 10^{-18} = 4.43 \times 10^{17}$ s $\approx$ 14 billion years.

(d) Distance ± 5% against wavelength shift 4%: the distance is slightly larger; but for nearby galaxies the shift is small, so its percentage uncertainty is large, and their own motions inside galaxy groups also matter more.

Conclusion: v is directly proportional to d (straight line through the origin).

(e) The expansion has not been at a constant rate: it slowed at first under gravity and is now speeding up because of dark energy, so $t = 1 \div H_o$ is only an estimate.

Check-up

1 $f_o = f_s \times v \div (v - v_s)$ (1); $f_o = 480 \times 340 \div (340 - 20)$ (1); $f_o = 510$ Hz (1).

2 $z = (134 - 122) \div 122 = 0.098$ (1); $v = z\,c$ (1) $= 0.098 \times 3.00 \times 10^8 = 3.0 \times 10^7$ m/s (1).

3 $t = 1 \div 2.3 \times 10^{-18} = 4.3 \times 10^{17}$ s (1); $\div 3.15 \times 10^7 = 1.4 \times 10^{10}$ years, about 14 billion years (1).

4 Open-ended (3 marks: a full, clear explanation of the main physics.) Points could include: galaxy rotation curves show much more mass than we can see (dark matter); the accelerating expansion needs dark energy; together they are thought to make up most of the Universe (around 95%), with ordinary matter only about 5%; but we do not yet know what they are, so the claim is based on indirect evidence.

5 Any one: the cosmic microwave background; the amounts of hydrogen and helium; (accept the temperature of the CMB matching predictions) (1).

About the author

C. Blewis has taught for 17 years, including 10 years in Additional Support Needs (ASN) provision, teaching sciences, maths, PE and more.

In many schools, especially smaller and specialist settings, teachers are often asked to teach outside their own subject. These books are written for them, and for the young people they teach: clear, practical and ready to use from the first lesson.