Physics Units 1 & 2

Chapter 14 — Scientific investigation

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Contents

Scope. This section is set out in the *VCE Physics Study Design*, Unit 2, Area of Study 3 — *How do physicists investigate questions?* — key knowledge block *Investigation design*. The two key knowledge dot points owned here are quoted verbatim below.

ID	Key knowledge (verbatim)
`U2.3.1`	"apply the physics concepts specific to the selected investigation and explain their significance, including definitions of key terms, and physics representations"
`U2.3.2`	"evaluate the characteristics of the scientific methodology relevant to the investigation, selected from: experiment; fieldwork, classification and identification, modelling, simulation, and the development of a product, process or system"

This section also gives first teaching of three of the study design's key science skills:

ID	Key science skill (verbatim)
`KSS.1.1`	"identify, research and construct aims and questions for investigation"
`KSS.1.2`	"identify independent, dependent and controlled variables in experiments"
`KSS.2.1`	"determine appropriate investigation methodology: case study; classification and identification; experiment; fieldwork; literature review; modelling; product, process or system development; simulation"

What is deliberately not taught here: formulating hypotheses and making predictions, and the distinction between an aim, a hypothesis, a model, a theory and a law, belong to Section 14D; accuracy, precision, repeatability, reproducibility, resolution and validity of data belong to Section 14B; health, safety and ethical guidelines belong to Section 14C. This section builds the front of the investigation plan; those sections build the rest.

Theory

What this chapter is for. Every earlier chapter of this book taught you physics. This chapter teaches you what physicists *do* with physics: they investigate questions. Unit 2, Area of Study 3 is titled *"How do physicists investigate questions?"*, and its outcome, verbatim: *"On completion of this unit the student should be able to draw an evidence-based conclusion from primary data generated from a student-adapted or student-designed scientific investigation related to a selected physics question"* (*VCE Physics Study Design*, Unit 2, Area of Study 3).

Notice the words **student-adapted or student-designed**. An investigation is **adapted** when you take a procedure that already exists — one demonstrated in class, or published somewhere reputable — and change part of it so that it answers your own question. An investigation is **designed** when you build the procedure yourself, from the question outward. Either way, the study design states that the investigation *"relates to knowledge and skills developed in Area of Study 1 and/or Area of Study 2"*: the physics of motion, forces and energy from Chapters 7–9, or the physics of the option you studied in Chapters 10–13. The investigation is where that physics gets used.

Scientific investigations may be undertaken in groups, but the study design is explicit: *all work for assessment must be completed individually*. The study design names one task type for the assessment of this outcome: *"a report of a practical investigation (student-designed or adapted) using an appropriate format, for example a scientific poster, practical report, oral communication or digital presentation."* It adds: *"Where teachers allow students to choose between tasks they must ensure that the tasks they set are of comparable scope and demand."*

One number matters to your timetable: the study design requires that *"a minimum of seven hours of class time should be devoted to undertaking, and communicating findings of, the student-adapted or student-designed scientific investigation"*. This book cannot spend those hours for you — they belong in the laboratory and the field, and your teacher plans them. What this chapter provides is everything around those hours:

Section	Builds
14A	The investigation plan: physics concepts, key terms and representations; aims and questions; variables; choosing and evaluating a methodology
14B	Generating primary data: method and equipment; accuracy, precision, repeatability, reproducibility, resolution and validity
14C	Health, safety and ethical guidelines: risk assessment, safety data sheets, ethical conduct
14D	Aims, hypotheses, models, theories and laws; predictions, and testing them against evidence
14E	Organising, analysing and evaluating primary data: patterns, outliers, error, uncertainty, linearised graphs
14F	The logbook: recording and authenticating generated primary data
14G	Communicating findings: report conventions, and the key findings in relation to physics concepts

And one obligation applies throughout: the study design requires students to *"maintain a logbook of practical activities in each of Units 1 to 4 for recording, authentication and assessment purposes"*, and the logbook *"is submitted as a requirement for satisfactory completion in each of Units 1 to 4"*. Section 14F teaches the practice in full — but from your first planning entry for this investigation, keep the logbook dated and complete.

The physics behind an investigation. An investigation is not a technique looking for something to measure. It is a question that can only be answered if you already know some physics — the concepts tell you what to measure, what could matter, and what an answer would mean. The first dot point of this section requires exactly that: apply the physics concepts specific to your selected investigation, and explain their **significance** — that is, not merely name the concepts, but say why each one matters to *this* question.

Three jobs make up this dot point.

(1) Identify the concepts, and explain their significance. Take the study design's own example question, *"Is momentum conserved in a football tackle?"* The concepts are momentum ($p = m v$, 8A), momentum conservation in an isolated system (8E), and the connection between net force and change in momentum ($\Delta p = F_{\text{net}} \Delta t$, 8A). Each comes with a significance: momentum is the quantity the tackle redistributes; conservation of momentum is the very relationship being tested; and the force–momentum connection matters if the investigation also asks about the forces during the collision.

(2) Define the key terms. A **key term** is a word on which the question turns. In the tackle question, *momentum* and *isolated system* are key terms, and each needs a definition as it applies in *this* investigation: momentum is the product of a body's mass and its velocity, a vector quantity (7A); the two players can be treated as approximately an isolated system during the brief collision because external forces such as friction with the ground are small compared with the force between the players over that short time. Definitions in your own investigations follow the study design's terminology rules (8C): the force due to gravity is F_{g} — never "weight"; the force in the normal direction between two surfaces in contact is the **normal force** — never "reaction force"; forces are labelled $F_{\text{on A by B}}$.

(3) Choose the physics representations. Physics has its own ways of showing ideas: algebraic equations, force (vector) diagrams, energy-transfer diagrams, circuit diagrams, ray diagrams, tables and graphs. Choose the representation that does the job at hand, and say why. For the tackle question, momentum is a vector, so a table of *signed* momenta — one direction positive, the opposite negative — before and after the collision shows the comparison directly. The conventions for drawing and labelling these representations (graphs, vector diagrams, units, significant figures) are skills you have been using since 1A and 7B, and 14G applies them to your written report.

Aims and questions. The first key science skill of this section has three verbs: *identify, research and construct* aims and questions for investigation. They are stages of the one job.

Identify. Investigations start with curiosity about something observed. The study design offers its own example starting questions: *"Does the shape of the cornea or the material of the lens have a greater effect on refraction?"*, *"How do the structures of winged seeds affect their dispersal?"*, *"How do buttresses affect the stability of a church?"* A starting question is allowed to be broad and messy — it is the raw material, not the plan.

Research. Before a starting question becomes an investigation, find out what is already known about it: what physics describes it, what others have measured, what methods have been used. This is the territory of the **literature review** methodology, taught below, and the source-evaluation skills of 10A decide which sources you trust. Research usually narrows a question — often by showing that the interesting part is smaller than the question as first asked.

Construct. Refine the question into one that a school physics investigation can actually answer. An investigable physics question has four marks:

1. It is answerable by observation or measurement — it is a scientific question in the sense of 10A, not a question of opinion or values.
2. Its variables can be identified: something can be changed, something can be measured in response, and the rest can be kept constant (or at least monitored).
3. Its scope fits the equipment, time and safety constraints available to you.
4. It names the system precisely — not *"how fast do things fall?"* but *"how does the drop height affect the rebound height of a basketball dropped onto a wooden floor?"*

The **aim** is the investigation's purpose in one sentence. A reliable pattern is: *to investigate how* [independent variable] *affects* [dependent variable] *of* [system] — for example, *"to investigate how the release height of a cart affects the cart's speed at the bottom of a ramp."* The aim is not the question copied out, and it is not the method: *"to time a cart with a stopwatch"* describes an action, not a purpose. The aim is also not a hypothesis — a hypothesis is a testable statement of what you expect to happen, and Section 14D teaches how to formulate one.

Variables. The study design's experiment definition (below) names three kinds of variable, and identifying them is the skill this section owns: *"It may include investigating the relationship between an independent variable and a dependent variable, controlling all other variables."*

- The **independent variable** is the quantity the investigator deliberately changes.
- The **dependent variable** is the quantity measured in response to that change.
- The **controlled variables** are all the other quantities that could affect the dependent variable, kept constant so that any change in it can be put down to the independent variable alone.

For the ramp investigation: the release height of the cart is the independent variable; the cart's speed at the bottom of the ramp is the dependent variable; the cart itself (same mass), the ramp surface, the release procedure (from rest, no push) and the position where the speed is measured are controlled variables.

Control is what makes the result meaningful. If the release height and the ramp surface were both changed between trials, a change in speed could not be attributed to either one — the investigation would have two independent variables and no clear finding. Where a quantity cannot be perfectly controlled (the temperature of the room, for instance), it is monitored and recorded so that its influence can be considered later; sources of error and causes of uncertainty of this kind are the subject of 14B.

The variables also shape everything downstream: the columns of the data table, the axes of the graph (independent variable on the horizontal axis, dependent on the vertical, by the conventions of 7B), and the kind of conclusion that can be drawn. Note the dot point's precise wording — variables are identified *in experiments*. The other methodologies below organise their work differently (fieldwork records site data; product development works against design criteria), though asking *what will I change, what will I measure, what will I keep the same?* is useful thinking for any of them.

Investigation methodologies. The study design puts it plainly: *"Scientific investigations can be undertaken in a variety of ways depending on the aim of the investigation and the question under investigation."* A **methodology** is the overall approach by which an investigation answers its question. Eight methodologies are named in the study design (key science skills) and in its "Scientific investigation methodologies" passage; the definitions below are the study design's own, quoted from that passage.

- **Case study.** *"An investigation of a particular event or problem that contains a real or hypothetical situation and includes the complexities that would be encountered in the real world."* Case studies can be historical (analysing causes and consequences), based on a real situation or a role-play of an imagined one, or problem-solving in form. Choose it when the question is about one particular event with real-world complexity that cannot be recreated cleanly in a laboratory.
- **Classification and identification.** *"Classification is the arrangement of phenomena, objects or events into manageable sets, whereas identification is a process of recognition of phenomena as belonging to particular sets or possibly being part of a new or unique set."* The study design notes this methodology is common in fields such as astrophysics, where stars are arranged into classification categories (13A). Choose it when the question asks what kinds of things there are, and how a new observation fits the scheme.
- **Experiment.** *"A procedure undertaken to demonstrate a known fact, test a hypothesis or make a discovery. It may include investigating the relationship between an independent variable and a dependent variable, controlling all other variables, as part of the scientific method."* This is the methodology most often used in this course, and the one the variables of the previous block belong to. Choose it when the question asks how one quantity affects another.
- **Fieldwork.** *"Fieldwork involves students undertaking their own investigation to solve a problem or to investigate an issue at a specific location. Students may note the context of the site and the relevance of the site to an investigation, prediction and/or hypothesis prior to recording site data for later processing. The generation of site-specific data should be recorded in the student's logbook."* Choose it when the question only makes sense at a real place — a ride at a theme park, a slope, a stretch of coast.
- **Literature review.** *"Involves the collation and analysis of secondary data related to other people's scientific findings and/or viewpoints in order to answer a question or provide background information to help explain observed events, or as preparation for an investigation to generate primary data."* Choose it when what is needed is what others have already found — either as the whole investigation, or as its background. Secondary information and how to judge it are treated in 10A.
- **Modelling.** *"Involves the construction of: a physical model, such as a small-scale or large-scale representation of an object; a conceptual model, which represents a system involving concepts that help people know, understand or simulate the system; or a mathematical model, which describes a system using mathematical equations that involve relationships between variables and that can be used to make predictions."* You have already met all three kinds: the ray diagrams of 1C and 12A, the DC circuit model of 6B, the kinetic-energy model of evaporation in 2A, and $v = f\lambda$ as a mathematical model in 1A. Choose modelling when the question asks how a system can be represented, understood or predicted.
- **Product, process or system development.** *"Design of an artefact, process or system to meet a human need, which may involve technological applications in addition to scientific knowledge and procedures."* The study design's own example — *"What is the optimal design of the lightest capsule that is able to prevent an egg breaking during a drop?"* — is this methodology. Choose it when the question asks for something that works against stated design criteria, rather than data about a relationship.
- **Simulation.** *"A process of using a model to study the behaviour of a real or theoretical system. The modelling and manipulation of variables in a real system is useful because often the variables cannot be controlled as the system may be too complex, too large or small, too fast or slow, not accessible or too dangerous."* Choose it when the real system is out of reach and a model can stand in for it.

Note the pair: modelling *constructs* a model; a simulation *uses* a model to study a system's behaviour. A simulation is therefore built on modelling, and the two often appear together.

Determining the methodology. The methodology is chosen by the question, not by preference. Start from what the question needs:

The question needs …	So the methodology is …
a measured relationship between quantities, with other quantities controlled	experiment
data recorded at a specific location, in its real context	fieldwork
things arranged into sets, or a new observation recognised as belonging to a set	classification and identification
a representation built to understand, explain or predict a system	modelling
the behaviour of a system too complex, large, small, fast, slow, distant or dangerous to study directly	simulation
an artefact, process or system designed to meet a need against criteria	product, process or system development
what others have already found, collated and analysed	literature review
the analysis of one particular event with its real-world complexity intact	case study

Many real investigations combine more than one methodology. A theme-park energy investigation, for instance, might be **fieldwork** — video of the ride is site data — supported by **modelling** — the energy analysis applied to that video. When that happens, name the leading methodology and say how the other supports it.

Evaluating the characteristics of a methodology. The second dot point of this section asks you to *evaluate the characteristics* of the methodology relevant to your investigation. The **characteristics** of a methodology are its defining features — what the methodology involves by definition, the kinds of data it generates, and the kinds of conclusion it can support. A complete evaluation works through five questions:

1. **What does this methodology involve?** State its defining features, as in the definitions above.
2. **Why is it the most appropriate methodology for this question?** Connect its characteristics to what the question needs.
3. **What kinds of data does it generate?** Qualitative or quantitative; primary (generated by you, recorded in the logbook) or secondary (collated from sources others produced — the distinction taught in 10A).
4. **What are its limitations?** What can this methodology *not* show about the question? An experiment cannot claim more than its controlled variables allow; a simulation is only as good as the model behind it; fieldwork cannot control the site.
5. **How would an alternative methodology be weaker (or stronger)?** Evaluation means comparison, not just description.

The planning framework. Everything in this section fits onto one page of your logbook. The framework below is used again in every later section of this chapter; each of 14B–14G fills in one more row.

Planning element	The question it answers	Built in
Investigation question	What am I trying to find out?	14A
Aim	What is the purpose of the investigation?	14A
Key physics concepts, key terms, representations	What physics is the investigation built on, and what does each part mean here?	14A
Methodology and justification	How will the question be answered,	14A

Planning element	The question it answers	Built in
	and why is that the right approach?	
Variables (independent, dependent, controlled)	What will be changed, measured, and kept constant?	14A
Method, equipment, and the data to be generated	Exactly what will be done, with what, recording what?	14B
Accuracy, precision, repeatability, reproducibility, resolution, validity	How good must the data be, and how will that be judged?	14B
Health, safety and ethical guidelines	What risks and ethical considerations apply, and how are they managed?	14C
Hypothesis and prediction	What do I expect to happen, and why?	14D
Analysis and evaluation of the data	What do the data show, and how good were the method and the data?	14E
Logbook record	How are the primary data dated, documented and authenticated?	14F
Report and key findings	How is the conclusion communicated, and how does it relate to the physics?	14G

Units 3 & 4 preview. The investigation skills built in this chapter are assumed, without revision, when you design and conduct the student investigation of Unit 4, Area of Study 2, at Units 3 & 4. Content under this banner is not assessed in this book's topic tests or practice examinations.

Worked examples

Example 1 — scaffolded

"Is momentum conserved in a football tackle?" is one of the study design's own example investigation questions (*VCE Physics Study Design*, Unit 2, Area of Study 3). A student adapts it to the laboratory as a collision between two trolleys on a straight track, analysed from video.

(a) Identify the physics concepts specific to this investigation, and explain the significance of each.
(b) Define two key terms of the investigation.
(c) Identify one physics representation suited to the investigation, and justify the choice.

Working	Comment
Momentum, $p = m v$ (8A). Significance: momentum is the quantity redistributed in the tackle, so the masses and velocities of the two players (or trolleys) before and after the collision give the momenta to be compared.	The concept supplies the quantity to measure.
Conservation of momentum in an isolated system (8E). Significance: this is the relationship being tested — if the system is approximately isolated during the collision, the total momentum before should equal the total momentum after.	The concept supplies the relationship under test.
Change in momentum and net force, $\Delta p = F_{net} \Delta t$ (8A). Significance: links the force between the players during the collision to each player's change of momentum, if the investigation also examines the forces involved.	A concept that matters if the question is extended.
Key terms: **momentum** — the product of a body's mass and its velocity, a vector quantity (7A), so direction	Key terms are defined as they apply in this investigation.

Working	Comment
must be included. **Isolated system** — a system on which the net external force is negligible; during the brief collision the force between the players is much larger than external forces such as friction with the ground, so the two players are approximately isolated.	
Representation: a table of signed momenta — one direction along the line of the tackle taken as positive, the opposite direction negative — for each player before and after the collision. Justification: momentum is a vector, so the direction convention is needed before any "before equals after" comparison is meaningful.	The representation is chosen to suit the physics, and the reason is stated.

Example 2 — scaffolded

"What are the energy transformations during a theme park ride?" is another of the study design's example questions. A student adapts it to the laboratory: a cart rolls from rest down a ramp, released from different heights, and its speed is measured at the bottom of the ramp.

(a) Write the aim of the investigation.
(b) Identify the independent, dependent and controlled variables.
(c) State the physics relationship you expect to connect the two variables.

Working	Comment
Aim: *to investigate how the release height of a cart on a ramp affects the cart's speed at the bottom of the ramp.*	The aim states the purpose, names both variables, and names the system. It is not the method and not a hypothesis.
Independent variable: the release height h of the cart.	The quantity deliberately changed.
Dependent variable: the speed v of the cart at the bottom of the ramp.	The quantity measured in response.
Controlled variables: the same cart (same mass); the same ramp and surface; the same release procedure (from rest, no push); the speed measured at the same position on the ramp each time.	Kept constant so that any change in v can be attributed to h alone.
Expected relationship: energy conservation (9C). Gravitational potential energy $E_g = mg\Delta h$ is transformed into kinetic energy $E_k = 1/2\, m v^2$, giving $v = \sqrt{2gh}$: the speed increases as the release height increases, and v^2 is proportional to h.	The physics predicts how the dependent variable responds. Section 14D turns such an expectation into a hypothesis.

Example 3 — unscaffolded

Determine the most appropriate investigation methodology for each of the following, choosing from the eight methodologies of the study design. Justify each choice by naming the defining characteristic that decides it.

(i) How does the extension of a spring depend on the force applied to it?
(ii) What are the energy transformations of a roller-coaster carriage during a ride? The student records video during a visit to the ride and processes the data afterwards.
(iii) How long would a parachute of a given design take to fall from a height too great for a safe drop? The student uses a computer program that models the falling parachute, including air resistance, and varies the canopy area in the program.
(iv) What is the lightest capsule that can protect an egg from breaking when dropped from $2\,\mathrm{m}$?

Each scenario matches one methodology's defining characteristic.

(i) **Experiment.** The question asks for the relationship between two quantities — force (independent variable) and extension (dependent variable) — with the other factors that affect extension, such as the spring itself and how it is mounted, controlled. Investigating a relationship between an independent and a dependent variable while controlling all other variables is the study design's own definition of experiment. (This is the investigation of Hooke's Law, 9B.)

(ii) **Fieldwork.** The data are generated at a specific location — the ride itself — and the student notes the context of the site and records the site-specific data (the video) in the logbook for later processing, exactly as the study design's definition of fieldwork describes. The video analysis that follows is part of the method, but the methodology is fieldwork because the data come from the site.

(iii) **Simulation.** The real system cannot be used — the drop height is too great for a safe drop — so the student uses a model to study the behaviour of the system, manipulating the canopy area within the program. "The system may be … too dangerous" and "the variables cannot be controlled" are the study design's own reasons for choosing simulation. Note that a model had to be constructed first: simulation is built on modelling.

(iv) **Product, process or system development.** The question asks for an artefact — the capsule — designed to meet a human need (protecting the egg) against stated criteria (lightest mass; egg survives a $2\,\mathrm{m}$ drop). Success is judged against the design criteria, not only by data about a relationship. This is one of the study design's own example questions for this methodology.

Example 4 — unscaffolded

A student investigates the question *"Is kinetic energy conserved in a collision between two trolleys on a straight track?"* by **experiment**: two trolleys collide on a level track, video analysis gives their speeds immediately before and immediately after the collision, and $1/2\,m\,v^2$ is calculated for each trolley on both sides of the collision.

Evaluate the characteristics of the experimental methodology relevant to this investigation.

A full response works through the five evaluation questions of this section.

What the methodology involves. An experiment is a procedure undertaken to test a hypothesis or make a discovery, investigating the relationship between an independent and a dependent variable while controlling all other variables. Here the student can vary the mass of one trolley between trials (independent variable) and measure the kinetic energy before and after each collision (dependent variable), with the track, the trolleys' wheels and the collision arrangement controlled.

Why it is appropriate. The question asks whether a measurable relationship holds in the real world, and only an experiment generates the primary quantitative data — real speeds, real masses — needed to answer it. The procedure can be repeated, trial after trial, and the control of variables means any pattern found can be attributed to the collision itself.

Limitations. The track can never be perfectly frictionless, so the trolley system is not perfectly isolated and some kinetic energy is transformed into thermal energy and sound (9C) — the investigation must expect the "after" total to be slightly smaller even when the physics is handled well, and this limitation belongs in the discussion. The trolleys are also a laboratory-scale system: the finding is about low-speed collisions between trolleys, not about every collision in the world.

Comparison with alternatives. A simulation could explore collisions under ideal, friction-free conditions, but it would only show what its model assumes — it could not discover whether kinetic energy is conserved for these real trolleys, and it generates no primary data. Modelling could describe the collision but not test it. The experiment is therefore the appropriate methodology, provided its limitations are acknowledged.

∴ Experiment suits this question because it generates primary, quantitative, repeatable data about a real relationship under controlled variables; its limitations are that friction means the system is never perfectly isolated and the finding applies to laboratory-scale collisions only; a simulation or model alone could not test the real system.

Practice questions

Question 1 *(scaffolded)* A student adapts the study design's example question *"What are the forces experienced by a netballer's ankle?"* into a laboratory investigation: *how does the drop height of a basketball affect its rebound height?* The student drops the ball from rest at different heights above a wooden floor and measures the height it rebounds to. (a) Identify the independent variable and the dependent variable. (b) Identify two controlled variables. (c) Explain why the controlled variables must be kept constant.

Question 2 *(scaffolded)* A student who studied Option 2.8 takes the study design's starting question *"Does the shape of the cornea or the material of the lens have a greater effect on refraction?"* (a) Identify two physics concepts specific to an investigation of this question, and explain the significance of each. (b) Define one key term of the investigation as it applies here. (c) Identify one physics representation suited to the investigation, and justify the choice.

Question 3 *(scaffolded)* The study design offers *"How do buttresses affect the stability of a church?"* as an example starting question (the physics of forces and torques, 8F). (a) Identify two reasons this question, as written, is too broad for a school investigation. (b) Rewrite it as an investigable question about a scale-model tower that can be tested in the laboratory. (c) Write an aim for your rewritten question.

Question 4 *(scaffolded)* Match each investigation below with the most appropriate methodology from the list: *case study; classification and identification; experiment; fieldwork; literature review; modelling; product, process or system development; simulation*. Justify each match with one defining characteristic. (i) How does the current in a filament globe depend on the potential difference across it? (ii) Into what sets can a collection of velocity–time graphs be arranged, according to the type of motion each graph represents? (iii) What is the sound intensity level at different positions around the school hall during a rehearsal? (iv) How would a roller-coaster carriage behave on a proposed track design, including friction, when no full-size version of the design exists to test? (v) What does published research report about the acceleration due to gravity measured at different locations on Earth? (vi) What is the most effective arrangement of insulation around a hot-water container for keeping water hot, built to meet a stated cooling-time criterion?

Question 5 *(scaffolded)* A student's investigation plan for a cart rolling down a ramp contains the sentence: *"The weight of the cart pulls it down the ramp, and the reaction force of the ramp pushes back on the cart."* (a) Identify the two terms in the sentence that do not follow the study design's terminology conventions. (b) Rewrite the sentence using the correct terms. (c) Define the normal force as it applies in this investigation.

Question 6 *(scaffolded)* Match each communication job below with the most appropriate representation from the list: *energy-transfer diagram; force diagram with labelled forces; I–V graph*. Justify each choice in one sentence. (i) Show the energy transformations of a cart as it rolls from the top of a ramp to the bottom, where friction is not negligible. (ii) Show how the current in a filament globe changes as the potential difference across it changes. (iii) Show the forces acting on a book at rest on a sloping surface.

Question 7 Consider these two questions: A: *"Does a heavier parachute fall more slowly than a lighter one of the same canopy?"* B: *"Is it fair that broadcasters use slow-motion replays to umpire close calls in sport?"* (a) Identify which question can be investigated by physics measurement, and explain why the other cannot, naming the kind of question it is instead. (b) Rewrite question A as a precisely investigable question, naming the system, the independent variable and the dependent variable.

Question 8 A student investigates *"What are the energy transformations of a roller-coaster carriage during a ride?"* by **fieldwork**: visiting the ride, noting the context of the site, recording video of several carriages, and analysing the video later to compare gravitational potential energy at the top of drops with kinetic energy at the bottom. Evaluate the characteristics of fieldwork as the methodology for this investigation.

Question 9 Classify each of the following as **modelling** or **simulation**, using the study design's definitions, and justify each classification. (i) A student constructs a ray diagram and uses the thin lens equation to predict where a convex lens will form an image of a candle. (ii) A student uses a computer program to study the motion of a roller-coaster carriage including friction and air resistance, because the real ride cannot be altered and a full range of speeds would be dangerous to test.

Question 10 The study design's example question *"What is the optimal design of the lightest capsule that is able to prevent an egg breaking during a drop?"* is investigated by a student who builds and tests capsule designs from paper and tape. (a) Identify the methodology of this investigation. (b) State two ways this methodology differs from an experiment. (c) Propose two design criteria for the capsule, and identify what data the student would generate when testing against them.

Question 11 (a) Describe the difference between a **literature review** and a **case study**, using the study design's definitions. (b) Identify the methodology of each investigation below, and justify your identification: (i) A student collates published measurements of the acceleration due to gravity at different locations on Earth to answer the question *"Does the value of g vary with location?"* (ii) A student analyses the forces and torques in one particular church building — the study design's own example context — to understand how its buttresses contribute to its stability, taking into account the building's real materials, shape and history.

Question 12 A student writes: *"Aim: to use a stopwatch to time a cart."* (a) Identify what is wrong with this aim. (b) Rewrite it as a correct aim for an investigation of how the angle of a ramp affects the time a cart takes to roll a fixed distance from rest. (c) For your rewritten aim, identify the independent, dependent and one controlled variable.

Question 13 In the ramp investigation of Example 2, the cart is released from rest at a height $h = 0.45\ \text{m}$ above the bottom of the ramp. Use $g = 9.8\ \text{m s}^{-2}$. (a) Assuming all of the gravitational potential energy is transformed into kinetic energy, calculate the speed of the cart at the bottom of the ramp. Give your answer to two significant figures. (b) Explain how this calculation helps the student plan the investigation. (c) The student's measured speed is $2.4\ \text{m s}^{-1}$, less than the calculated value. Explain why.

Question 14 A student investigates how the surface of a ramp affects how far a cart rolls after leaving the ramp. Between trials the student changes both the surface and the release height of the cart. (a) Identify the flaw in this design. (b) Explain why the flaw prevents the student from drawing a conclusion. (c) State which characteristic of an experiment, from the study design's definition, the design fails to satisfy.

Question 15 A student investigates the question *"How does the speed of a marble as it leaves the edge of a bench affect the horizontal distance it travels before landing?"* by rolling the marble off the bench at different speeds and measuring where it lands (horizontal motion at constant velocity, 7A). (a) Identify the methodology of this investigation, and justify your choice by naming the defining characteristic that decides it. (b) Explain why a literature review alone could not answer this question. (c) Identify the independent variable, the dependent variable and two controlled variables.

Question 16 (a) Using the study design's definitions, describe the difference between **classification** and **identification**. (b) The study design notes that this methodology is common in astrophysics, where stars are arranged into classification categories (13A). Explain, in general terms, what "arrangement of phenomena into manageable sets" means in that example, and what identification would involve for a newly observed star. (You do not need the star physics itself here.) (c) Give one example of a Unit 2 Area of Study 1 investigation that would use this methodology, and name the sets involved.

Question 17 A student investigates collisions using two trolleys on a straight track: *"How does the mass of one trolley affect the speed of the two trolleys after they collide and move together?"* The student adds masses to one trolley, releases it at a fixed speed toward the second trolley, and uses video analysis to measure their shared speed after the collision. Write a short plan for this investigation containing: (a) the aim; (b) two key physics concepts, each with a one-sentence significance; (c) the methodology, with a one-sentence justification; (d) the independent, dependent and two controlled variables.

Question 18 A group of three students proposes the investigation question *"How can we make our school more energy-efficient?"* (a) Identify two reasons this question cannot be submitted as an investigation question as it stands. (b) Rewrite it as an investigable question using physics from Unit 2 Area of Study 1 (motion, forces or energy). (c) The group intends to work together and hand in one report. Identify what the study design requires instead, quoting the relevant statement.

Answers

Question 1 (a) independent: drop height; dependent: rebound height; (b) e.g. same ball, same floor surface; (c) see solution. **Question 2** (a) e.g. refraction and Snell's Law, image formation by a lens — see solution; (b) e.g. refraction — see solution; (c) ray diagram — see solution. **Question 3** (a) real churches cannot be modified or controlled; "stability" needs a measurable meaning; (b) and (c) see solution. **Question 4** (i) experiment; (ii) classification and identification; (iii) fieldwork; (iv) simulation; (v) literature review; (vi) product, process or system development. **Question 5** (a) "weight", "reaction force"; (b) see solution; (c) see solution. **Question 6** (i) energy-transfer diagram; (ii) I–V graph; (iii) force diagram. **Question 7** (a) question A; question B is a question of values, not measurement; (b) see solution. **Question 8** Rubric-style model answer in the fully-worked solutions. **Question 9** (i) modelling; (ii) simulation — see solution. **Question 10** (a) product, process or system development; (b) see solution; (c) see solution. **Question 11** (a) see solution; (b) (i) literature review; (ii) case study. **Question 12** (a) it states a method, not a purpose, and names no relationship or variables; (b) and (c) see solution. **Question 13** (a) $3.0\,\mathrm{m\,s^{-1}}$; (b) and (c) see solution. **Question 14** (a) two variables changed at once; (b) and (c) see solution. **Question 15** (a) experiment; (b) and (c) see solution. **Question 16** (a) and (b) see solution; (c) e.g. arranging velocity–time graphs into sets by type of motion — see solution. **Question 17** Rubric-style model plan in the fully-worked solutions. **Question 18** (a) see solution; (b) see solution; (c) all work for assessment must be completed individually.

Fully-worked solutions

Question 1 (a) The independent variable is the drop height of the basketball — the quantity the student deliberately changes. The dependent variable is the rebound height — the quantity measured in response. (b) Any two quantities that could affect the rebound and must be kept constant, for example: the same basketball (same ball, same inflation); the same floor surface; the same release method (from rest, no throw); rebound height measured the same way each time. (c) The controlled variables must be kept constant so that any change in the rebound height can be attributed to the change in drop height alone. If, say, a different ball were used at some heights, a difference in rebound could be caused by the ball rather than by the drop height, and the investigation would have no clear finding.

Question 2 (a) Any two concepts with their significance, for example: **refraction** — the bending of light as it crosses a boundary between media of different refractive index (1C) — is the phenomenon the question is about; its significance is that both the cornea and the lens refract the light entering the eye. **Snell's Law**, $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ (1C), is significant because it relates the refractive indices of the materials and the angles to the amount of bending — it is the relationship that would let the student compare the effect of the lens material against the effect of the cornea's shape. **Image formation by a convex lens** (12A) is significant because the purpose of the refraction is to form a clear image, and the investigation could judge "effect on refraction" by where the image forms. (b) One definition as it applies here, for example: **refraction** — the change in direction of light as it passes from one medium to another of different refractive index; in this investigation, the bending of light at the surfaces of the model cornea and lens. (c) A ray diagram showing the light passing through the cornea and lens models. Justification: refraction is a change in the path of light, and ray diagrams are the representation that shows paths, angles and image positions directly.

Question 3 (a) Any two reasons, for example: a real church is a unique, fixed structure — it cannot be modified, controlled or repeated, so the question as written is not testable at school; the word "stability" has no measurement attached until the investigation gives it one (for example, the force needed to tip the structure, or the angle of lean it can withstand). (b) For example: *How does the presence of a buttress affect the force needed to tip a scale-model tower?* — now a laboratory question with identifiable variables. (c) For example: *to investigate how adding a buttress to a scale-model tower affects the horizontal force needed to tip the tower over.*

Question 4 (i) **Experiment.** The question asks for the relationship between two quantities — potential difference (independent variable) and current (dependent variable) — with the globe and its conditions controlled. This is the study design's defining characteristic of experiment (this investigation is the circuits counterpart of the force-and-extension investigation of 9B). (ii) **Classification and identification.** The graphs are being arranged into manageable sets — for example: constant velocity, constant acceleration, changing acceleration — according to a property of each graph. Arrangement of phenomena into sets is the defining characteristic of classification. (iii) **Fieldwork.** The data are generated at a specific location — the school hall — with its real context; the student records site-specific data there and processes them later. (iv) **Simulation.** The real system does not exist to test and would be dangerous if it did; the student uses a model to study the behaviour of the system, manipulating variables within the program. "Not accessible” and “too dangerous” are the study design’s own reasons for simulation. (v) **Literature review.** The student collates and analyses secondary data — other people’s published measurements — to answer the question; no primary data are generated. (vi) **Product, process or system development.** The student designs an arrangement to meet a human need (keeping water hot) against a stated criterion; success is judged against the criterion, not only by data about a relationship.

Question 5 (a) “weight” and “reaction force”. The study design states that the force due to gravity is referred to as F_g with no reference made to weight, and that the accepted term for the force in the normal direction between two surfaces in contact is “normal force”, never “reaction force” (8C). (b) For example: *The force due to gravity, F_g, acts on the cart toward the centre of the Earth, and the normal force of the ramp acts on the cart perpendicular to the ramp surface.* In the force-labelling convention: $F_{\text{on cart by Earth}}$ and $F_{\text{on cart by ramp}}$. (c) The normal force is the force in the normal (perpendicular) direction between two surfaces in contact; in this investigation it is the force the ramp surface exerts on the cart, perpendicular to the ramp.

Question 6 (i) **Energy-transfer diagram.** The job is to show energy changing form — gravitational potential energy transforming into kinetic energy and, because friction is not negligible, into thermal energy — and energy-transfer diagrams exist to show exactly that (9C). (ii) **I–V graph.** The job is to show how one quantity (current) changes as another (potential difference) changes, and a graph of current against potential difference is the representation that displays that relationship (5D). (iii) **Force diagram with labelled forces.** The job is to show the forces acting on one body — $F_{\text{on book by Earth}}$, the normal force $F_{\text{on book by slope}}$, and the friction force — at their points of application, and a labelled force diagram is the representation that does this (8C).

Question 7 (a) Question A can be investigated by physics measurement: masses can be set, fall times measured, and a relationship tested. Question B cannot: “fair” is a question of values and opinion — no instrument measures fairness, and the question is settled by argument and preference, not by observation. It is a non-scientific question in the sense of 10A (not because it is unimportant, but because measurement cannot settle it). (b) For example: *How does the mass attached to a parachute of fixed canopy area affect the time taken to fall a fixed height?* — the system is the parachute-and-mass, the independent variable is the attached mass, and the dependent variable is the fall time.

Question 8 A full response works through the five evaluation questions. **What fieldwork involves:** an investigation undertaken at a specific location; the student notes the context of the site and its relevance to the investigation before recording site-specific data, which is recorded in the logbook for later processing (the study design’s own definition). **Why it is appropriate:** the question is about a real ride at a real place, and only at the site can the student generate data about that ride — its actual heights, speeds and energy losses. Video records the event for later frame-by-frame analysis, as the study design itself suggests video analysis for such questions. **Kinds of data:** primary quantitative data (heights from the structure, speeds from the video), recorded in the logbook with the site context. **Limitations:** the student cannot control the variables — the carriage mass, the track and the weather are fixed by the site — and the ride cannot be repeated with changed conditions, so the investigation describes this ride rather than testing a general relationship. Access, safety and permission constraints apply. **Comparison:** a laboratory ramp experiment (Example 2) could control variables and test a relationship, but could not capture the real ride; fieldwork trades control for authenticity, which is the right trade for this question.

Question 9 (i) **Modelling.** The student is constructing a representation of the system — a ray diagram (conceptual/physical representation) and the thin lens equation, a mathematical model describing the system with equations that can be used to make predictions (12A). Constructing the model is the defining characteristic of modelling. (ii) **Simulation.** The student is using a model — the program — to study the behaviour of a real system, because the real system cannot be altered and the full range of conditions would be dangerous. That is the study design’s defining characteristic of simulation: the system “may be too complex, too large or small, too fast or slow, not accessible or too dangerous”. Note the connection: the simulation rests on a model of the ride, so modelling is inside it.

Question 10 (a) Product, process or system development — the design of an artefact to meet a human need. (b) Any two differences, for example: the purpose is an artefact that meets design criteria, not data about a relationship between variables; success is judged against the criteria (lightest mass; egg unbroken) rather than by a tested hypothesis; there is no single independent/dependent variable structure — the student iterates designs, testing each against the criteria. (c) Criteria, for example: the capsule must be the lightest of the designs tested; the egg must survive a drop from $2\,\text{m}$ onto a hard floor. Data generated: the mass of each capsule (quantitative), the drop height (quantitative), and the outcome of each drop — egg intact or broken (qualitative, recorded as pass/fail against the criterion).

Question 11 (a) A literature review collates and analyses secondary data — other people's scientific findings and viewpoints — to answer a question or provide background; it generates no new primary data. A case study investigates one particular event or problem, keeping the complexities that would be encountered in the real world; it analyses that case in depth rather than collating many sources. (b) (i) **Literature review.** The student collates published measurements — secondary data produced by others — and analyses them to answer the question. The defining characteristic is collation and analysis of secondary data. (ii) **Case study.** The student investigates one particular building with its real-world complexities — its actual materials, shape and history — intact. The defining characteristic is a particular event or problem retaining real-world complexity.

Question 12 (a) The sentence states a method (timing, with a stopwatch), not a purpose. It names no relationship, no variables and no system — there is nothing in it that says what the investigation is trying to find out. (b) For example: *to investigate how the angle of a ramp affects the time a cart takes to roll a fixed distance from rest.* (c) Independent variable: the angle of the ramp. Dependent variable: the time taken to roll the fixed distance. Controlled variable (any one): the same cart; the same distance measured; the same ramp surface; release from rest each time.

Question 13 (a) Energy conservation with all gravitational potential energy transformed into kinetic energy (9C):

$$mg\Delta h = 1/2\, m v^2 \Rightarrow v = \sqrt{2gh}.$$

$$v = \sqrt{2 \times 9.8 \times 0.45} = \sqrt{8.82} = 2.969\ldots = 3.0\,\mathrm{m\ s^{-1}}$$

to two significant figures (the height is given to two significant figures). (b) The calculation predicts the size of the dependent variable: a speed of about $3\,\mathrm{m\ s^{-1}}$ for the $0.45\,\mathrm{m}$ release. Knowing the expected size before measuring helps the student plan the method — the timing or speed-measuring approach must resolve speeds of a few metres per second (14B builds this into the full method) — and it gives a check on the data once collected. (c) In the real investigation some of the gravitational potential energy is transformed into thermal energy and sound through friction in the wheels and between the cart and the ramp, and into the kinetic energy of the wheels' rotation, so less of it becomes the cart's translational kinetic energy (9C, 9D). The measured speed is therefore smaller than the idealised value — the difference is a measure of the energy the simple model does not account for.

Question 14 (a) The student changes two quantities — the surface and the release height — between trials. The design has two independent variables. (b) If the rolling distance changes, the student cannot tell whether the change was caused by the surface, by the release height, or by both. The result cannot be attributed to either variable, so no conclusion about the surface can be drawn. (c) The study design defines an experiment as one that may include "investigating the relationship between an independent variable and a dependent variable, controlling all other variables". This design fails the control of all other variables.

Question 15 (a) **Experiment.** The question asks for the relationship between the speed of the marble as it leaves the bench (independent variable) and the horizontal distance it travels (dependent variable), with everything else — the bench height, the marble, the landing surface — controlled. A relationship between variables under controlled conditions is the defining characteristic of experiment. (b) A literature review collates what others have found — it could provide background, such as published measurements of the same kind of motion, but it could not generate data about *this* bench and *this* marble, and the question asks exactly for that. (If the student did use published data, the investigation would be answering a different question.) (c) Independent variable: the speed of the marble as it leaves the edge of the bench. Dependent variable: the horizontal distance travelled before landing. Controlled variables (any two): the height of the bench above the floor; the same marble; the same launch point at the edge of the bench; the same landing surface. (With the height fixed, the fall time is the same for every trial, so any change in horizontal distance can be attributed to the change in speed — a point worth stating in the plan.)

Question 16 (a) Classification is the arrangement of phenomena, objects or events into manageable sets; identification is the recognition of a phenomenon as belonging to a particular set — or as possibly part of a new or unique set. Classification builds the scheme; identification uses it on a new case. (b) In the star example, classification means taking the many observed stars and arranging them into sets according to their properties — sets that astronomers develop as classification categories (13A). Identification then means taking a newly observed star and recognising which of those sets it belongs to — or recognising that it fits none of them and may belong to a new or unique set. The methodology is about the scheme and its use, not about any one star. (c) For example: a student collects velocity–time graphs for several motions and arranges them into sets by type of motion — at rest, constant velocity, constant acceleration — then uses the scheme to classify new graphs. The sets are the motion types; the classification is by the gradient of each graph (7B).

Question 17 A full plan would include: (a) Aim: *to investigate how the mass of one trolley affects the shared speed of two trolleys after they collide and move together.* (b) Concepts, for example: momentum, $p = m v$ (8A) — significance: momentum is the quantity redistributed in the collision, calculated from each trolley's mass and velocity. Momentum conservation in an isolated system (8E) — significance: it is the relationship being tested; the total momentum before the collision is expected to equal the total momentum after, and the measured shared speed is checked against that expectation. (c) Methodology: experiment — the question asks for the relationship between an independent variable (the mass added to one trolley) and a dependent variable (the shared speed after the collision) with all other variables controlled. (d) Independent variable: the mass of the loaded trolley. Dependent variable: the shared speed of the two trolleys after the collision. Controlled variables (any two): the mass of the second trolley; the speed of the first trolley before the collision (released the same way each time); the same track and trolleys; the collision measured over the same region of the track.

Question 18 (a) Any two reasons, for example: the question is too broad — "our school" covers lighting, heating, cooling, appliances, transport and more, and no single investigation can address all of it; "energy-efficient" is not defined — nothing in the question says what measurement would decide the matter; and as written it is a question of action and values ("how can we …") rather than a question answerable by one physics measurement. (b) For example: *How does the mass of a cart affect its speed at the bottom of a ramp?* or *How does the angle of a ramp affect the force needed to pull a block up it at constant speed?* — motion, forces or energy from Unit 2 Area of Study 1, with identifiable variables. (An option-based question from Unit 2 Area of Study 2 would also satisfy the study design's requirement.) (c) The study design states that scientific investigations may be undertaken in groups, *"but all work for assessment must be completed individually."* The group may plan and work together, but each student must produce their own assessment work — the report, and the logbook entries that authenticate it (14F).

Chapter 14 Scientific investigation — 14B Generating primary data: accuracy, precision, resolution and validity

Scope — *VCE Physics Study Design, Unit 2, Area of Study 3, Key knowledge — Investigation design*: "apply techniques of primary qualitative and quantitative data generation relevant to the investigation" (`U2.3.3`) · "identify and apply concepts of accuracy, precision, repeatability, reproducibility, resolution, and validity of data in relation to the investigation" (`U2.3.4`).

Theory

Unit 2, Area of Study 3 asks one question: *how do physicists investigate questions?* Its outcome, verbatim from the study design, is that you should be able to *"draw an evidence-based conclusion from primary data generated from a student-adapted or student-designed scientific investigation related to a selected physics question"* (*VCE Physics Study Design, Unit 2, Area of Study 3*). Every word of that outcome matters, and this chapter takes the words in order. Subtopic 14A handled the design: the physics concepts behind the investigation, the methodology, the aim, the question and the variables. This subtopic handles the **generating**: how you actually produce data, and the six concepts — accuracy, precision, repeatability, reproducibility, resolution and validity — by which you judge the data you have produced. Subtopic 14C covers the health, safety and ethical guidelines, 14D distinguishes aims, hypotheses, models, theories and laws, 14E analyses and evaluates the data, 14F covers the logbook that authenticates them, and 14G covers communicating the findings.

The study design itself sets the tone for this subtopic in its cross-study specifications: *"A commitment to accuracy, precision and integrity in observation is an important precursor to critical thinking when generating primary data"* (*VCE Physics Study Design, Critical and creative thinking*). Notice the order: the thinking comes *after* the observing. Data that were carelessly generated cannot be argued back into good data later, no matter how clever the analysis. This subtopic teaches four of the study design's key science skills for the first time: *"design and conduct investigations: select and use methods appropriate to the selected investigation methodology, including consideration of equipment and procedures, taking into account potential sources of error and causes of uncertainty; determine the type and amount of qualitative and/or quantitative data to be generated or collated"*; *"systematically generate and record primary data, and collate secondary data, appropriate to the investigation, including use of databases and reputable online data sources"*; *"identify and analyse experimental data qualitatively, handling, where appropriate, concepts of: accuracy, precision, repeatability, reproducibility, resolution and validity of measurements; and errors (random and systematic)"*; and *"repeat experiments to evaluate the precision of data"* (*VCE Physics Study Design, key science skills*).

One honest note before the physics: the study design requires a minimum of seven hours of class time for undertaking and communicating the student investigation in this area of study. Those hours happen in the laboratory and in the field, under your teacher's supervision. This subtopic supplies the concepts and the method; you supply the measurements.

Primary data, and the two kinds of it. In 10A you met the distinction in the context of sources: **primary data** are the data you generate yourself in an investigation and record in your logbook; **secondary data** are data other people generated, which you **collate** — gather together — from sources such as databases and reputable online data sources. This subtopic is about the primary kind: making it, and judging it.

Primary data come in two forms, and a good investigation usually generates both.

- **Quantitative data** are measurements expressed as numbers with units: a time of $1.57\,\text{s}$, a current of $0.60\,\text{A}$, an angle of refraction of 26°. Quantitative data can be counted, compared, graphed and calculated with.
- **Qualitative data** are observations expressed in words: *"the ray bent towards the normal as it entered the block"* (1C), *"the spring returned to its original length when the load was removed"* (9B), *"the warm ball clearly bounced higher"*. Qualitative data record the behaviour of the system — the patterns and surprises the numbers alone might not explain.

Do not treat the qualitative half as optional. A numerical table that says the current rose as the potential difference rose (5D) is one thing; the accompanying observation that the resistor grew noticeably warm is what explains *why* the later readings drifted off the straight line. Record both, in your logbook, as you go (the logbook conventions themselves are taught in 14F).

Techniques for generating data. Dot point `U2.3.3` asks you to *apply techniques of primary qualitative and quantitative data generation*. The techniques you will draw on across Units 1 and 2 include:

- **Direct measurement with an instrument.** A ruler, a stopwatch, a thermometer, a balance, an ammeter, a voltmeter or a multimeter (5C). Choose the instrument *before* you start, and choose it for the job: its **resolution** must be fine enough, and its **range** large enough. Read it correctly — with your eye directly in front of the scale, to avoid parallax.
- **Repeated readings.** Measure the same quantity several times under the same conditions. Repeating exposes mistakes, reveals the spread in your readings, and lets you use the mean as your final result. Repeating is so central that one of this subtopic's key science skills is simply *"repeat experiments to evaluate the precision of data"*.
- **Timing many cycles.** When a single event is too quick to time reliably — one swing of a pendulum, for example — time twenty swings and divide by twenty. The same start-and-stop uncertainty is then shared across all twenty periods, so its effect on each one is far smaller.
- **Video analysis.** The study design itself names video analysis as a way to investigate questions such as *"Is kinetic energy conserved in a pole vault?"* A recording fixes the event: different observers can replay it frame by frame and read the same instants, which removes reaction-time error and makes the readings reproducible.
- **Sensors and data loggers.** A sensor (for position, force, temperature, light intensity and so on) connected to a data logger can take many readings per second and store them directly, which improves both resolution and repeatability.
- **Collating secondary data.** Where your question needs information you cannot measure yourself — decades of temperature records, for example — gather it from databases and reputable online data sources, and evaluate the source using the validity checklist of 10A.

Before any of this begins, the key science skills require two planning decisions: **the type and amount of data** to be generated (which quantities, qualitative or quantitative, how many values of the independent variable, how many repeats at each), and **the equipment and procedures**, chosen *taking into account potential sources of error and causes of uncertainty*. Both decisions belong in your method, written before the first reading — not reconstructed afterwards.

Resolution. The study design defines **resolution** in its "Terms used in this study" section:

> *"The smallest change in the quantity being measured that causes a perceptible change in the value indicated on the measuring instrument, for example, the resolution of a ruler may be 1 mm while the resolution of a stop watch may be 0.1 s."* (*VCE Physics Study Design, Terms used in this study*)

A metre ruler marked in millimetres has a resolution of $1\,\text{mm}$: two lengths that differ by half a millimetre cannot be told apart on it. A stopwatch that displays $0.1\,\text{s}$ has a resolution of $0.1\,\text{s}$. Resolution is a property of the *instrument*, not of the person using it — and it limits what you may honestly write down. A length measured with a millimetre ruler can be recorded as $0.472\,\text{m}$ but not as $0.4721\,\text{m}$: that final digit claims a tenth of a millimetre the ruler cannot show. Recording digits an instrument cannot support contradicts the significant-figure rules of 1A, which say a calculated or recorded value must not pretend to more precision than the measurement it came from.

Choosing an instrument is therefore a two-part check:

1. **Resolution** — is it fine enough for the question? Measuring a bench-top to the nearest centimetre needs only a centimetre tape; measuring a wavelength of $0.47\,\text{m}$ to check the wave equation (1A) to three significant figures needs millimetres.
2. **Range** — can it reach the quantity? A $30\,\text{cm}$ ruler cannot measure a $2.4\,\text{m}$ table in one placement, even though its resolution is excellent.

More resolution is not automatically better: an instrument with far more resolution than the question needs adds cost and trouble without adding information. The skill is matching the instrument to the job — and then writing readings to exactly the resolution the instrument displays (5D).

Accuracy and precision. These two words are not synonyms, and confusing them is one of the commonest errors in experimental physics. The study design defines both:

> *"Accuracy: A measurement value is considered to be accurate if it is judged to be close to the true value of the quantity being measured. Accuracy is a qualitative term; a measurement value or measurement result may be described, for example, as being 'less accurate' or 'more accurate' when compared with a true value."* (*VCE Physics Study Design, Terms used in this study*)
>
> *"Precision: A measure of the repeatability or reproducibility of scientific measurements and refers to how close two or more measurements are to each other. A set of precise measurements will have values very close to the mean value of the measurements. Precision gives no indication of how close the measurements are to the true value and is therefore a separate consideration to accuracy. The spread of individual measured values provides an indication of the (final) measurement's precision."* (*VCE Physics Study Design, Terms used in this study*)

Both definitions lean on one prior idea: the **true value** — *"the value that would be found if the quantity could be measured perfectly"* (*VCE Physics Study Design, Terms used in this study*). In practice the true value is usually unknown (if we knew it, we would not need to measure it), so accuracy is judged against the best available substitute: an accepted value (such as $g = 9.8\,\mathrm{m\,s^{-2}}$ near Earth's surface, from 8C), or the result of a better instrument or a different method.

So:

- **Accuracy** asks *how close am I to the true value?* It is judged by comparing your result with the true or accepted value, and it is reported qualitatively — "more accurate", "less accurate" — not as a number.
- **Precision** asks *how close are my readings to each other?* It is judged by the **spread** of the readings: a set whose values all sit close to its mean is precise; a set scattered widely is not.

The two questions are independent, and every combination is possible.

	Close to the true value (accurate)	Not close to the true value
Readings close together (precise)	accurate and precise	precise but **not** accurate
Readings spread out (not precise)	accurate on average but **not** precise	neither accurate nor precise

The dangerous combination is the top-right one: readings that are tightly clustered *and* wrong. A precise set looks convincing — the values agree with one another, after all — but agreement between readings is no guarantee of agreement with the truth. A bathroom scale that reads $1.5\,\mathrm{kg}$ too heavy gives beautifully consistent, perfectly useless masses. The cause of a consistent offset like that is a **systematic error**, treated next.

Errors: random and systematic. In this study, a **measurement error** is *"the difference between a measurement result and the 'true' value"* (*VCE Physics Study Design, Terms used in this study*). Errors divide into two kinds, and the distinction explains most of what you will see in your own data.

Random errors are, in the study design's words, *"unpredictable variations in the measurement process"* that *"result in a spread of readings"* and *"affect the precision of a measurement"* (*VCE Physics Study Design, Terms used in this study*). They push each reading a little differently — one reading slightly high, the next slightly low — so their signature in a data set is **scatter**. Examples from investigations in this book:

- small variations in a student's reaction time when starting and stopping a stopwatch;
- a gentle draught making a balance reading wander while the mass is being read;

- judging the exact top of a bounce, or the exact instant a pendulum passes its mark, slightly differently each trial.

Random errors cannot be eliminated, but their effect is reduced by **repeating the measurement and taking the mean**: the high readings and the low readings tend to cancel, so the mean sits closer to the true value than a typical single reading. That is the reason *"repeated measurements are made to reduce the effect of random errors (and reduce likelihood of mistakes)"* (*VCE Physics Study Design, Terms used in this study*).

Systematic errors *"cause readings to differ from the true value in a systematic manner so when a particular value is measured repeatedly, the error is the same"* (*VCE Physics Study Design, Terms used in this study*). Every reading is shifted in the same direction by the same amount, so the signature of a systematic error is a **consistent offset**: precise-looking data that all miss the true value together. The study design names three origins: *"limitations in the instrument itself or incorrect calibration, or inappropriate methods (including parallax)"*. Examples:

- a balance that reads $+0.6\,\mathrm{g}$ with nothing on the pan — every mass is $0.6\,\mathrm{g}$ too high;
- a ruler whose zero end is worn away — every length measured from that end is short by the worn amount;
- a stopwatch that runs slow — every time interval it records is too long;
- a consistent parallax error — reading a scale from the same wrong angle every time.

Repeating a measurement **does not** reduce a systematic error: the same offset reappears in every reading, and the mean inherits it. Systematic errors affect **accuracy**, and they are exposed not by more repeats of the same method but by checking the instrument's calibration, changing the method, or having the measurement reproduced under changed conditions (below).

One more category, and it is not an error at all: a **mistake** — the study design calls it a *personal error* — is a reading known to have been made wrongly: the ball was released before the timer was ready, the wrong scale was read, the result was written in the wrong column. *"Mistakes ... should not be included in reporting and analysis. Rather, the experiment should be repeated correctly"* (*VCE Physics Study Design, Terms used in this study*). Cross the reading out in your logbook so it remains visible, note what went wrong, and take the reading again (14F) — never quietly delete a number and never invent a replacement. The broader task of identifying suspect points in a completed data set — outliers — is practised in 14E.

Repeatability and reproducibility. Both words describe how well measurements agree when they are done again — and the difference between them is the conditions under which "again" happens.

> *"Repeatability: The closeness of the agreement between the results of successive measurements of the same quantity being measured in an experiment, carried out under the same conditions of measurement."* Those conditions, the study design specifies, include *"the same observer, the same measurement procedure, the same measuring instrument used under the same conditions, the same location, and replicate measurements on the same or similar objects over a short period of time."* (*VCE Physics Study Design, Terms used in this study*)
>
> *"Reproducibility: The closeness of the agreement between the results of measurements of the same quantity being measured, carried out under changed conditions of measurement"* — a different observer, a different method, a different instrument, a different location, or a different time. (*VCE Physics Study Design, Terms used in this study*)

In short: **repeat** it yourself, same bench, same equipment, same day; **reproduce** it by changing something that matters.

The study design gives reproducibility two purposes: *"checking of claimed precision and uncovering of any systematic errors that may affect accuracy from one or other experiments/groups"*, and it notes that *"reproducibility links closely to the accuracy of an experiment"* (*VCE Physics Study Design, Terms used in this study*). The logic is the one already used above: if your readings are precise but carry a hidden systematic offset, a second group using a different instrument or method will land somewhere else — and the disagreement is the signal that at least one method is shifted. Precision alone never shows that; reproduction does.

Both concepts connect back to the definition of precision itself, which the study design describes as *"a measure of the repeatability or reproducibility of scientific measurements"*. So when this subtopic's key science skill says *"repeat experiments to evaluate the precision of data"*, it means exactly this: take the readings again under the same conditions, look at how closely the new values agree with the old ones, and report that agreement as the precision of your measurement.

Validity. The last of the six concepts is about the investigation as a whole rather than any single reading:

> *"Validity: A valid experiment investigates what it sets out and/or claims to investigate. Both experimental design and the implementation should be considered when evaluating validity. An experiment and its associated data may not be valid, for example, if the investigation is flawed and controlled variables have been allowed to change. Data may not be valid, for example, if there is observer bias."* (*VCE Physics Study Design, Terms used in this study*)

Two ways data lose validity are named there, and both are common.

- **Controlled variables allowed to change.** In 14A you identified the independent variable (the one you change), the dependent variable (the one you measure) and the controlled variables (everything kept constant so the comparison is fair). If a controlled variable drifts — the drop height changes between trials, the same investigation is run on different surfaces, the wire heats up and its resistance changes while readings are being taken — then a change in the dependent variable can no longer be attributed to the independent variable alone. The investigation no longer tests what it claims to test, and its data are not valid for its question.
- **Observer bias.** If the observer knows or expects a particular result, judgement calls can drift towards it: reading the bounce "about $60\,\text{cm}$" because that is what was predicted, re-running a trial until it "looks right", or recording only the trials that support the hypothesis. The cure is built into the method: automate the measurement where possible (a light gate, video analysis, a data logger), blind the observer to which trial is which when practical, and record every trial — the ethical side of this is 14C's.

Validity is judged by asking one question of the whole investigation: *do these data, gathered this way, actually answer the question that was asked?* Accuracy and precision are properties of the readings; validity is a property of the design and of how it was carried out. A beautifully precise, apparently accurate data set can still be invalid for the question — and an invalid data set cannot be rescued by any analysis.

Uncertainty: what you are, and are not, required to do. When a measurement result is reported, the true value is expected to lie in an interval around it. The study design's representation of that interval is **mean ± uncertainty**: for a result reported as $20 \pm 1\,\text{mm}$, the uncertainty is $1\,\text{mm}$ and the interval runs from $19\,\text{mm}$ to $21\,\text{mm}$ (*VCE Physics Study Design, Terms used in this study*). On a graph the same interval is drawn as an **uncertainty bar**: a short bar centred on the plotted point, stretching from the bottom of the interval to the top.

The study design also fixes a hard ceiling, and this subtopic respects it exactly:

> *"Determining uncertainty for a set of measurements is beyond the scope of VCE Physics because it requires understanding of instrument characteristics for systematic errors, and of probability for random errors."* (*VCE Physics Study Design, Terms used in this study*)

You will **not** be asked to calculate an uncertainty from a data set. What you *are* required to do, verbatim, is:

1. *"recognise the representation of uncertainty as mean ± uncertainty (for example, 'the temperature is* $20 \pm 2^\circ\text{C}$*') or graphically as uncertainty bars"*;
2. *"draw uncertainty bars given a numerical representation of the uncertainty"*;
3. *"state the numerical value for uncertainty given a graphical representation of an uncertainty bar"*.

(*VCE Physics Study Design, Terms used in this study*)

Three skills, all of them about reading and drawing the representation, never about computing the number from scratch. In this book, whenever an uncertainty is needed, it is **given** to you — by your teacher, by the instrument's specification, or by the question.

One related definition completes the set. The **measurement result** is the final reported value, *"usually the average of several measurement values"*, and it *"may also include an estimate of uncertainty"* — though, again, VCE Physics students are not required to determine that estimate themselves (*VCE Physics Study Design, Terms used in this study*). The mean of your repeats is your best estimate of the quantity; the given uncertainty states the interval within which the true value is expected to lie.

Bringing the six concepts together. Each concept answers its own question about the data.

Concept	The question it answers	What you look for in the data
Resolution	Can the instrument even show the difference I care about?	The smallest change the instrument indicates; whether the recorded digits match it
Accuracy	How close is the result to the true value?	Comparison with the true or accepted value; a consistent offset suggests systematic error
Precision	How close are the readings to one another?	The spread of the readings around their mean; scatter signals random error
Repeatability	Do I get the same result when I measure again, same conditions?	Agreement between successive readings by the same observer, instrument and method
Reproducibility	Does the result survive a change of observer, method or instrument?	Agreement under changed conditions; disagreement uncovers systematic errors
Validity	Does the investigation actually test what it claims to test?	Controlled variables held constant; no observer bias in design or implementation

And the pipeline continues from here: you will analyse these data in 14E — organising them into tables and graphs (5D, 7B), identifying patterns, and evaluating the causes of error and uncertainty — before 14D tests them against your hypothesis, 14F authenticates them in your logbook, and 14G communicates them. But none of that downstream work can be better than the data it is given. Generate them carefully: accurate where you can check them, precise where you can repeat them, at the resolution the question needs, and valid for the question you asked.

Worked examples

Example 1 — scaffolded

Four groups each determine the acceleration of a falling object, g, whose accepted value near Earth's surface is $9.8\,\mathrm{m\,s^{-2}}$ (8C). Their four results, in $\mathrm{m\,s^{-2}}$, are:

Group	Results ($\mathrm{m\,s^{-2}}$)
A	$9.7, 9.8, 9.8, 9.9$
B	$9.4, 10.2, 9.5, 10.1$
C	$8.9, 8.8, 9.0, 8.9$
D	$11.4, 9.0, 11.8, 9.4$

For each group, determine whether the results are accurate, precise, both, or neither, and identify the kind of error (random, systematic, both, or negligible) that best accounts for the pattern.

Working	Comment
Mean of A: $(9.7+9.8+9.8+9.9)/4=9.8\text{ m s}^{-2}$; the spread is only 0.2 m s^{-2}.	The mean equals the accepted value (accurate) and the readings sit close together (precise). **Both; errors negligible.**
Mean of B: $(9.4+10.2+9.5+10.1)/4=9.8\text{ m s}^{-2}$; but the readings scatter from 9.4 to 10.2 m s^{-2}.	The mean is on the accepted value (accurate on average), yet the spread is large (not precise). **Accurate but not precise; random error** — unpredictable variations scatter the readings around the true value.
Mean of C: $(8.9+8.8+9.0+8.9)/4=8.9\text{ m s}^{-2}$; the spread is a tight 0.2 m s^{-2}.	The readings cluster tightly (precise) but all sit about 0.9 m s^{-2} below the accepted value (not accurate). **Precise but not accurate; systematic error** — the same offset shifts every reading, as a mis-measured length or a mis-calibrated timer would.
Mean of D: $(11.4+9.0+11.8+9.4)/4=10.4\text{ m s}^{-2}$; the spread is a wide 2.8 m s^{-2}.	The readings are widely scattered (not precise) and their mean sits well above the accepted value (not accurate). **Neither; both error types** — scatter shows random error, and the offset shows systematic error as well.

Notice Group C: its four readings agree so well that they *look* trustworthy. Precision alone never proves accuracy — a consistent offset is invisible until the result is compared with the true value or reproduced by a different method.

Example 2 — scaffolded

(a) State what is meant by the resolution of an instrument, and give the resolution of (i) a ruler marked in millimetres and (ii) a stopwatch displaying tenths of a second.

(b) A student must measure a length of about 2.4 m to the nearest centimetre, and a second length of about 0.47 m to the nearest millimetre. Available are a 30 cm ruler with millimetre marks and a 5 m tape measure with centimetre marks. Match each measurement to the better instrument and justify each choice.

(c) The mean of several current readings is 0.56 A, and the uncertainty is given as 0.02 A. Write the result in the study design's format and state the interval.

(d) An uncertainty bar on a graph stretches from 0.52 m to 0.58 m, centred on the plotted point at 0.55 m. State the result as mean ± uncertainty.

Working	Comment
(a) Resolution is the smallest change in the quantity being measured that causes a perceptible change in the value indicated on the instrument (*VCE Physics Study Design, Terms used in this study*). (i) 1 mm; (ii) 0.1 s.	These are the study design's own two examples. Resolution belongs to the instrument, not the observer.
(b) The 2.4 m length: the 5 m **tape measure**. Its range covers 2.4 m in one placement, and its 1 cm resolution matches the "nearest centimetre" requirement. The 30 cm ruler cannot reach.	Check range first, then resolution.
(b) The 0.47 m length: the 30 cm **ruler** — but $0.47\text{ m}=47\text{ cm}$ exceeds the ruler's 30 cm range, so the ruler must be repositioned part-way along. Its 1 mm resolution matches "nearest millimetre"; the tape's 1 cm resolution cannot.	Resolution decides here; the range shortfall is handled by repositioning, at the cost of an extra joint to read carefully.
(c) $0.56\pm0.02\text{ A}$; the interval runs from 0.54 A to 0.58 A.	The result is written mean ± uncertainty; the true value is expected to lie inside the interval.
(d) The bar runs from 0.52 m to 0.58 m, so the uncertainty is half the bar's length:	Read the centre (the mean) and half the bar's total length (the uncertainty).

$(0.58-0.52)/2=0.03\,\text{m}$. The result is $0.55\pm0.03\,\text{m}$.

Example 3 — unscaffolded

A student investigates the acceleration of a falling object by dropping a steel ball from a measured height $h=1.25\,\text{m}$ and timing the fall with a hand stopwatch. Five timed falls give: $0.62\,\text{s}$, $0.65\,\text{s}$, $0.61\,\text{s}$, $0.63\,\text{s}$, $0.64\,\text{s}$. (a) Calculate the mean fall time and hence the student's value of g, using the constant-acceleration result for a fall from rest, $h=1/2\,g\,t^2$ (7C). (b) Assess the accuracy and the precision of the student's value of g, taking the accepted value to be $9.8\,\text{m s}^{-2}$ (8C). (c) Identify the random and the systematic error present in this method, and explain how each shows itself in the data.

The mean fall time is

$$t=\frac{0.62+0.65+0.61+0.63+0.64}{5}=\frac{3.15}{5}=0.63\,\text{s}.$$

Rearranging $h=1/2\,g\,t^2$ for g and substituting,

$$g=\frac{2h}{t^2}=\frac{2\times1.25}{0.63^2}=\frac{2.50}{0.3969}=6.298\ldots\,\text{m s}^{-2}\approx6.3\,\text{m s}^{-2}$$

to two significant figures, since the mean time is given to two significant figures (1A).

(b) The student's value, $6.3\,\text{m s}^{-2}$, is far below the accepted $9.8\,\text{m s}^{-2}$, so the result is **not accurate**. The five readings themselves, though, all lie between $0.61\,\text{s}$ and $0.65\,\text{s}$ — a spread of only $0.04\,\text{s}$ around their mean — so the measurements are **reasonably precise**. This is the dangerous combination of Example 1's Group C: consistent, tightly clustered readings that miss the true value.

(c) The **random error** is the variation in the student's reaction time from trial to trial: the instant the stopwatch is stopped relative to the instant of impact changes slightly each drop, producing the observed spread of $0.04\,\text{s}$. The **systematic error** is the reaction delay itself, which acts in one direction: the student always stops the watch *after* the ball has landed, so every recorded time is too long. A fall from $1.25\,\text{m}$ at $g=9.8\,\text{m s}^{-2}$ actually takes $t=\sqrt{2h/g}=\sqrt{2.50/9.8}\approx0.51\,\text{s}$, and every reading is about $0.12\,\text{s}$ longer than this. Because $g=2h/t^2$, times that are too long give a g that is too small. Repeating the timing reduces the random scatter but cannot remove the offset; changing the method — a light gate, or video analysis replayed frame by frame — is what removes it.

∴ the mean fall time is $0.63\,\text{s}$, giving $g=6.3\,\text{m s}^{-2}$: precise but not accurate, because varying reaction time supplies a random error (the spread) and a consistent stopping delay supplies a systematic error (the offset).

Example 4 — unscaffolded

A student investigates the question *"Does the temperature of a tennis ball affect how high it bounces?"* The method is:

- Trial 1: the ball is warmed in the sun to about 35°C, dropped from $1.0\,\text{m}$ onto a concrete floor, and the bounce height judged by eye.
- Trial 2: the ball is cooled in a refrigerator to about 5°C, dropped from $1.2\,\text{m}$ onto a carpet, and the bounce height judged by eye.

The student predicted the warm ball would bounce higher, and recorded the warm ball's bounce as "about $60\,\text{cm}$" and the cold ball's as "about $40\,\text{cm}$", having watched mainly for the bounce they expected in each case.

Evaluate the validity of this investigation and its data, applying the study design's definition: *"A valid experiment investigates what it sets out and/or claims to investigate"* (*VCE Physics Study Design, Terms used in this study*).

The investigation is **not valid**, on both counts the definition names — design and implementation.

On design: the question asks about **temperature alone**, but between the two trials two controlled variables were allowed to change. The drop height changed ($1.0\,\mathrm{m}$ became $1.2\,\mathrm{m}$), and a higher drop produces a higher bounce regardless of temperature. The surface changed (concrete became carpet), and the surface changes how much energy the collision returns. With three differences between the trials — temperature, height and surface — the $20\,\mathrm{cm}$ gap between the recorded bounces cannot be attributed to temperature, so the data do not test what the investigation claims to test.

On implementation: the bounce heights were judged by eye by an observer who had already predicted the outcome and "watched mainly for the bounce they expected". That is **observer bias**, the study design's own example of data that "may not be valid". The numbers recorded are estimates pulled towards the prediction, not measurements.

To make the investigation valid, the design must hold everything except temperature constant — one drop height, one surface, one ball — and the implementation must remove the bias: measure the temperature with a thermometer, record the bounce on video and read the height from the recording frame by frame, repeat each temperature several times, and record every trial in the logbook (14F). The direction the student expects — a warmer pressurised tennis ball does bounce higher, because warming raises the pressure of the air inside and the rubber returns more of the impact energy — may well be correct; but this method, carried out this way, cannot show it.

∴ neither the design (drop height and surface changed with temperature) nor the implementation (bounce heights judged by an observer biased by their own prediction) supports the claim being made; the data are not valid for the question.

Practice questions

Question 1 *(scaffolded)* Match each description (i)–(vi) with one of the following terms: *accuracy, precision, resolution, repeatability, reproducibility, validity*. Each term is used once. (i) how close a measurement is judged to be to the true value of the quantity (ii) the smallest change in the measured quantity that causes a perceptible change in the value indicated on the instrument (iii) how close two or more measurements of the same quantity are to each other (iv) the closeness of agreement between measurements of the same quantity carried out under the same conditions — same observer, procedure, instrument and location (v) the closeness of agreement between measurements of the same quantity carried out under changed conditions — different observer, method, instrument or time (vi) whether the experiment investigates what it sets out and/or claims to investigate

Question 2 *(scaffolded)* (a) State the resolution of each instrument: (i) a $30\,\mathrm{cm}$ ruler with millimetre marks; (ii) a stopwatch that displays hundredths of a second; (iii) a thermometer with marks every $0.5^{\circ}\mathrm{C}$. (b) A student must measure a distance of about $2.0\,\mathrm{m}$ to the nearest millimetre. Available are a $3\,\mathrm{m}$ tape measure with millimetre marks and a $5\,\mathrm{m}$ tape measure with centimetre marks. Identify the better instrument and justify your choice using the ideas of resolution and range. (c) The student records the length from (b) as $2.0437\,\mathrm{m}$. Explain what is wrong with this recording, with reference to the resolution of the instrument used and the significant-figure conventions of 1A.

Question 3 *(scaffolded)* (a) A result is reported as $24 \pm 1\,\mathrm{cm}$. State the uncertainty and the interval. (b) The mean of several current readings is $0.56\,\mathrm{A}$ and the uncertainty is given as $0.02\,\mathrm{A}$. Write the result in the study design's mean ± uncertainty format. (c) On a graph, an uncertainty bar stretches from $0.52\,\mathrm{m}$ to $0.58\,\mathrm{m}$, centred on the plotted point at $0.55\,\mathrm{m}$. State the result as mean ± uncertainty.

Question 4 *(scaffolded)* Four students each use a balance to measure the mass of an object labelled $100.0\,\mathrm{g}$. Their readings, in grams, are:

Student	Readings (g)
A	$100.1, 99.9, 100.0, 100.0$
B	$98.4, 101.7, 99.1, 100.8$
C	$96.2, 96.3, 96.1, 96.2$
D	$105.1, 97.4, 104.2, 98.1$

(a) Identify which student's readings are precise but not accurate, and support your answer with the mean and the spread of the readings.

(b) Identify which student's readings are accurate but not precise.
(c) For the student identified in (a), identify the kind of error most likely present and justify your choice.

Question 5 *(scaffolded)* (a) Classify each of the following as a **random** or a **systematic** error: (i) a balance that reads $+0.3\,\mathrm{g}$ with nothing on the pan; (ii) a gentle draught that makes a balance reading wander while it is being read; (iii) a ruler whose zero end has worn away; (iv) variations in a student's reaction time when starting and stopping a stopwatch. (b) State which of accuracy and precision is mainly affected by each kind of error. (c) Explain why repeating a measurement and averaging the readings reduces the effect of random errors but not of systematic errors.

Question 6 *(scaffolded)* A student investigates the motion of a trolley rolling down a ramp. (a) She runs the trolley three more times immediately, using the same stopwatch, the same ramp and the same release point, to see whether she obtains the same times. Identify which concept — repeatability or reproducibility — she is testing, and state two of the conditions the study design requires to be the same. (b) A class at another school follows her written method but times the trolley with light gates and uses a different trolley. Identify which concept this tests. (c) State the two purposes of reproducing an experiment given by the study design.

Question 7 A student timing a pendulum records the time for 20 complete oscillations as $31.4\,\mathrm{s}$ on a stopwatch with a resolution of $0.1\,\mathrm{s}$. (a) Calculate the period of the pendulum. (b) Explain why timing 20 oscillations and dividing gives a more trustworthy period than timing a single oscillation, in terms of the start-and-stop uncertainty of the timing.

Question 8 A student measuring the time for an object to fall records $1.3\,\mathrm{s}$, $1.4\,\mathrm{s}$, $1.3\,\mathrm{s}$, $1.4\,\mathrm{s}$ and $2.1\,\mathrm{s}$. In the final trial, she notes in her logbook that she accidentally released the object before the timer was ready and then re-measured from too great a height. Explain how the $2.1\,\mathrm{s}$ reading should be treated, distinguishing between a mistake (personal error) and a random error as the study design does.

Question 9 A student measures the width of a block five times: $12.3\,\mathrm{mm}$, $12.5\,\mathrm{mm}$, $12.4\,\mathrm{mm}$, $12.3\,\mathrm{mm}$, $12.5\,\mathrm{mm}$. (a) Calculate the mean width. (b) The uncertainty is given as $0.1\,\mathrm{mm}$. Report the result in the study design's format and state the interval. (c) Explain why the mean of several readings is used as the measurement result rather than any single reading.

Question 10 A student investigates the question *"How does the drop height affect the depth of the crater made in sand?"* For the small drop heights she uses a glass marble, and for the large drop heights she switches to a larger, heavier steel ball, reasoning that it will be easier to see. Evaluate the validity of the data for this question, identifying the variables that should have been controlled.

Question 11 A voltmeter whose pointer does not rest at zero reads $+0.1\,\mathrm{V}$ when nothing is connected (5C). A student uses it to measure several potential differences in a circuit. (a) Classify the resulting error as random or systematic, and justify your classification. (b) State whether the error mainly affects the accuracy or the precision of the readings. (c) In the same investigation, an ammeter connected correctly gives readings that scatter slightly from one trial to the next. Classify this variation and explain the difference between the two situations.

Question 12 A digital balance reads $+0.6\,\mathrm{g}$ when its pan is empty. A student adds sand until the display reads $50.0\,\mathrm{g}$. (a) Calculate the true mass of the sand. (b) Classify the error and state its effect on the accuracy and the precision of the measurement. (c) State one thing the student could have done to avoid this error.

Question 13 Two classes measure the resistance of the same resistor, labelled $100\,\Omega$ (5D). Class A obtains $98\,\Omega$, $99\,\Omega$, $98\,\Omega$ using multimeter M1. Class B obtains $105\,\Omega$, $106\,\Omega$, $105\,\Omega$ using multimeter M2. (a) Assess the precision of each class's readings, and explain what the disagreement between the two classes suggests. (b) State one way the disagreement could be resolved.

Question 14 The study design notes that video analysis can be used to investigate questions such as *"Is kinetic energy conserved in a pole vault?"* State two advantages of video analysis over a hand-held stopwatch for timing a moving object, and for each advantage name the concept from this subtopic it most directly improves (choose from accuracy, precision, repeatability, reproducibility, resolution, validity).

Question 15 A student measures the speed of a trolley five times using hand timing: $0.61\,\mathrm{m\,s^{-1}}$, $0.59\,\mathrm{m\,s^{-1}}$, $0.62\,\mathrm{m\,s^{-1}}$, $0.60\,\mathrm{m\,s^{-1}}$, $0.58\,\mathrm{m\,s^{-1}}$. A light gate later gives the speed as $0.64\,\mathrm{m\,s^{-1}}$. (a) Calculate the mean of the student's five readings. (b) Assess the precision and the accuracy of the student's measurements, giving the evidence for each judgement. (c) Identify the kind of error most likely responsible for the difference between the student's mean and the light-gate value, and justify your choice.

Question 16 Investigating refraction through a glass block (1C), a student writes in her logbook: *"The ray bent towards the normal as it entered the block,"* and records an angle of incidence of 40° and an angle of refraction of 26°. (a) Identify which of these is qualitative data and which is quantitative data. (b) State one thing each type of data contributes to the investigation. (c) Explain why the quantitative data are necessary to test Snell's Law, $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$.

Question 17 A student says: *"My five readings are all very close to each other, so they must be accurate."* Evaluate this claim using the study design's definitions of accuracy and precision, and support your evaluation with a concrete example of readings that are precise but not accurate.

Question 18 A student adapts the investigation question *"How does the extension of a spring depend on the force applied to it?"* (9B). (a) Determine the type and amount of data to be generated: state which quantities will be measured, with their units, how many values of the independent variable are needed, and how the readings at each value should be taken. Include one qualitative observation worth recording. (b) Select the equipment for the investigation, stating the resolution each measuring instrument must have for the data to answer the question. (c) Identify one likely source of random error and one likely source of systematic error in this method. (d) Describe how the student would test the repeatability of the extension reading at one chosen force. (e) Explain why deciding the type and amount of data *before* starting the investigation matters for the quality of the conclusion.

Answers

Question 1 (i) accuracy; (ii) resolution; (iii) precision; (iv) repeatability; (v) reproducibility; (vi) validity. **Question 2** (a) (i) $1\,\text{mm}$; (ii) $0.01\,\text{s}$; (iii) 0.5°C; (b) the $3\,\text{m}$ tape with millimetre marks; (c) see solution. **Question 3** (a) uncertainty $1\,\text{cm}$, interval $23\,\text{cm}$ to $25\,\text{cm}$; (b) $0.56 \pm 0.02\,\text{A}$; (c) $0.55 \pm 0.03\,\text{m}$. **Question 4** (a) Student C; (b) Student B; (c) systematic error — see solution. **Question 5** (a) (i) systematic; (ii) random; (iii) systematic; (iv) random; (b) random errors affect precision; systematic errors affect accuracy; (c) see solution. **Question 6** (a) repeatability — same observer and same instrument (any two of the study design's conditions); (b) reproducibility; (c) checking claimed precision, and uncovering systematic errors. **Question 7** (a) $1.57\,\text{s}$; (b) see solution. **Question 8** Treat it as a mistake, not a random error: exclude it from the analysis and repeat the measurement correctly — see solution. **Question 9** (a) $12.4\,\text{mm}$; (b) $12.4 \pm 0.1\,\text{mm}$, interval $12.3\,\text{mm}$ to $12.5\,\text{mm}$; (c) see solution. **Question 10** Not valid — the ball's size, mass and material changed with the drop height; see solution. **Question 11** (a) systematic; (b) accuracy; (c) random — see solution. **Question 12** (a) $49.4\,\text{g}$; (b) systematic — reduces accuracy, leaves precision unaffected; (c) zero (tare) the balance first, or subtract the offset. **Question 13** (a) each set is precise; the disagreement suggests a systematic error in at least one multimeter; (b) see solution. **Question 14** Any two advantages with the correct concept — see solution. **Question 15** (a) $0.60\,\text{m s}^{-1}$; (b) precise but not accurate; (c) systematic — see solution. **Question 16** (a) the sentence is qualitative; the angles are quantitative; (b), (c) see solution. **Question 17** The claim is incorrect — precision gives no indication of accuracy; see solution. **Question 18** See the fully-worked solution for a model plan.

Fully-worked solutions

Question 1 (i) **Accuracy** — closeness to the true value. (ii) **Resolution** — the smallest change the instrument indicates. (iii) **Precision** — closeness of readings to each other. (iv) **Repeatability** — agreement under the same conditions (observer, procedure, instrument, location). (v) **Reproducibility** — agreement under changed conditions. (vi) **Validity** — whether the experiment tests what it claims to test.

Question 2 (a) (i) $1\,\text{mm}$; (ii) $0.01\,\text{s}$; (iii) 0.5°C. (b) The $3\,\text{m}$ tape measure with millimetre marks. Its range ($3\,\text{m}$) covers the $2.0\,\text{m}$ distance, and its resolution ($1\,\text{mm}$) matches the requirement to measure to the nearest millimetre. The $5\,\text{m}$ tape has the range but only centimetre resolution, which is ten times too coarse for the job. (c) The recording claims five significant figures, with a final digit in tenths of a millimetre ($2.0437\,\text{m} = 2043.7\,\text{mm}$). A millimetre tape cannot distinguish tenths of a millimetre, so the last digit is invented — the value pretends to more precision than the instrument can provide. Consistent with the significant-figure conventions of 1A, the length should be recorded to the nearest millimetre, e.g. $2.044\,\text{m}$ (or $2044\,\text{mm}$), and no further.

Question 3 (a) In $24 \pm 1\,\text{cm}$ the uncertainty is $1\,\text{cm}$ and the interval runs from $23\,\text{cm}$ to $25\,\text{cm}$ — the true value is expected to lie within it. (b) $0.56 \pm 0.02\,\text{A}$. (c) The centre of the bar is the mean, $0.55\,\text{m}$, and the uncertainty is half the bar's length: $(0.58 - 0.52)/2 = 0.03\,\text{m}$. The result is $0.55 \pm 0.03\,\text{m}$.

Question 4 (a) **Student C.** Mean: $(96.2 + 96.3 + 96.1 + 96.2)/4 = 96.2\,\text{g}$. The readings all lie within $0.2\,\text{g}$ of their mean, so they are precise; but the mean is $3.8\,\text{g}$ below the labelled $100.0\,\text{g}$, so they are not accurate. (b) **Student B.** Mean: $(98.4 + 101.7 + 99.1 + 100.8)/4 = 100.0\,\text{g}$, which agrees with the labelled value (accurate on average), but the readings scatter over $3.3\,\text{g}$ (from $98.4\,\text{g}$ to $101.7\,\text{g}$), so they are not precise. (Student A is both accurate and precise: mean $100.0\,\text{g}$, spread only $0.2\,\text{g}$; Student D is neither: mean $101.2\,\text{g}$, spread $7.7\,\text{g}$.) (c) A **systematic error**: the readings are tightly clustered yet all shifted in the same direction, which is the signature of an offset that acts the same way on every reading — for example, a balance that was not zeroed, or one whose calibration is slightly out. Random error would scatter the readings; it would not march them all to one side.

Question 5 (a) (i) systematic; (ii) random; (iii) systematic; (iv) random. (b) Random errors affect **precision** (they spread the readings); systematic errors affect **accuracy** (they shift every reading the same way from the true value). (c) Random errors push readings unpredictably high and low, so when several readings are averaged, the highs and lows tend to cancel and the mean sits closer to the true value than a typical single reading. A systematic error shifts every reading by the same amount in the same direction, so the average carries exactly the same shift: repeating cannot cancel what never varies.

Question 6 (a) **Repeatability.** The study design's conditions include the same observer, the same measurement procedure, the same measuring instrument used under the same conditions, the same location, and replicate measurements over a short period of time — any two of these. (b) **Reproducibility** — the observer, the instrument and the equipment have all changed. (c) Per the study design: **checking of claimed precision**, and **uncovering of any systematic errors** that may affect accuracy from one experiment or group to another.

Question 7 (a) $T = 31.4/20 = 1.57\,\text{s}$. (b) Starting and stopping the stopwatch each carry a reaction-time uncertainty, and that uncertainty is much the same whether one oscillation is timed or twenty. When twenty oscillations are timed, the same start-and-stop uncertainty is shared across all twenty periods, so its effect on each single period is far smaller than it would be for a one-period measurement. Equivalently: the measured quantity (the $31.4\,\text{s}$ total) is large compared with the stopwatch's resolution and with reaction time, so those limitations matter far less to the final period.

Question 8 The $2.1\,\text{s}$ reading is a **mistake** (a personal error), not a random error: the student knows the trial was carried out wrongly — the release and the height were not as required — and the reading is not a measurement of the intended quantity at all. The study design's rule is that mistakes *"should not be included in reporting and analysis"* and that *"the experiment should be repeated correctly"*. The correct treatment: leave the reading visible in the logbook with a note of what went wrong (cross it out, never erase it — 14F), exclude it from the mean, and repeat that trial properly. It must not be averaged with the good readings, and it must not be silently deleted either — honest recording is part of the integrity this area of study requires (14C). A random error, by contrast, is an unavoidable small variation in a properly conducted trial; such readings stay in the analysis and are handled by repeating and averaging. The formal identification and treatment of suspect points (outliers) in a completed data set is practised in 14E.

Question 9 (a) $\text{mean} = (12.3+12.5+12.4+12.3+12.5)/5 = 62.0/5 = 12.4\,\text{mm}$. (b) $12.4 \pm 0.1\,\text{mm}$; the interval runs from $12.3\,\text{mm}$ to $12.5\,\text{mm}$. (c) Individual readings carry random error — each is pushed a little differently from the true value. The study design defines the measurement result as *"usually the average of several measurement values"*: the high and low readings tend to cancel in the mean, so the mean is a better estimate of the true value than any single reading, and the spread of the readings around it indicates the precision.

Question 10 The data are **not valid** for the question. The question asks about the effect of drop height alone, so every other influence on crater depth must be held constant. But the ball changed with the drop height: its mass, its size and its material (glass versus steel) all changed at the same time as the independent variable, and each of them affects the crater depth. A deeper crater at the larger heights could be due to the greater height, the greater mass, the different size, or any combination of the three — the investigation cannot tell which. The variables that should have been controlled include the ball used (same object for every drop), the sand (same container, same preparation), and the way the depth is measured. A valid design changes only the drop height.

Question 11 (a) **Systematic.** The pointer offset shifts every reading by the same $+0.1\,\text{V}$, in the same direction, regardless of what is measured — exactly the study design's description of an error that is "the same" each time a value is measured. It is an instrument limitation, one of the study design's named origins of systematic error. (b) Mainly **accuracy**: every result is displaced from the true value by the same amount. The readings can still agree closely with one another, so precision is not what suffers. (c) The ammeter's scatter is a **random error** — small unpredictable variations from trial to trial, producing a spread of readings. The difference: the voltmeter's error is a constant offset in one direction (systematic, affecting accuracy), while the ammeter's error varies in size and direction from reading to reading (random, affecting precision).

Question 12 (a) The display reads $0.6\,\text{g}$ too high, so the true mass is $50.0 - 0.6 = 49.4\,\text{g}$. (b) A **systematic error**: the offset acts on every measurement made with this balance in the same way. It makes the result **inaccurate** (the reported mass is $0.6\,\text{g}$ from the true value) without harming **precision** — repeated weighings of the same sand would still agree with one another, all equally wrong. (c) Zero (tare) the balance with the empty pan before weighing, check the zero reading at the start of every session, or subtract the known $+0.6\,\text{g}$ offset from every reading.

Question 13 (a) Each class's readings are **precise**: Class A's three values lie within $1\,\Omega$ of one another, and Class B's within $1\,\Omega$. But the two means ($98.3\,\Omega$ and $105.3\,\Omega$) differ by about $7\,\Omega$, far more than either class's scatter. Since the conditions changed between the two measurements (different observers, different instruments), this is a reproducibility check, and per the study design its purpose is uncovering systematic errors: the disagreement suggests that at least one of the two multimeters carries a systematic error — for instance, a calibration fault — shifting all its readings one way. (b) Any one: measure the resistor with a third, known-good meter and see which class it agrees with; have both meters checked against a standard reference resistor; or calibrate both meters and repeat.

Question 14 Any two, each paired with a correct concept: - **Removes reaction-time error**: the start and stop instants are read from recorded frames rather than from a person's thumb, which improves the **accuracy** of the times (the systematic stopping delay of hand timing is gone). - **The recording can be replayed**: any observer, at any time, can read the same frames, which improves **repeatability** (the same observer can check their own reading) and **reproducibility** (a different observer or a different school can read the same event). - **Higher effective resolution**: with a camera recording at, say, 50 frames per second, instants can be located to within a frame interval, improving the **resolution** of the timing compared with reading a moving object against a hand-held watch. (Accept any two advantages clearly stated and correctly matched to a concept from this subtopic.)

Question 15 (a) $\text{mean} = (0.61+0.59+0.62+0.60+0.58)/5 = 3.00/5 = 0.60\ \text{m s}^{-1}$. (b) **Precision:** the five readings lie within $0.04\ \text{m s}^{-1}$ of one another (0.58 to $0.62\ \text{m s}^{-1}$), a small spread around their mean, so the measurements are reasonably precise. **Accuracy:** the light-gate value, $0.64\ \text{m s}^{-1}$, comes from an instrument that does not depend on human reaction time, and the student's mean sits $0.04\ \text{m s}^{-1}$ below it, so the hand-timed measurements are not accurate — they are consistently low. (c) A **systematic error**. All five readings, and their mean, sit below the light-gate value: the offset acts in one direction on every trial, which is the signature of a systematic error — most plausibly a consistent delay in starting or stopping the hand timing. Random error is also present (the small spread), but scatter alone would not shift the whole set one way.

Question 16 (a) The written observation — *"the ray bent towards the normal"* — is **qualitative** data; the angles (40°, 26°) are **quantitative** data. (b) The qualitative observation records the *behaviour* — the direction of the bending — which tells the student what is happening and lets her check that the numbers make sense (a refraction angle larger than the incidence angle for light entering glass would contradict the observation). The quantitative measurements give the *amounts* — values that can be compared, substituted into Snell's Law, graphed and tested. (c) Snell's Law, $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ (1C), is a mathematical relationship between the sines of the two angles. Testing it requires numerical values of θ_1 and θ_2: with 40° and 26°, $\sin 40^\circ / \sin 26^\circ \approx 1.5$, consistent with the refractive index of glass. Words alone — "bent towards the normal" — state the direction of the effect but cannot test the relationship or give the glass's refractive index.

Question 17 The claim is incorrect. Precision and accuracy are separate considerations. Per the study design, precision concerns how close the readings are **to each other**, and it *"gives no indication of how close the measurements are to the true value"*; accuracy concerns closeness to the **true value**. Readings can therefore be tightly clustered and still all miss the true value together. Concrete example: a balance that reads $+0.6\ \text{g}$ with an empty pan gives five readings of a $50.0\ \text{g}$ mass as $50.6\ \text{g}$, $50.6\ \text{g}$, $50.7\ \text{g}$, $50.6\ \text{g}$, $50.6\ \text{g}$ — very close to one another (precise), yet every one is $0.6\ \text{g}$ too high (not accurate). The student's reasoning would be valid only if a systematic error had already been ruled out; close agreement between readings is evidence of precision, and of nothing more.

Question 18 A full-mark answer would include: (a) **Type and amount of data.** Quantitative: the applied force F in newtons (independent variable) and the extension x in millimetres or centimetres (dependent variable). A suitable amount: at least six force values — for example, forces from $0.5\ \text{N}$ to $3.0\ \text{N}$ in $0.5\ \text{N}$ steps, applied with slotted masses, where each mass provides a force $F = mg$ with $g = 9.8\ \text{N kg}^{-1}$ (8C) — with the extension measured three times at each force and the mean used. Qualitative: record whether the spring returns to its original length when unloaded (the elastic behaviour described in 9B), and note if any reading is taken after the spring has stopped behaving elastically. (b) **Equipment.** A spring on a clamp stand; slotted masses (or a newtonmeter) to apply known forces; a ruler with **millimetre resolution** fixed beside the spring to read the extension — extensions of a few centimetres measured to the nearest centimetre would give too few distinct values to show the relationship. Read the ruler with the eye level with the mark to avoid a parallax error. (c) **Random error:** judging the exact position of the bottom of the spring against the ruler slightly differently each trial; slight settling or vibration of the spring as it is read. **Systematic error:** reading the ruler consistently from one wrong angle (parallax); a ruler whose zero end is worn; measuring extension from the wrong reference point each time (for example, from the top of the spring rather than from the starting position of its bottom), which shifts every extension by the same amount. (d) **Testing repeatability:** at one chosen force — say $2.0\ \text{N}$ — the same student, using the same ruler and the same procedure at the same bench, unloads and reloads the spring and measures the extension two or three more times within the same session, then compares how closely the new readings agree with the original one. Close agreement indicates good repeatability; the spread of the readings indicates the precision. (e) Deciding the type and amount of data first ensures the data can actually answer the question: enough force values are needed to show the pattern (whether extension is proportional to force), and repeats are needed so the precision can be evaluated and the mean used as the measurement result. Planning also forces the equipment and procedure to be chosen with their sources of error in mind — exactly what the key science skill requires — rather than having those weaknesses discovered only after the data exist.

Theory

The investigation you design in 14A and carry out in 14B is yours: your question, your method, your data. With that ownership comes responsibility. The method must be safe for you, for the people around you and for the place where the work happens, and the way you record and report the data must be honest. This subtopic teaches the guidelines that govern both responsibilities. It owns one key knowledge dot point, verbatim:

ID	Key knowledge (verbatim)
`U2.3.5`	"identify and apply health, safety and ethical guidelines relevant to the selected scientific investigation"

(*VCE Physics Study Design, Unit 2, Area of Study 3*)

It also teaches, for the first time, the three key science skills the study design groups under **Comply with safety and ethical guidelines**, verbatim:

ID	Key science skill (verbatim)
`KSS.3.1`	"demonstrate safe laboratory practices when planning and conducting investigations by using risk assessments that are informed by safety data sheets (SDS), and accounting for risks"
`KSS.3.2`	"apply relevant occupational health and safety guidelines while undertaking practical investigations"
`KSS.3.3`	"demonstrate ethical conduct when undertaking and reporting investigations"

(*VCE Physics Study Design, key science skills*)

You will be assessed on these skills in the report of your Unit 2 Outcome 3 investigation — *"a report of a practical investigation (student-designed or adapted)"* (*VCE Physics Study Design, Unit 2, Assessment*) — and Units 3 & 4 investigations assume you already have them. One thing this subtopic cannot do: it cannot supervise you. The study design states that *"all laboratory work should be supervised by the teacher"* and that the school is responsible for the duty of care — the legal responsibility to take reasonable steps to protect people from foreseeable harm. The practical hours required by the study are your school's obligation to provide; this subtopic teaches you the skills to identify and apply the guidelines once you are there (*VCE Physics Study Design, Unit 2, Safety and wellbeing*).

Why guidelines exist. The study design warns that *"the study may involve the handling of potentially hazardous substances and the use of potentially hazardous equipment"*. Physics investigations use hot objects and hot liquids (2A, 2B), stretched springs and falling masses (8C, 9B, 9C), electrical equipment (Chapters 5 and 6), bright light sources and lasers (Chapters 1 and 12) and, in some schools, sealed radioactive sources (Chapter 3). Each of these can harm someone who handles it carelessly. Safety guidelines exist so that everyone finishes the investigation uninjured. Ethical guidelines exist for a second purpose: so that the data you report can be trusted. A conclusion is only as good as the honesty of the data behind it.

The legal framework in Victoria. Occupational health and safety (OHS) law in Victoria sets duties for schools as workplaces and for every person in them. The study design's own *Safety and wellbeing* section names the relevant acts, regulations and codes:

- *Occupational Health and Safety Act 2004* (Vic.)
- *Occupational Health and Safety Regulations 2017* (Vic.)
- *Electricity Safety Act 1998* (Vic.)
- *Dangerous Goods (Storage and Handling) Regulations 2022* (Vic.)

- *Code of Practice for the Storage and Handling of Dangerous Goods 2013* (WorkSafe Victoria)
- *Compliance Code: Hazardous Substances, Edition 2, 2019* (WorkSafe Victoria)
- 'Occupational Health and Safety Management Systems' (AS/NZS ISO 45001:2018)

(*VCE Physics Study Design, Unit 2, Safety and wellbeing*)

WorkSafe Victoria, the Victorian government's workplace safety regulator, publishes the codes of practice and guidance that Victorian schools follow. Under the *Occupational Health and Safety Act 2004* (Vic.), the school must, so far as is reasonably practicable, provide and maintain a learning environment that is safe and without risks to health — and every person in the workplace has duties too. You must take reasonable care of your own health and safety and of other people's, and you must cooperate with the school's safety procedures. In practice, a student's duties look like this:

- follow the teacher's instructions at all times;
- use equipment only as you have been taught to use it;
- do nothing that could put yourself or another person at risk;
- report hazards, injuries, spills and breakages to the teacher immediately.

Hazards and risks. Two words that mean different things. A **hazard** is anything with the potential to cause harm — a Bunsen flame, a stretched spring, a frayed lead, a chemical. A **risk** is how likely it is that the hazard actually harms someone, and how badly — it depends on how the hazard is handled. A sealed radioactive source locked in its lead-lined box is a hazard with a low risk; the same source held in a bare hand is the same hazard with a much higher risk (3E). A **risk assessment** is the structured check you make *before* the practical work starts. It has four steps:

Step	What you do
1. Identify hazards	Read the whole method — setup, procedure, pack-up and clean-up — and list everything that could cause harm.
2. Assess the risks	For each hazard, state who could be harmed and how, and rate the risk by combining likelihood and consequence.
3. Control the risks	Choose measures that remove the hazard or reduce the risk, starting with the most effective (the hierarchy of controls, below).
4. Review	Re-assess whenever the method changes, something goes wrong, or new information appears, and record the changes in your logbook (14F).

A common way to rate a risk in step 2 is a grid of likelihood against consequence:

Likelihood ↓ Consequence →	Minor	Moderate	Severe
Likely	Moderate	High	High
Possible	Low	Moderate	High
Unlikely	Low	Low	Moderate

The rating tells you how urgently a control is needed: a *high* risk must be controlled before the investigation proceeds.

The hierarchy of controls. When you choose a control, Australian work health and safety practice ranks the options from most effective to least effective:

Level	What it means	Example in a school physics investigation
1. Elimination	Remove the hazard entirely	Drop the part of the method that needs an open flame

Level	What it means	Example in a school physics investigation
2. Substitution	Replace it with something less hazardous	Use a digital thermometer instead of a glass one
3. Isolation	Separate people from the hazard	A barrier between a drop zone and the rest of the class
4. Engineering controls	Physical features that reduce the risk	An RCD on the power circuit (6E); insulation on every lead
5. Administrative controls	Procedures, rules and training	Teacher supervision; a "switch off before rewiring" rule
6. Personal protective equipment (PPE)	What the person wears	Safety glasses, lab coat, gloves

Source: Safe Work Australia, How to Manage Work Health and Safety Risks — Code of Practice, retrieved 2026-08-18.

Read the table top to bottom: the best control removes the hazard, the worst merely stands between the hazard and you. PPE is the *last* line of defence because it does not remove the hazard — safety glasses help only if they are worn, and they do nothing to stop a spring from snapping. A good risk assessment uses the highest level that is practical, and adds PPE on top where a risk remains.

Safety data sheets. Substances carry their own information. A **safety data sheet (SDS)** is a document supplied by the manufacturer or importer of a substance that describes the substance's hazards and how to work with it safely. Under the *Occupational Health and Safety Regulations 2017* (Vic.), a workplace must keep a current SDS for every hazardous substance it holds and make it available to anyone who could be exposed; your school keeps its sheets in an SDS register. If your investigation uses a substance — a fuel, a solvent, a metal sample — read the SDS *while you are planning*, and let it inform your risk assessment. SDSs follow a standard 16-section international format set by the Globally Harmonized System of Classification and Labelling of Chemicals (GHS). The sections you will use most are:

SDS section	What it tells you
Section 1 — Identification	The substance's name and its supplier
Section 2 — Hazard identification	What the substance can do: flammable, toxic, corrosive, an irritant
Section 4 — First-aid measures	What to do immediately after skin, eye, inhalation or swallowing exposure
Section 6 — Accidental release measures	What to do about a spill
Section 7 — Handling and storage	How to handle it safely and what to keep it away from
Section 8 — Exposure controls / personal protection	Ventilation and PPE requirements

Source: Safe Work Australia, Globally Harmonized System of Classification and Labelling of Chemicals (GHS), retrieved 2026-08-18.

Remember the limit of an SDS: it describes a *substance*. A spring, a trolley, a laser and a falling mass have no SDS at all — for those hazards, identification comes from reading the method itself (step 1 above). An SDS informs the risk assessment; it does not replace it.

Electrical safety — the study design's hard limits. Electricity is treated with special strictness because its hazards are invisible. The study design's *Safety and wellbeing* section is explicit:

> Only persons who hold an appropriate current electrical license are permitted to carry out electrical work on products or equipment that require voltages greater than 50 volts AC or 120 volts ripple-free DC. This requirement means that students are not permitted to carry out any electrical work on the internal

> components of electrical products or equipment that operates above 50 volts AC or 120 volts ripple-free DC.

(*VCE Physics Study Design, Unit 2, Safety and wellbeing*)

and:

> Students are permitted to work with approved apparatus, appliances and testing equipment that operate at voltages up to 240 volts (which may include appliances such as electric drills or electric soldering irons); however, they must not access or modify any component on such apparatus or appliances.

(*VCE Physics Study Design, Unit 2, Safety and wellbeing*)

In words: an appliance that runs from the mains may be *used* if it is approved and intact — a soldering iron or an electric drill, for example — but never opened or modified. Any equipment operating at up to 50 V AC or 120 V DC in a supervised class must comply with the Wiring Rules (AS/NZS 3000:2000) and the general requirements for electrical equipment (AS/NZS 3100:2002) (*VCE Physics Study Design, Unit 2, Safety and wellbeing*). The Australian domestic supply is 230 V AC at 50 Hz (6B) — well above the 50 V AC student limit — so the inside of any mains-powered device is off-limits to students, whatever state the switch is in. These limits exist because current through the human body is what causes harm, and the body's resistance is low enough for household voltages to drive dangerous currents (6E). The safe practice for your own circuits follows from the same rules: school power packs supply well below the limits, but you still check leads and plugs for damage before connecting, keep hands dry and water away from electrical equipment, switch off before changing any wiring, and rely on the RCD as a backstop (6E).

Hazards you will actually meet. The table below collects the common hazards of the investigations in this book with the controls that suit them:

Area (subtopic)	Typical hazards	Controls
Thermal energy (2A, 2B)	Hot water, hot glass, hot metal blocks; burns	Heat only as far as the method needs; use tongs or heat-resistant gloves; stand hot vessels on a heat-resistant mat away from the bench edge; allow cooling time before handling
Springs and forces (9B)	A spring snapping or slipping off its support; a stretched spring aimed at a face	Do not stretch a spring far beyond its working range; secure both ends; wear safety glasses; keep your face out of the line of stretch
Falling masses (8C, 9C)	Masses dropped on feet; anything or anyone beneath a drop	Keep the drop zone clear and mark it; nobody stands or reaches under a suspended or falling mass; drop from modest heights; wear closed shoes
Circuits (Chapters 5–6)	Damaged insulation; water near electrical equipment; components becoming hot	Inspect leads and plugs first; keep liquids away; switch off before rewiring; remember that components can stay hot after switch-off
Light and optics (Chapters 1, 12)	Bright sources; laser beams and their reflections	Never direct a laser beam — or a reflection from a mirror or watch glass — toward anyone's eyes; secure optical parts so beams cannot wander
Radioactive sources (Chapter 3)	Exposure to ionising radiation	Use sealed sources only, under teacher supervision, applying time, distance and shielding (3E); never open a source container

Area (subtopic)	Typical hazards	Controls
Sound (12C)	Loud sound over long periods can damage hearing	Keep sound levels moderate and exposure times short; the decibel scale is treated in 12C
Fieldwork	Traffic, weather, UV radiation, working in public	Check the site first; stay clear of traffic and wear something visible near roads; protect against the sun whenever the UV index is 3 or above (10A); tell your teacher exactly where you are working

What "ethical" means in this subtopic. *Ethical* is a contested word — different people use it in different senses — so this subtopic states its frame. The study design does not give a dictionary definition; instead, its *Ethical understanding* specification sets the working meaning for this subject. Applying an ethical understanding enables students to, verbatim:

- *"consider the implications of their own and others' investigations on living and non-living things and the environment"*;
- *"apply integrity when recording and reporting the outcomes of their own investigations, and when using their own and others' data"*;
- *"reach a position about science-related ethical issues based on an understanding of ethical concepts and scientific knowledge and skills, considering current and future needs"*;
- *"recognise the importance of values, and of sociocultural, economic, political and legal factors in responsible science-related decision-making."*

(*VCE Physics Study Design, Ethical understanding*)

For your investigation, the first two bullets do most of the work: what your investigation does to the world around it, and the honesty of your data.

Integrity in data. Integrity means honesty and consistency in how you record, use and report data. Three breaches have names you should know. **Fabrication** is recording data you never obtained — writing readings without doing the trial. **Falsification** is changing or selectively omitting real data so they fit what you expected or hoped. **Plagiarism** is presenting someone else's work, words or data as your own. Each one breaks the chain between evidence and conclusion (10A), and each one is detectable — logbook entries are dated and authenticated (14F), and investigations may be undertaken in groups, but *"all work for assessment must be completed individually"* (*VCE Physics Study Design, Scientific investigation*).

The study design gives one rule that applies ethics directly to your data, verbatim: *"Outliers in data must be further analysed and accounted for, rather than being automatically dismissed, as an ethical approach to dealing with data"* (*VCE Physics Study Design, Terms used in this study*). An **outlier** is a data point that differs significantly from the others (14E). Deleting an awkward point because it weakens your conclusion is falsification. The honest treatment is to investigate it: if you can point to a known mistake in that trial — a misread scale, a wrongly set instrument — then, per the study design, mistakes *"should not be included in reporting and analysis. Rather, the experiment should be repeated correctly"* (*VCE Physics Study Design, Terms used in this study*). If no cause is found, the point stays in the data and your analysis accounts for it (14E) — a conclusion that honestly handles its awkward data is stronger, in a marker's eyes, than one that quietly hides them.

Honesty extends to the report itself: state the limitations of your data and method (14E), distinguish what the evidence shows from what you think (10A), and acknowledge every source and every person who assisted you (14G). The *Copyright Act 1968* (Cth) protects other people's work, which is one reason acknowledgement is not optional (*VCE Physics Study Design, Legislative compliance*).

People as participants. Some investigations generate data about people — reaction times of classmates, hearing thresholds, forces in a sporting action. Ethical conduct then requires:

- **informed consent**: participants are told what will happen and agree to take part;
- **de-identification**: data are recorded under a code, not a name, so no person can be identified in your report;
- **care of the information**: records are kept safely and deleted once they are no longer needed.

Privacy legislation applies to such information: the *Privacy and Data Protection Act 2014* (Vic.), the federal *Privacy Act 1988*, and the *Health Records Act 2001* (Vic.) where health information is collected (*VCE Physics Study Design, Legislative compliance*).

Effects on the environment and on others. The first bullet of *Ethical understanding* asks you to consider what your investigation does to living and non-living things and to the environment. In practice: leave a fieldwork site as you found it; dispose of materials properly — nothing down the sink unless your teacher says it is safe; keep noise moderate; recover or recycle the materials your device trials use (an egg-drop capsule, a model bridge); and never disturb people, animals or habitats without a reason your method states.

Putting it together. In your investigation report, this subtopic appears in three places. In the planning, your risk assessment names the relevant guidelines — the act, the SDS, the electrical limits, the laboratory rules — and shows the controls you chose, from the highest practical level of the hierarchy. In the method and logbook, your conduct matches the plan: the controls were actually applied, and any change was reviewed and recorded (14F). In the discussion and conclusion, your data handling shows integrity — real readings, outliers accounted for, limitations stated, sources acknowledged (14E, 14G). Subtopic 14A designs the investigation, 14B generates its data; this subtopic keeps both of them safe and honest.

Worked examples

Example 1 — scaffolded

A class adapts the specific heat capacity investigation of Subtopic 2B: an electric immersion heater, powered by a low-voltage power pack, heats 200 mL of water in a glass beaker while students record the water's temperature every 30 s. Complete the safety part of the risk assessment for this investigation.

Working	Comment
Step 1 — identify hazards: reading the method from setup to clean-up: hot water and hot glass; the hot heater element; electricity near water; the glass beaker can be knocked over.	Hazards come from the whole method, not just the exciting step.
Step 2 — assess risks: hot water and hot glass can burn whoever touches them — likelihood *possible*, consequence *moderate*: a **moderate** risk. Electricity near water could give a shock — likelihood *unlikely* with a low-voltage pack and dry hands, consequence *severe*: still **moderate**. A knocked beaker spills hot water and breaks glass — **moderate**.	Rate each hazard by likelihood and consequence. A severe consequence keeps a rating up even when the likelihood is low.
Step 3 — controls (highest level first): heat only to the temperature the method needs, well below boiling (**administrative**); use a beaker standing on a heat-resistant mat, filled no more than half, away from the bench edge (**engineering/isolation**); use tongs or heat-resistant gloves to move hot glass (**PPE / isolation of hands**); keep the power pack and leads dry, hands dry before touching plugs, leads inspected before use, supply protected by an RCD (**engineering**, 6E); switch off and let the heater cool on the mat before packing away.	No single control does everything; the risk assessment layers them. The immersion heater and power pack are well below the study design's 50 V AC student limit, but water and electricity still stay apart.
Step 4 — review: if the method changes — for example, if the water is replaced by a smaller volume	A risk assessment is a living document, not a form to fill in once.

Working	Comment
that heats faster — the risk assessment is re-checked and the change is recorded in the logbook (14F).	

Example 2 — scaffolded

A student plans the evaporation-cooling investigation of Subtopic 2A: a few drops of ethanol on a cotton swab wrapped around a thermometer bulb, with the temperature recorded as the ethanol evaporates. The teacher provides this simplified SDS excerpt. Use it to complete the safety part of the risk assessment.

Section	Information (simplified excerpt for classroom use)
Identification	Ethanol (ethyl alcohol), the main component of methylated spirits
Hazard identification	Highly flammable liquid and vapour. Causes serious eye irritation. Vapour may cause drowsiness or dizziness in high concentrations.
First-aid measures	Eye contact: rinse gently with water for several minutes. Skin contact: wash with soap and water. If inhaled in quantity: move to fresh air.
Handling and storage	Keep away from flames, sparks and hot surfaces. Use in a well-ventilated room. Store in a tightly closed container in a cool, well-ventilated place.
Exposure controls / PPE	Safety glasses; lab coat; avoid breathing vapour in high concentrations.
Accidental release	Remove all ignition sources, ventilate the area, and absorb the spill with an inert material such as sand.

Always work from the full SDS in your school's register; this excerpt is a classroom simplification of one.

Working	Comment
Hazards from section 2: ethanol is highly flammable — its vapour can ignite at room temperature — and it is a serious eye irritant.	The hazard identification section is read first; it drives every control.
Flammability controls: no flames, sparks or hot surfaces anywhere in the room while ethanol is open; use only a few drops at a time; keep the bottle closed between uses.	The handling section names what to keep the substance away from. Small quantities are a form of substitution: less ethanol, less vapour, less risk.
Eye-irritation control: wear safety glasses for the whole activity.	PPE from the exposure-controls section, added on top of the other controls.
Vapour control: work in a ventilated room and do not lean over the open bottle.	From sections 2 and 8.
Readiness: know where the eyewash station is and what section 4 says before the first drop is poured, not after.	First aid works only if you already know it.
Spill plan: if ethanol spills, remove ignition sources, ventilate, and absorb with sand (section 6).	A spill is not the moment to start reading the SDS.

Example 3 — unscaffolded

A student designing an investigation about household circuits (6B) proposes to open the case of a power board and measure the potential difference across its internal switch, arguing that the board is switched off, so "there is no electricity in it". Evaluate this proposal against the study design's electrical safety rules, and state what the student may do instead.

The proposal is **not permitted**. The study design states that students *"are not permitted to carry out any electrical work on the internal components of electrical products or equipment that operates above 50 volts AC or 120 volts* *ripple-free DC"* (*VCE Physics Study Design, Unit 2, Safety and wellbeing*). A power board is designed for the domestic supply, which in Australia is $230\,\mathrm{V}$ AC at $50\,\mathrm{Hz}$ (6B) — far above the $50\,\mathrm{V}$ AC student limit — so only a person holding a current electrical licence may work on its internal components. The student's argument also fails on the physics: a switch in the off position is not a guarantee that nothing inside is live, and the rule does not depend on the state of the switch — the equipment *operates above* the limit, which is enough.

The permitted alternative is exactly the method the study design itself prescribes: *"model household (AC) electrical systems as simple direct current (DC) circuits"* (6B). The student builds the model with a low-voltage school power pack — well below the student limit — with a switch, a fuse or circuit breaker model, and loads wired in parallel (6A, 6B), and measures there. The model answers the physics question; the real power board stays closed.

∴ the proposal must be refused: the equipment operates at $230\,\mathrm{V}$ AC, above the $50\,\mathrm{V}$ AC student limit, and internal work on it is restricted to licensed persons; the student investigates the same question with the low-voltage DC circuit model of 6B.

Example 4 — unscaffolded

During a momentum-conservation investigation (8E), one of a pair's ten trials gives a result far from the trend of the other nine. Their partner says: "Delete that one — it makes the conclusion look weak, and nobody will ever know." Evaluate this suggestion using the study design's guidance on outliers and ethical conduct, and state what the pair should do instead.

The suggestion is **falsification** — selectively removing real data so the remainder fit the expected conclusion — and it breaches the study design's own rule: *"Outliers in data must be further analysed and accounted for, rather than being automatically dismissed, as an ethical approach to dealing with data"* (*VCE Physics Study Design, Terms used in this study*). "Nobody will ever know" is also wrong in practice: the logbook is dated and authenticated (14F), and the pair's record of the trial exists before the suggestion was made.

The honest procedure has three steps. First, check the trial for a known mistake — a misread scale, a sensor nudged, a trolley that caught on the track. If a specific mistake is found, the study design's rule applies: mistakes *"should not be included in reporting and analysis. Rather, the experiment should be repeated correctly"* — so repeat that trial and record both the mistake and its replacement in the logbook. Second, if no cause is found, the point stays: it remains in the data set, is identified as an outlier, and the analysis accounts for it (14E). Third, the report discusses the outlier openly — its size, its possible causes such as friction or measurement error, and its effect on the conclusion. A marker rewards a conclusion that honestly handles its awkward data; a fabricated data set, if detected, destroys the credibility of the whole report.

∴ the pair must not delete the trial. They check it for a known mistake, repeat the trial correctly if one is found, and otherwise keep the outlier, account for it in the analysis, and discuss it in the report.

Practice questions

Question 1 *(scaffolded)* A group plans an investigation in which a trolley rolls down a ramp and strikes a wooden block at the bottom. (a) Define *hazard*. (b) Define *risk*, and state the two factors combined to rate it. (c) Identify two hazards in this investigation. (d) For each hazard, give one control from a higher level of the hierarchy than PPE.

Question 2 *(scaffolded)* A student writes the method for an investigation and says: "I will do the safety part of the risk assessment last, once I know exactly what happened." (a) Name the four steps of a risk assessment in order. (b) State when the risk assessment should actually be done, and why. (c) State what must happen if the method is changed after the risk assessment was first written.

Question 3 *(scaffolded)* A class lists six possible controls for an investigation.

Control
I Remove the part of the method that needs an open flame
II Use a digital thermometer instead of a glass thermometer
III Put a barrier between the drop zone and the rest of the class

Control
IV Protect the circuit with an RCD (6E)
V Require everyone to wear safety glasses
VI Apply a teacher-supervised "switch off before rewiring" rule

(a) Name the six levels of the hierarchy of controls, most effective first.
(b) Match each control I–VI to its level.
(c) Explain why PPE should never be the only control for a moderate risk.

Question 4 *(scaffolded)* A school is about to use a chemical substance in a physics investigation for the first time. (a) State what a safety data sheet (SDS) is, and who supplies it. (b) State where a copy must be kept at the school, and under which Victorian regulation. (c) Match each piece of information to the SDS section where it is found: (i) whether the substance is flammable; (ii) what to do after eye contact; (iii) ventilation and PPE requirements; (iv) what to do about a spill.

Question 5 *(scaffolded)* State whether each action is permitted, and cite the study design rule that decides it. (a) A student opens the case of a toaster rated at $240\,\mathrm{V}$ AC to examine its heating element. (b) A student uses an approved electric soldering iron in class under teacher supervision, without opening its case. (c) A student builds and tests a series circuit using the school's $12\,\mathrm{V}$ power packs.

Question 6 *(scaffolded)* Use the study design's *Safety and wellbeing* section, as quoted in the theory of this subtopic. (a) State who must supervise all laboratory work. (b) Name two acts or regulations from the study design's list that bear directly on hazardous substances. (c) State two responsibilities of students given in this subtopic. (d) State what the study design requires of any product operating at up to $50\,\mathrm{V}$ AC or $120\,\mathrm{V}$ DC in a supervised class.

Question 7 A class investigates the extension of a spring under load (9B): masses are hung from a spring held in a clamp on a stand, and the extension is measured with a ruler. Construct the safety part of the risk assessment for this investigation: identify three hazards, rate one of them using likelihood and consequence, suggest controls beginning at the highest practical levels of the hierarchy, and explain why no safety data sheet is required for this investigation.

Question 8 A group investigates sound (12C) by measuring the sound level at different distances from a busy road. They will work on the nature strip beside the road for one hour during the school day. Construct the safety part of the risk assessment for this fieldwork. Your answer should cover traffic, hearing, sun protection, and communication with the school.

Question 9 A teacher demonstrates the penetrating power of radiation (3B) using a sealed source and a detector, and the technician brings out the lead-lined storage box that holds the source. State the three principles that keep the class safe during the demonstration, and apply each one to this situation. Explain why students must never open the source container.

Question 10 Two groups carry out the same thermal investigation (2B). Group A's data look "better" than Group B's, so Group B copies Group A's data and tweaks a few of the values so the two sets are not identical. Identify every breach of ethical conduct in this scenario, citing the relevant principle or rule from this subtopic for each.

Question 11 (a) State the study design's guidance on how outliers in data must be treated. (b) Distinguish between an outlier caused by a known mistake and one with no identifiable cause, stating what should happen in each case. (c) Explain why quietly deleting an outlier because it weakens the conclusion is falsification.

Question 12 A student investigates the reaction times of ten classmates and wants to compare the results across the group. State the three ethical requirements that apply when people are participants, and name one act that applies to the information collected.

Question 13 Explain why personal protective equipment (PPE) sits at the bottom of the hierarchy of controls, using one example from this subtopic's hazards table.

Question 14 A student hands in this risk assessment for a thermal conductivity investigation: "Hazards: hot water. Risk: low. Controls: be careful." Critique this risk assessment using the four steps and the hierarchy of controls. State three specific deficiencies.

Question 15 Explain why the risk assessment must be completed before the practical work begins rather than after it, and why it must be reviewed whenever the method changes.

Question 16 The study design gives as an example of an investigable question: “What is the optimal design of the lightest capsule that is able to prevent an egg breaking during a drop?” For an investigation based on this question, state two safety hazards with a control for each, and two ethical or environmental considerations.

Question 17 A group uses a laser to investigate the refraction of light through a rectangular glass block (1C). State the guidelines that protect the class from the beam itself and from the reflections at the block’s surfaces, including what should be done about the arrangement of the optical components before the laser is switched on.

Question 18 A student investigates how the drop height affects the rebound height of a ball (9C), dropping the ball from heights up to $2.0\,\mathrm{m}$ beside a laboratory bench and filming the rebound with a phone camera. (a) Construct the safety part of the risk assessment: identify two hazards and give a control for each. (b) State one way the student can show integrity when recording the rebound heights. (c) Write one sentence, suitable for the report, that links the risk assessment to a relevant guideline.

Answers

Question 1 (a) anything with the potential to cause harm; (b) how likely it is that the hazard harms someone and how badly — rated by combining likelihood and consequence; (c), (d) model answer in solutions. **Question 2** (a) identify hazards, assess the risks, control the risks, review; (b), (c) model answer in solutions. **Question 3** (a) elimination, substitution, isolation, engineering controls, administrative controls, personal protective equipment (PPE); (b) I elimination, II substitution, III isolation, IV engineering, V PPE, VI administrative; (c) model answer in solutions. **Question 4** (a) a document supplied by the manufacturer or importer of a substance describing its hazards and how to work with it safely; (b) the school's SDS register; Occupational Health and Safety Regulations 2017 (Vic.); (c) (i) Section 2; (ii) Section 4; (iii) Section 8; (iv) Section 6. **Question 5** (a) not permitted — see solution; (b) permitted — see solution; (c) permitted — see solution. **Question 6** (a) the teacher; (b) any two of: Dangerous Goods (Storage and Handling) Regulations 2022 (Vic.), Occupational Health and Safety Act 2004 (Vic.), Occupational Health and Safety Regulations 2017 (Vic.); (c) any two from the list in the theory; (d) it must comply with the Wiring Rules (AS/NZS 3000:2000) and the general requirements for electrical equipment (AS/NZS 3100:2002). **Question 7** Model answer in solutions. **Question 8** Model answer in solutions. **Question 9** Model answer in solutions. **Question 10** Model answer in solutions. **Question 11** Model answer in solutions. **Question 12** Model answer in solutions. **Question 13** Model answer in solutions. **Question 14** Model answer in solutions. **Question 15** Model answer in solutions. **Question 16** Model answer in solutions. **Question 17** Model answer in solutions. **Question 18** Model answer in solutions.

Fully-worked solutions

Question 1 (a) A hazard is anything with the potential to cause harm. (b) A risk is how likely it is that the hazard actually harms someone, and how badly; it is rated by combining the likelihood of the harm with its consequence. (c), (d) Model answer (4 marks: 1 mark for each hazard identified, 1 mark for each control). Example: *hazard 1* — the trolley leaving the ramp at the bottom and striking someone's feet; *control* — keep the run-out zone clear and mark it, so nobody stands in the trolley's path (isolation/administrative). *Hazard 2* — the wooden block flying when struck; *control* — place a barrier between the ramp and the rest of the class (isolation). Answers whose only control is PPE do not earn the control mark, because the question asks for a higher level.

Question 2 (a) 1 Identify hazards; 2 assess the risks; 3 control the risks; 4 review. (b) Model answer (2 marks: 1 mark for the timing, 1 mark for the reason). The risk assessment must be completed before the practical work begins, because the controls it selects must be in place from the first trial — a hazard identified only after someone is harmed has already caused the harm the assessment exists to prevent. (c) Model answer (1 mark). The assessment is re-checked (reviewed) because a changed method can bring new hazards, and the change is recorded in the logbook (14F).

Question 3 (a) Elimination, substitution, isolation, engineering controls, administrative controls, personal protective equipment (PPE). (b) I elimination; II substitution; III isolation; IV engineering control; V PPE; VI administrative control. (c) Model answer (2 marks: 1 mark for the reason, 1 mark for the point that PPE does not act on the hazard). PPE does not remove or reduce the hazard — it only stands between the hazard and the person — and it protects only while it is worn and intact. A moderate risk must first be met with controls that act on the hazard itself, with PPE added on top where a risk remains.

Question 4 (a) A safety data sheet (SDS) is a document supplied by the manufacturer or importer of a substance that describes the substance's hazards and how to work with it safely. (b) A current copy must be kept in the school's SDS register and made available to anyone who could be exposed; this is required under the Occupational Health and Safety Regulations 2017 (Vic.). (c) (i) Section 2 — hazard identification; (ii) Section 4 — first-aid measures; (iii) Section 8 — exposure control / personal protection; (iv) Section 6 — accidental release measures.

Question 5 (a) Model answer (2 marks: 1 mark for the judgement, 1 mark for the rule). Not permitted. The toaster operates at 230–240 V AC, above the 50 V AC student limit, so the study design does not permit students to carry out electrical work on its internal components; only a person who holds an appropriate current electrical licence may do so. The state of any switch does not change this — the equipment *operates above* the limit. (b) Model answer (2 marks: 1 mark for the judgement, 1 mark for the rule). Permitted. The study design permits students to work with approved apparatus that operates at voltages up to 240 V — it names electric soldering irons as an example — provided they do not access or modify any internal component. The iron is still a hot object, so burns controls apply.

(c) Model answer (2 marks: 1 mark for the judgement, 1 mark for the rule). Permitted. The 12 V power pack is far below the student limit of 50 V AC or 120 V DC. The usual low-voltage rules still apply: check leads and plugs before connecting, keep water away, switch off before rewiring, and rely on the RCD as a backstop (6E).

Question 6 (a) The teacher: *"All laboratory work should be supervised by the teacher."* (b) Any two of: the *Occupational Health and Safety Act 2004* (Vic.); the *Occupational Health and Safety Regulations 2017* (Vic.); the *Dangerous Goods (Storage and Handling) Regulations 2022* (Vic.). (The WorkSafe Victoria codes of practice — the storage and handling code and the hazardous substances compliance code — also apply.) (c) Any two of: follow the teacher's instructions at all times; use equipment only as taught; do nothing that could put yourself or another person at risk; report hazards, injuries, spills and breakages to the teacher immediately. (d) Any product that requires voltages up to 50 V AC or 120 V DC in a supervised class must comply with the Wiring Rules (AS/NZS 3000:2000) and the general requirements for electrical equipment (AS/NZS 3100:2002).

Question 7 Model answer (6 marks: 1 mark for three hazards, 1 mark for the rating with both factors named, 2 marks for controls at higher levels of the hierarchy, 1 mark for the SDS explanation, 1 mark for a coherent risk-assessment structure). Hazards: the spring snapping or slipping off its support under load; a mass falling on a foot if it comes off the hanger; the clamp stand toppling as the load increases. Example rating: mass falling on a foot — likelihood *possible*, consequence *moderate*, giving a **moderate** risk. Controls, highest practical level first: do not stretch the spring beyond its working range and secure both ends (administrative); place a box or tray beneath the spring to catch falling masses and keep feet out from under the stand (isolation); wear safety glasses and closed shoes (PPE, added on top). SDS: none is required because a spring, masses and a clamp stand are equipment, not substances — an SDS describes substances only, and for these hazards identification comes from reading the method (step 1).

Question 8 Model answer (5 marks: 1 mark for each of traffic, hearing, sun protection and communication, 1 mark for controls at appropriate hierarchy levels). Traffic: stay on the nature strip well clear of the carriageway, wear something visible, and never step onto the road to take a reading (administrative controls, with distance as isolation). Hearing: exposure is limited to the one-hour session, and sound levels are measured, not generated; if levels are high, the group keeps its distance, since intensity falls with distance from the road (12C). Sun protection: whenever the UV index is 3 or above — hat, sunscreen, and shade between readings (10A). Communication: the teacher knows exactly where the group is working and when it returns, and the group works where the supervisor can see it. The site is left as found.

Question 9 Model answer (4 marks: 1 mark for each principle correctly applied, 1 mark for the container point). Time: the source stays out of its storage box only for as long as the readings require. Distance: the source remains at the demonstration bench, metres rather than centimetres from the class — because the intensity of radiation falls rapidly with distance, distance is the cheapest shield (3E). Shielding: the lead-lined box stores and transports the source, and it is closed between readings. Students must never open the container because opening it brings an unshielded source close to skin and converts a low-risk demonstration into a high-risk exposure; sealed sources are handled only by trained staff under the teacher's supervision (3E).

Question 10 Model answer (4 marks: 1 mark for each breach correctly identified with its principle or rule). Plagiarism: Group B presents Group A's work as its own. Falsification: the tweaked values are data Group B never obtained — changing values to disguise the copying does not fix the breach, it adds a second one. Breach of the individual-assessment rule: *"Scientific investigations may be undertaken in groups, but all work for assessment must be completed individually"* (VCE Physics Study Design). Breach of integrity: the report's conclusion would no longer rest on Group B's own evidence, breaking the chain between evidence and conclusion (10A).

Question 11 Model answer (5 marks: 2 marks for (a), 2 marks for (b), 1 mark for (c)). (a) *"Outliers in data must be further analysed and accounted for, rather than being automatically dismissed, as an ethical approach to dealing with data"* (VCE Physics Study Design, Terms used in this study). (b) If a known mistake caused the trial — a misread scale, a wrongly set instrument — then the study design's rule applies: mistakes *"should not be included in reporting and analysis. Rather, the experiment should be repeated correctly"*, with both the mistake and the repeat recorded in the logbook. If no cause can be found, the point stays in the data set, is identified as an outlier, and the analysis accounts for it (14E). (c) Deleting the point to protect the conclusion is falsification — selectively removing real data so that the rest fit what was expected — and it breaks integrity. The logbook still records the trial, so the report would no longer match the authenticated record (14F).

Question 12 Model answer (4 marks: 1 mark for each of the three requirements, 1 mark for a correctly named act). Informed consent: each classmate is told what will happen and agrees to take part. De-identification: results are recorded under a code, not a name, so no person can be identified in the report. Care of the information: records are kept safely and deleted once they are no longer needed. Acts (any one): *Privacy and Data Protection Act 2014* (Vic.); *Privacy Act 1988* (Cth); *Health Records Act 2001* (Vic.) if health information is collected.

Question 13 Model answer (2 marks: 1 mark for the reason, 1 mark for the example). PPE is the least effective level because it does nothing to the hazard itself — the hazard remains at full strength, and the PPE only stands between the hazard and the person. It also protects only while it is worn, fits properly and stays intact. Example: safety glasses reduce the chance of an eye injury if a spring snaps (9B), but they do nothing to stop the snap — keeping the spring within its working range and securing its ends act on the hazard itself and are therefore more effective.

Question 14 Model answer (3 marks: 1 mark for each specific deficiency; any three). Step 1 is incomplete: a thermal conductivity investigation also involves hot metal or glass, electrical equipment near water, and hot surfaces — "hot water" alone is unlikely to be the full hazard list. Step 2 is asserted, not assessed: "low" is given without naming a likelihood or a consequence. Step 3 has no real control: "be careful" is at best a vague administrative instruction; nothing from a higher level of the hierarchy appears. Step 4 is absent: there is no provision for review if the method changes.

Question 15 Model answer (4 marks: 2 marks for the before-point, 2 marks for the review-point). Before: the purpose of the risk assessment is to choose controls that are in place from the first trial — completed afterwards, it can only describe what already happened rather than prevent it, and key science skill KSS.3.1 requires risk assessments to be used *when planning and conducting* investigations (VCE Physics Study Design, key science skills). Review: a changed method can change the hazards — new equipment, new quantities, new procedures — so the assessment is re-checked and the change recorded in the logbook (14F); a risk assessment is a living document, not a form filled in once.

Question 16 Model answer (4 marks: 1 mark for each hazard–control pair, 1 mark for each ethical or environmental consideration). Safety: falling capsules and debris — clear and mark the drop zone, and nobody stands or reaches beneath a suspended or falling mass; retrieving capsules from a height (a balcony or stairs) — teacher-supervised retrieval with a barrier below. Ethical/environmental: the first bullet of the study design's Ethical understanding — consider the implications on living and non-living things and the environment: recover or recycle the capsule materials, clean up all broken egg so the site is left as found, and keep noise and disturbance to nearby classes to a minimum.

Question 17 Model answer (3 marks: 1 mark for the beam rule, 1 mark for reflections, 1 mark for securing the optics). Never direct the laser beam toward anyone's eyes. The block's surfaces also reflect part of the beam, and a reflection can leave the bench at an unexpected angle, so the block's position is checked before the laser is switched on, shiny objects such as watches are kept out of the beam path, and the beam is kept below eye height and away from walkways. The laser and block are clamped tightly so that the beam cannot wander if a component is nudged.

Question 18 Model answer (5 marks: 2 marks for the two hazard–control pairs, 1 mark for integrity, 2 marks for the report sentence). (a) Hazards and controls: the ball striking someone's feet or knocking equipment as it rebounds — keep the drop zone clear, drop away from the bench edge, and mark the zone; the phone falling while the rebound is filmed — secure the phone on a stand or have the camera set up before the drop begins. (b) Record every rebound height exactly as read, including any awkward values, at the time of the trial; do not adjust readings toward the expected trend (14F). (c) Example: "The risk assessment identified the hazards of the method and applied controls from the highest practical level of the hierarchy of controls, consistent with the study design's Safety and wellbeing guidance and the school's laboratory rules." (1 mark for linking the method to the risk assessment, 1 mark for naming a relevant guideline.)

Chapter 14 Scientific investigation — 14D Aims, hypotheses, models, theories and laws

Theory

Unit 2, Area of Study 3 asks the question *How do physicists investigate questions?* Its outcome, verbatim from the study design: *"On completion of this unit the student should be able to draw an evidence-based conclusion from primary data generated from a student-adapted or student-designed scientific investigation related to a selected physics question"* (VCE Physics Study Design, Unit 2, Area of Study 3).

The study design introduces Unit 2 with the idea that runs through this whole subtopic: *"In this unit students explore the power of experiments in developing models and theories"* (VCE Physics Study Design, Unit 2). Physics has a small family of words for the parts of that process — **aim**, **hypothesis**, **model**, **theory** and **law** — and everyday speech blurs them constantly. This subtopic defines each word, distinguishes each from the others, and then turns to the question behind the second dot point: what it means for an observation or an experiment to be *consistent with* a model or a theory, and what happens when one *challenges* it.

This subtopic owns two key knowledge dot points, verbatim:

ID	Key knowledge (verbatim)
`U2.3.6`	"distinguish between an aim, a hypothesis, a model, a theory and a law"
`U2.3.7`	"identify and explain observations and experiments that are consistent with, or challenge, current models or theories"

It also teaches three of the study design's key science skills for the first time: *"formulate hypotheses to focus investigations"*; *"predict possible outcomes of investigations"*; and *"evaluate data to determine the degree to which the evidence supports or refutes the initial prediction or hypothesis"* (VCE Physics Study Design, key science skills).

Where this subtopic sits: 14A constructs aims and investigation questions and identifies variables; 14B teaches how primary data are generated and what accuracy, precision and repeatability mean; 14C sets the safety and ethical guidelines. This subtopic supplies the ideas that shape the work on both sides of the data — the aim, hypothesis and prediction that come *before* data are generated, and the models, theories and laws that physics builds *from* many investigations. Subtopics 14E, 14F and 14G then analyse the data, authenticate them in the logbook, and write the findings up.

A note about the words themselves. The study design uses these five words throughout, but its "Terms used in this study" section defines none of them as knowledge terms. So, as this series does with any term the curriculum leaves undefined: the VCE Physics Study Design uses the terms *aim*, *hypothesis*, *model*, *theory* and *law* but does not define them. This subtopic therefore treats them in the sense given below, and every question in it is answerable on these definitions alone. Other senses exist — the everyday sense of *theory* in particular — and they are not interchangeable with the scientific ones. Two anchors from the study design itself are used along the way: its definition of the modelling methodology (which says what a model can be) and its statement of what models are for.

Aim. An **aim** is a statement of what an investigation intends to find out, determine or compare. It is usually written as a single sentence beginning *"To investigate…"*, *"To determine…"* or *"To compare…"*, and it names the quantities involved: *"To determine the relationship between the force applied to a spring and the extension of the spring."* An aim is a goal, not an answer. It contains no guess and no result — a student who has not yet generated any data can still state the aim perfectly. Constructing aims and investigation questions is taught in 14A; here the point is the distinction: the aim says *what you set out to do*.

Hypothesis. A **hypothesis** is a proposed, testable explanation for an observation, or a proposed answer to an investigation question, based on prior knowledge or observations. Three features matter:

- **It is testable.** There must be some possible observation or measurement that could show it to be wrong. A statement that no observation could ever test is not a hypothesis — it is something else (10A).
- **It proposes a relationship.** In an experiment it usually states how the dependent variable is expected to respond to the independent variable (variables: 14A): *"The greater the force applied to the spring, the greater its extension."*
- **It has grounds.** A hypothesis is not a random guess. It rests on physics you already know, on earlier observations, or on the results of other investigations.

Formulating hypotheses is one of the key science skills this subtopic teaches. A workable method: start from the investigation question; ask what the physics you already know suggests the answer will be; then state that suggestion as a claim about the variables. Two common forms are *"The greater the X, the greater the Y, because…"* and *"If X is changed, then Y will…, because…"*. Any form earns the mark that is clear, testable and grounded.

Prediction. A **prediction** states what you expect to observe *if the hypothesis is correct*. It is the testable consequence of the hypothesis, and it is often quantitative: from the hypothesis *"extension is directly proportional to force"*, the prediction follows that *"if* $4.0\,\mathrm{N}$ *produces an extension of* $2.0\,\mathrm{cm}$*, then* $8.0\,\mathrm{N}$ *will produce* $4.0\,\mathrm{cm}$*"*, or that *"a graph of extension against force will be a straight line"*.

Distinguish the two carefully: the **hypothesis** proposes the explanation; the **prediction** states the observation that should follow. One hypothesis usually supports many predictions. Notice also the study design's wording of the skill: predict *possible outcomes* — a good prediction says both what you expect to see if the hypothesis holds and what you would see if it did not.

Model. The study design's own definition of the modelling methodology says a model can be: *"a physical model, such as a small-scale or large-scale representation of an object; a conceptual model, which represents a system involving concepts that help people know, understand or simulate the system; or a mathematical model, which describes a system using mathematical equations that involve relationships between variables and that can be used to make predictions"* (VCE Physics Study Design, scientific investigation methodologies). The study design's scope statement adds what models are for: *"Models, including mathematical models, are used to explore, simplify and predict how physical systems behave"* (VCE Physics Study Design, Scope of study).

You have already worked with all three kinds in this book:

- the **wave model of light**, in which light is represented as transverse waves with amplitude, wavelength, frequency and speed (Chapter 1) — a conceptual model;
- the **simple kinetic energy model** used to explain why evaporation cools a liquid (2A) — a conceptual model of particles;
- the **simple DC circuit model** of a household electrical system (6B) — a model of a real system, used to reason about fuses, switches, parallel appliances and power;
- the circuit analogies of 5B — the water circuit, the rope loop, the delivery round — which are models built from a familiar comparison;
- mathematical models such as the constant-acceleration equations (7C) and $I = \dfrac{V}{R}$ (5A), whose equations relate variables and whose values can be predicted.

Every model works within a domain and breaks down somewhere; knowing where a model breaks down is part of understanding it (5B). Modelling as an investigation methodology — choosing it, planning with it, evaluating it — belongs to 14A.

Theory. A **theory** is a broad, well-supported explanation of some aspect of the natural world, built from many observations, experiments and tested hypotheses. A theory organises many separate phenomena into one account and generates new predictions that can themselves be tested. The **wave theory of light** is the example you know best: it organises reflection, refraction, dispersion and the behaviour of all electromagnetic radiation (Chapter 1, 10A).

Everyday speech uses *theory* to mean a hunch — *"I have a theory about why the traffic is bad."* In science the word means almost the opposite: a theory is one of the most strongly supported kinds of knowledge science produces. Two further points follow:

- A hypothesis that survives one test does not thereby become a theory. Theories are built from many independent lines of evidence, not promoted from single hypotheses.
- A theory remains open to challenge. The study design itself uses exactly this language: Option 2.17 describes the Big Bang as *"a currently held theory that explains the origins of both time and space"*, and asks students to evaluate the evidence for it (13D). "Currently held" is not a weakness — it is the honest statement that the theory stands because the evidence supports it.

Law. A **law** is a concise statement — often a single relationship that can be written mathematically — that describes a pattern observed in nature under stated conditions. The laws you have met in this course include **Newton's three laws of motion** (8B), of which the second is $a = \frac{F_{\text{net}}}{m}$, and **Hooke's Law** for an ideal spring, $F = -k\,x$ (9B). A law states the pattern — *what happens*, quantitatively — while models and theories do the explaining of *why*.

One honesty note: working physicists use these words with some flexibility — Newton's "laws" sit inside a broader theory of motion, and conservation of momentum is often called a law even though it also follows from deeper ideas. What this subject assesses is the operational distinction above: aim, hypothesis and prediction shape a single investigation; models, theories and laws are what physics produces from many of them.

The five terms side by side.

Term	What it is	What it does	Example from this course
Aim	A statement of what an investigation intends to find out	Sets the goal; names the quantities involved	"To determine the relationship between the force applied to a spring and its extension."
Hypothesis	A proposed, testable explanation, based on prior knowledge	Proposes a relationship between variables; focuses the investigation	"The extension of the spring is directly proportional to the applied force."
Prediction	What should be observed if the hypothesis is correct	Turns the hypothesis into a checkable observation	"Doubling the force will double the extension."
Model	A simplified representation — physical, conceptual or mathematical	Stands in for a system so it can be reasoned about, simulated and predicted with	The wave model of light; the simple DC circuit model of a home (6B)
Theory	A broad, well-supported explanation built from many lines of evidence	Organises many phenomena and generates new testable predictions	The wave theory of light
Law	A concise statement of an observed pattern, often mathematical	Describes what happens under stated conditions	Newton's laws of motion (8B); Hooke's Law (9B)

Three common wrong ideas, and their corrections:

Wrong idea	What is wrong with it	The correction
"A theory is just a guess."	Uses the everyday sense of the word.	In science a theory is a broad, well-supported explanation — among the strongest kinds of knowledge science has. The everyday "hunch"

Wrong idea	What is wrong with it	The correction
		is closer to a hypothesis.
"With enough evidence, a theory gets promoted to a law."	Treats laws as stronger than theories, as though they were rungs on one ladder.	Theories and laws are different kinds of knowledge: a theory explains, a law describes a pattern. More evidence strengthens a theory; it does not convert it into a law.
"A model that breaks down is useless."	Demands more of a model than any model can give.	Every model breaks down somewhere; the breakdown marks the model's domain and tells you where a different model is needed (5B).
"Evidence consistent with a hypothesis proves it."	Treats support as proof.	Consistent evidence supports; no collection of observations rules out a future challenge. It is a reliable, repeatable observation that *conflicts* with a prediction that forces revision.

Consistent with, or challenge. Every model, theory and law carries expectations about what will be observed. An observation or experiment whose results match those expectations is **consistent with** the model or theory — it supports it. An observation or experiment whose results conflict with those expectations **challenges** it. (An *experiment*, in the study design's own words, is *"a procedure undertaken to demonstrate a known fact, test a hypothesis or make a discovery"* — VCE Physics Study Design, scientific investigation methodologies; the methodologies themselves are treated in 14A.)

Support is never proof, and a challenge is not automatically fatal. When an observation appears to challenge a model or theory, there are three cases to separate:

1. **The observation tests the model's conditions, not the model.** Near Earth's surface, objects fall with acceleration $g = 9.8\ \mathrm{m\ s^{-2}}$ *when air resistance can be neglected* (7C, 8C). A flat sheet of paper drifts down far more slowly than a falling mass. The paper is not challenging the model — it is an object for which the model's condition fails, because air resistance on it is large. The observation refines where the model applies; it does not refute the model.
2. **The observation tests the method.** Momentum is conserved in an isolated system (8E). If a collision on a track gives less total momentum after than before, the first question is not "is conservation of momentum wrong?" but "was the system isolated?" — a track that is not level lets a component of the force due to gravity act along the track. The method is evaluated (14E) before the law is questioned.
3. **The observation genuinely conflicts.** If a reliable, repeatable observation conflicts with a model or theory's predictions, and the method survives scrutiny, then the model or theory must be revised, restricted to a narrower domain, or replaced. That is how physics develops. As the study design's purpose statement puts it: *"While much scientific understanding in physics has stood the test of time, many other areas continue to evolve, leading to the development of more complex ideas and technological advances and innovation"* (VCE Physics Study Design, Introduction). A scientific idea changes when the evidence changes (10A).

Two cautions belong here. First, one odd reading is not yet a challenge: an outlier must be further analysed and accounted for, not automatically dismissed — the study design calls that *"an ethical approach to dealing with data"* (VCE Physics Study Design, Terms used in this study) — but it must be checked before it is allowed to overturn anything. Second, a challenge must be repeatable: before a model is revised, other investigators must be able to reproduce the conflicting observation.

Evidence and your own investigation. The third key science skill this subtopic teaches is the one that closes the loop on your own work: evaluate the data to determine *the degree to which* the evidence supports or refutes the initial prediction or hypothesis. After the analysis in 14E, a conclusion does this in four steps:

1. restate the hypothesis or prediction;
2. state what the data actually show;
3. state whether the two are consistent;
4. state the *degree* of support, with reasons — how close the data are to the prediction, how much scatter there is, how many readings were taken, and what the limitations were.

Use graded language: the evidence *fully supports*, *supports*, *partially supports*, *does not support* or *refutes* the hypothesis. And note this carefully: **a refuted hypothesis is not a failed investigation.** A clear refutation is an evidence-based result, and reporting it honestly is exactly what the investigation was for (ethics: 14C). The study design's own report structure places *"a clear aim, a hypothesis and/or prediction"* in the introduction, and asks the discussion to link the results to the aim *"to evaluate and explain whether the investigation data and findings support the hypothesis"* (VCE Physics Study Design, scientific poster format) — the full conventions of report writing are taught in 14G.

From here, 14E takes over the data themselves — organising, analysing and evaluating them, including error, uncertainty and limitations — and 14F and 14G complete the work with logbook authentication and the written report. The investigation vocabulary built in this chapter is used again in Units 3 & 4, where it is assumed rather than re-taught.

Worked examples

Example 1 — scaffolded

A student investigates how the extension of a spring depends on the force applied to it (9B). Classify each statement about the investigation as an **aim**, a **hypothesis**, a **prediction**, a **model** or a **law**. Give the reason in each case.

(i) "To determine the relationship between the force applied to the spring and its extension."
(ii) "The extension of the spring is directly proportional to the force applied to it."
(iii) "If a force of $4.0\,\mathrm{N}$ produces an extension of $2.0\,\mathrm{cm}$, then a force of $8.0\,\mathrm{N}$ will produce an extension of $4.0\,\mathrm{cm}$."
(iv) "The spring is treated as an ideal spring: its own mass is neglected and it obeys $F=-k\,x$ exactly."
(v) "The pattern that extension is proportional to force is observed for many springs under many conditions, and is stated as Hooke's Law, $F=-k\,x$."

Statement	Classification	Reason
(i)	Aim	States what the investigation intends to determine; names the two quantities; contains no guess and no result.
(ii)	Hypothesis	A proposed, testable relationship between the two variables, stated before the data are collected.
(iii)	Prediction	States the specific observation expected *if the hypothesis is correct* — a checkable consequence of (ii).
(iv)	Model	A simplified representation of the real spring (massless, perfectly linear), used so the system can be reasoned about; a real spring only approximately matches it.
(v)	Law	A concise statement of a pattern observed widely, written as the mathematical relationship $F=-k\,x$ (9B).

Example 2 — scaffolded

Each of the following comes from earlier chapters of this book. Classify each as a **model**, a **theory** or a **law**, and justify each classification in one sentence.

(i) The statement $a=\frac{F_{\text{net}}}{m}$ relating acceleration, net force and mass (8B).

(ii) The wave theory of light, which organises reflection, refraction and dispersion (Chapter 1).

(iii) The simple DC circuit model of a household electrical system (6B).

(iv) The explanation of why evaporation cools a liquid, using a simple kinetic energy model of particles (2A).

(b) State one difference between a theory and a law, using one example from part (a).

Item	Classification	Justification
(i)	Law	A concise, mathematical statement of a pattern — the acceleration a net force produces on a mass — under stated conditions (Newton's second law, 8B).
(ii)	Theory	A broad, well-supported explanation that organises many phenomena (reflection, refraction, dispersion) into one account (10A).
(iii)	Model	A simplified representation of a real system — a home's wiring as a DC circuit — used to reason about fuses, switches and parallel appliances; it has known limitations (6B).
(iv)	Model	A simplified picture of a liquid's particles, used to explain an observation (evaporation cools); it leaves much out, such as the rate of evaporation (2A).

(b) A theory explains; a law describes a pattern. The wave theory of light (ii) explains *why* light behaves as it does at boundaries, while $a=\frac{F_{\text{net}}}{m}$ (i) states *what* happens — the acceleration a given net force produces — without explaining the mechanism. The two are different kinds of knowledge, not rungs on one ladder.

Example 3 — unscaffolded

On a level air track, cart A of mass $0.60\,\text{kg}$ moves at $0.40\,\text{m s}^{-1}$ toward cart B of mass $0.20\,\text{kg}$, which is at rest. The carts collide and join, and after the collision the joined carts move at $0.30\,\text{m s}^{-1}$. The student's hypothesis is: *"the total momentum after the collision equals the total momentum before the collision."* (a) Evaluate the degree to which the data support or refute the hypothesis. (b) A second group uses the same procedure but their track is not quite level, and they find the total momentum after the collision is $18\,\%$ less than before. They conclude that conservation of momentum is wrong. Evaluate this conclusion. (c) Write a one-sentence conclusion the first group could record.

(a) From $p=mv$ (8A):

$$p_{\text{before}}=0.60\times0.40=0.24\,\text{kg m s}^{-1}$$

since cart B is at rest, and after the collision the joined mass is $0.80\,\text{kg}$, so

$$p_{\text{after}}=0.80\times0.30=0.24\,\text{kg m s}^{-1}.$$

The two totals are equal, so the data support the hypothesis. (As a check on understanding: the kinetic energy is *not* conserved here — $E_k=\frac{1}{2}mv^2$ falls from $\frac{1}{2}\times0.60\times0.40^2=0.048\,\text{J}$ to $\frac{1}{2}\times0.80\times0.30^2=0.036\,\text{J}$ — which is consistent with the carts joining. Momentum conservation does not require kinetic energy to be conserved.)

(b) The conclusion is not justified. Conservation of momentum applies to an isolated system (8E). A track that is not level lets a component of the force due to gravity act on the carts along the track, so the system is not isolated and the law's condition was not met. The observation challenges whether the experiment satisfied the condition, not the law. The group should evaluate the method (14E) — level the track and repeat — before drawing any conclusion about the law.

(c) For example: *"The data support the hypothesis: within the precision of the measurements, the total momentum before the collision (*$0.24\,\text{kg m s}^{-1}$*) equalled the total momentum after it."*

∴ $p_{\text{before}}=p_{\text{after}}=0.24\,\text{kg m s}^{-1}$ — the hypothesis is supported; the second group's result tests their method, not the law.

Example 4 — unscaffolded

A student tests the hypothesis: *"near Earth's surface, objects of different mass fall with the same acceleration when air resistance can be neglected."* A $0.50\,\text{kg}$ mass and a $1.0\,\text{kg}$ mass are each dropped from $2.0\,\text{m}$, and each fall takes $0.64\,\text{s}$. (a) Show that a fall time of $0.64\,\text{s}$ from $2.0\,\text{m}$ corresponds to an acceleration of about $9.8\,\text{m s}^{-2}$. (b) State whether the results support the hypothesis. (c) A flat sheet of paper released from the same height takes far longer to reach the floor. Does this observation refute the hypothesis? Explain. (d) State what this example shows about models in general.

(a) From the constant-acceleration equation $s=\frac{1}{2}at^2$ with $u=0$ (7C):

$$a=\frac{2s}{t^2}=\frac{2\times2.0}{0.64^2}=\frac{4.0}{0.4096}=9.8\,\text{m s}^{-2}\,(\text{to 2 s.f.})$$

which is the study design's value of g near Earth's surface.

(b) The results support the hypothesis: both masses — different by a factor of two — took the same time and therefore had the same acceleration, within the precision of the timing.

(c) No. The hypothesis carries a stated condition: *when air resistance can be neglected*. For a flat sheet of paper, air resistance is large compared with the force due to gravity, so the condition is not met. The observation does not refute the hypothesis; it marks the boundary of the situations to which the hypothesis applies. (To test the hypothesis properly, compare objects for which air resistance is negligible — or remove the air.)

(d) Models, theories, hypotheses and laws all work within a domain — a range of situations where their conditions are met. An observation that conflicts with a prediction does not always mean the idea is wrong; it may mean the conditions were not met. The first question after a conflict is always which of the two it is.

∴ $a\approx9.8\,\text{m s}^{-2}$ for both masses — the hypothesis is supported; the paper tests the hypothesis's conditions, not the hypothesis itself.

Practice questions

Question 1 *(scaffolded)* A student investigates how temperature affects the resistance of a thermistor (6C). Classify each statement as an **aim**, a **hypothesis**, a **prediction** or a **model**, giving a reason in each case. (i) "To investigate how the resistance of a thermistor changes with its temperature." (ii) "As the temperature of the thermistor increases, its resistance decreases." (iii) "The resistance of the thermistor at $60\,°\text{C}$ will be less than its resistance at $20\,°\text{C}$." (iv) "The thermistor is treated as a resistor whose resistance depends only on its temperature."

Question 2 *(scaffolded)* Each of the following comes from this course. Classify each as a **model**, a **theory** or a **law**, and justify each classification in one sentence. (i) Hooke's Law for an ideal spring: $F = -k\,x$ (9B). (ii) The statement that momentum is conserved in collisions in an isolated system (8E). (iii) Modelling the force due to gravity on a body as though it acted at a single point — the body's centre of mass (8C). (iv) The Big Bang, described in the study design as "a currently held theory that explains the origins of both time and space" (13D).

Question 3 *(scaffolded)* A student investigates how the drop height of a ball affects the height of its first bounce. Three statements from the student's plan are: A: "To investigate how the drop height of a ball affects the height of its first bounce." B: "The greater the drop height, the greater the bounce height, because more gravitational potential energy is available to be returned as kinetic energy (9C)." C: "Doubling the drop height will double the height of the first bounce." (a) Identify which statement is the aim, which is the hypothesis and which is the prediction. (b) Explain the difference between statement B and statement C. (c) In the study design's report structure, in which section of the report do these three statements appear?

Question 4 *(scaffolded)* A student chooses the investigation question: *"How does the potential difference across a resistor affect the current in it?"* (a) State an aim for the investigation. (b) Formulate a hypothesis, including the physics it is based on. (c) Derive one quantitative prediction from your hypothesis. (d) State one result that would refute your hypothesis.

Question 5 *(scaffolded)* Two students test the hypothesis *"the extension of a spring is directly proportional to the applied force."* Student X takes eight readings from $1.0\,\mathrm{N}$ to $8.0\,\mathrm{N}$; the calculated ratios $\frac{x}{F}$ all lie between 1.95 and $2.05\,\mathrm{cm\,N^{-1}}$. Student Y takes three readings; the ratios show the same trend but vary by $\pm 15\,\%$. For each student, choose the best phrase from *fully supports / supports / partially supports / refutes* for the degree to which the evidence supports the hypothesis, and justify your choice. (b) For the student whose evidence is weaker, state what should be done before a conclusion is drawn.

Question 6 *(scaffolded)* Each sentence below uses one of this subtopic's words incorrectly. Identify the error and rewrite the sentence correctly. (i) "I have a theory about why the toast always lands butter-side down." (ii) "The simple DC model of household electricity breaks down when the supply alternates, so the model is useless." (iii) "Newton's laws have been confirmed so many times that they are better than a theory."

Question 7 A student tests the hypothesis *"the extension of this spring is directly proportional to the applied force"* and records:

Force F (N)	1.0	2.0	3.0	4.0	5.0
Extension x (cm)	2.0	4.1	5.9	8.2	9.9

(a) Calculate the ratio $\frac{x}{F}$ for each reading.

(b) Evaluate the degree to which the data support the hypothesis.

(c) Use your result to predict the extension when the force is $6.0\,\mathrm{N}$.

Question 8 A radioactive sample has a half-life of 3.0 days, and its count rate at the start of the investigation is 1200 counts per minute (3C). A student hypothesises that *"the count rate halves every* 3.0 *days."* (a) Predict the count rate after 9.0 days. (b) The measured count rate after 9.0 days is 160 counts per minute. Evaluate the degree to which this supports the hypothesis. (c) A second group measures 600 counts per minute after 9.0 days and concludes the hypothesis is wrong. State two things the group should check before rejecting the hypothesis.

Question 9 After an investigation, a student writes: *"My results prove my hypothesis is correct."* (a) Identify two problems with this sentence, using the language of this subtopic. (b) Rewrite the sentence in a form a scientific report could use, assuming the data showed the predicted trend with small scatter.

Question 10 In 6B, a home's electrical system was modelled as a simple DC circuit: a supply, fuses and switches in series, and appliances in parallel. (a) State two things this model organises or helps to explain. (b) The actual household supply in Australia is $230\,\mathrm{V}$ alternating current at $50\,\mathrm{Hz}$: the current flows one way and then the other, completing 50 full back-and-forth cycles each second. Explain why this observation is beyond what the DC model can represent. (c) State what should be done with the model in light of this observation.

Question 11 On a level track, cart A of mass $0.40\,\mathrm{kg}$ moves at $0.60\,\mathrm{m\,s^{-1}}$ toward cart B of mass $0.20\,\mathrm{kg}$, which is at rest. After the collision, cart A moves in the same direction at $0.20\,\mathrm{m\,s^{-1}}$ and cart B moves at $0.80\,\mathrm{m\,s^{-1}}$. (a) Calculate the total momentum before and after the collision. (b) Evaluate the hypothesis *"the total momentum is conserved in this collision."* (c) Calculate the total kinetic energy before and after the collision, and state whether this collision is consistent with the momentum result.

Question 12 A science article carries the headline: *"Big Bang finally upgraded from theory to law after new observations confirm it."* (a) Identify what the headline gets wrong about the words *theory* and *law*. (b) Rewrite the headline so that it uses both words correctly.

Question 13 The wave theory of light organises reflection, refraction and dispersion (Chapter 1). (a) Identify two observations from Chapter 1 that are consistent with the wave model of light. (b) Explain what it means to say these observations are "consistent with" the model. (c) State what physicists should do if a reliable, repeatable observation is found that conflicts with the predictions of a theory.

Question 14 A student hypothesises that *"for ripples travelling at constant speed, the wavelength is inversely proportional to the frequency."* The data are:

Frequency f (Hz)	2.0	4.0	5.0	8.0
Wavelength λ (m)	0.20	0.10	0.08	0.05

(a) Test the hypothesis by calculating the product λf for each reading (1A).
(b) Evaluate the degree to which the data support the hypothesis.
(c) Predict the wavelength when the frequency is $10\,\mathrm{Hz}$.

Question 15 A student asks: *"Does the colour of a surface affect how much infrared radiation it absorbs?"* (a) State an aim for the investigation. (b) Formulate a hypothesis, including a reason based on prior knowledge or observation. (c) Derive one testable prediction from your hypothesis.

Question 16 A student's evidence refutes their hypothesis. Before writing the report, the student edits two readings so that the conclusion supports the hypothesis. (a) Explain why a refuted hypothesis is a valid and valuable outcome of an investigation. (b) Identify what is wrong with editing the readings, with reference to the conduct of investigations (14C). (c) State what the student should report instead.

Question 17 A student tests the hypothesis *"at a fixed potential difference, the current in a resistor is inversely proportional to its resistance"* (5A, 5D) at $V = 6.0\,\mathrm{V}$:

Resistance R (Ω)	10	20	30	60
Current I (A)	0.60	0.31	0.19	0.10

(a) Calculate the product IR for each reading.
(b) Evaluate the degree to which the data support the hypothesis.
(c) Predict the current when $R = 40\,\Omega$.

Question 18 A student submits this paragraph about their investigation:

> *"I wanted to find out how the length of a wire affects its resistance. I thought that the longer the wire, the greater its resistance, because the charge carriers have further to travel. I predicted that doubling the length would double the resistance. I modelled the wire as a perfect resistor. My results supported my idea, so my theory is now a law."*

(a) Identify the aim, the hypothesis, the prediction and the model in the paragraph.
(b) Identify the error in the final sentence and rewrite it correctly.

Answers

Question 1 (i) aim; (ii) hypothesis; (iii) prediction; (iv) model — reasons in the solution. **Question 2** (i) law; (ii) law; (iii) model; (iv) theory — justifications in the solution. **Question 3** (a) A aim, B hypothesis, C prediction; (b) B proposes the explanation, C states the expected observation; (c) the introduction (14G). **Question 4** Examples in the solution; the aim names both quantities, the hypothesis is testable and grounded, the prediction follows from it, and the refuting result conflicts with it. **Question 5** X: supports (or fully supports) — many readings, tight ratios; Y: partially supports — trend only, few readings, large scatter; (b) repeat readings to improve precision (14B). **Question 6** (i) everyday "theory" = guess → hypothesis; (ii) models have domains — not useless; (iii) laws and theories are different kinds of knowledge, not rungs — see solution. **Question 7** (a) 2.0, 2.05, 1.97, 2.05, $1.98\,\text{cm N}^{-1}$; (b) supports — ratio approximately constant; (c) about $12\,\text{cm}$. **Question 8** (a) 150 counts per minute; (b) supports — close to the prediction, and decay is random (3C); (c) e.g. the elapsed time, and background count or the instrument — see solution. **Question 9** (a) "prove" and "correct" overstate what evidence can do; (b) e.g. "the data support the hypothesis" — see solution. **Question 10** (a) e.g. parallel appliances operate independently; series fuses protect the whole home; (b) DC has one direction only; (c) keep it within its domain; use an AC description where alternation matters. **Question 11** (a) $0.24\,\text{kg m s}^{-1}$ both before and after; (b) supported; (c) $0.072\,\text{J}$ both — consistent. **Question 12** (a) theories are not upgraded to laws — they are different kinds of knowledge; (b) e.g. "New observations add further support to the Big Bang theory." **Question 13** (a) e.g. refraction obeying Snell's Law; colour dispersion in prisms; (b) the results match what the model predicts — support, not proof; (c) revise, restrict or replace the theory. **Question 14** (a) $\lambda f = 0.40\,\text{m s}^{-1}$ for every reading; (b) supports — product constant; (c) $0.040\,\text{m}$. **Question 15** Examples in the solution; the aim names both quantities, the hypothesis is testable with a reason, and the prediction is checkable. **Question 16** (a) a refutation is an evidence-based result; (b) dishonest reporting — ethical conduct is required (14C); (c) the real data and a conclusion that refutes the hypothesis. **Question 17** (a) 6.0, 6.2, 5.7, $6.0\,\text{V}$; (b) supports — product approximately constant; (c) $0.15\,\text{A}$. **Question 18** (a) see solution; (b) one investigation supports a hypothesis — it cannot turn anything into a law, and "theory" was misused — see solution.

Fully-worked solutions

Question 1 (i) **Aim** — it states what the investigation intends to find out and names the two quantities (resistance and temperature); it contains no guess and no result. (ii) **Hypothesis** — a proposed, testable relationship between the two variables, based on prior knowledge of thermistors, stated before the data are collected. (iii) **Prediction** — a specific, checkable observation expected if the hypothesis is correct. (iv) **Model** — a simplified representation of the thermistor that leaves out everything except the one dependence being studied; a real thermistor's resistance can also depend on other quantities, such as the current heating it.

Question 2 (i) **Law** — a concise mathematical statement of an observed pattern: the extension-force relationship for an ideal spring (9B). (ii) **Law** — a concise statement of a pattern observed in isolated systems, confirmed by many collision experiments (8E). (Conservation statements such as this are commonly called conservation laws.) (iii) **Model** — a real, extended body is simplified so the force due to gravity can be treated as acting at a single point; the body's size, shape and rotation are left out of the model (8C). (iv) **Theory** — the study design's own words: a currently held, broad explanation of the origins of time and space, supported by evidence such as the cosmic background radiation and open to evaluation (13D).

Question 3 (a) A is the **aim** (what the investigation sets out to do); B is the **hypothesis** (a proposed, testable explanation, with grounds in energy ideas from 9C); C is the **prediction** (the specific observation expected if the hypothesis is correct). (b) Statement B proposes the explanation — it says how the bounce height responds to the drop height and gives a reason. Statement C states what should be observed if B is correct — a checkable consequence of it. The hypothesis explains; the prediction forecasts the observation. (c) The **introduction**: the study design's report structure places *"a clear aim, a hypothesis and/or prediction"* there (VCE Physics Study Design, scientific poster format). Whether the data support the hypothesis is then evaluated in the discussion — the full conventions are taught in 14G.

Question 4 A full-mark answer would include: (a) For example: *"To investigate how the potential difference across a resistor affects the current in it."* The aim names both quantities and contains no guess. (b) For example: *"The greater the potential difference across the resistor, the greater the current in it, because potential difference is the energy* *transferred per unit charge and a greater energy transfer per coulomb drives more charge through per second"* — or, more simply, based on $I=\frac{V}{R}$ from 5A: at fixed resistance the current increases with the potential difference. The hypothesis must be testable and grounded. (c) For example: *"Doubling the potential difference will double the current"* or *"a graph of current against potential difference will be a straight line."* The prediction must follow from the hypothesis and be checkable. (d) Any result that conflicts with the hypothesis, for example: a reading showing the current staying the same or falling as the potential difference increases.

Question 5 Student X: **supports** (or fully supports). Eight readings were taken and all eight ratios lie within a narrow band (± about 3% about $2.0\,\text{cm N}^{-1}$): the data closely match the prediction of a constant ratio, which is what direct proportionality requires. Student Y: **partially supports**. The predicted trend is present, but three readings with $\pm 15\%$ scatter give weak grounds: the trend could be masked or mimicked by the scatter. (b) Repeat the readings — more values of force, and repeats at each value — to improve the precision of the data before drawing a conclusion (repeatability: 14B).

Question 6 A full-mark answer would include: (i) The everyday word *theory* here means a hunch. In science a theory is a broad, well-supported explanation; what the speaker has is a **hypothesis** (a proposed, testable explanation). Rewrite: for example, *"I have a hypothesis about why the toast always lands butter-side down."* (ii) Every model breaks down somewhere; the breakdown marks the model's domain rather than making the model useless (5B). Rewrite: for example, *"The simple DC model of household electricity works for questions where the direction of the current does not matter; where the alternating supply matters, a different model is needed."* (iii) Laws are not "better than" theories — they are different kinds of knowledge. A theory explains; a law describes a pattern; evidence strengthens a theory without converting it into a law. Rewrite: for example, *"Newton's laws of motion have been confirmed by a very wide range of observations, and the theory of mechanics they belong to remains well supported."*

Question 7 Data: the five (F, x) pairs. (a) The ratios $\frac{x}{F}$ are: $\frac{2.0}{1.0}=2.0$, $\frac{4.1}{2.0}=2.05$, $\frac{5.9}{3.0}=1.97$, $\frac{8.2}{4.0}=2.05$, $\frac{9.9}{5.0}=1.98\,\text{cm N}^{-1}$. (b) The data **support** the hypothesis. If x is directly proportional to F, the ratio $\frac{x}{F}$ must be constant; the five ratios all lie within about $\pm 3\%$ of $2.0\,\text{cm N}^{-1}$, and the small scatter is normal in real measurements. (c) Using the mean ratio, about $2.0\,\text{cm N}^{-1}$:

$$x=2.0\times 6.0=12\,\text{cm}.$$

Question 8 Half-life 3.0 days; initial count rate 1200 counts per minute. (a) 9.0 days is three half-lives, so the prediction is $1200\rightarrow 600\rightarrow 300\rightarrow 150$: 150 **counts per minute**. (b) The measurement (160) is close to the prediction (150) — within about 7%. Radioactive decay is random (3C), so readings fluctuate about the predicted value; a result this close **supports** the hypothesis. (c) Any two, clearly stated: that the elapsed time really was 9.0 days; that the background count was allowed for; that the same instrument and geometry were used each time; that the readings were taken for long enough. The method is evaluated (14E) before the hypothesis is rejected.

Question 9 A full-mark answer would include: (a) First, *"prove"* overstates what evidence can do: consistent data support a hypothesis, but no collection of observations rules out a future challenge. Second, the sentence gives no degree of support and says nothing about the data's limitations; a conclusion states the degree to which the evidence supports the hypothesis, with reasons. (b) For example: *"The data support the hypothesis: the predicted trend was observed with small scatter across the readings taken."* (Graded language — fully supports, supports, partially supports, does not support, refutes — in place of "proves".)

Question 10 A full-mark answer would include: (a) Any two: appliances in parallel each receive the full supply potential difference and operate independently (6A); fuses and switches in series with the supply can protect or isolate the whole home (6B); power to each appliance can be discussed with $P=V\,I$ and energy counted in kilowatt-hours (5A, 5C). (b) In the DC model the current has one fixed direction. An alternating current reverses direction twice in each of its 50 cycles each second — 100 times each second in total ($50\,\text{Hz}$) — which the model cannot represent. The model has no way to show the alternation, the frequency, or anything that depends on them. (c) The model is kept, within its domain: it remains a good tool for the questions it can represent. For questions where the alternation matters, a different description — one that includes AC — is used. A model is not discarded because it has limits; the limits are stated.

Question 11 $m_A = 0.40\,\text{kg}$, $u_A = 0.60\,\text{m s}^{-1}$; $m_B = 0.20\,\text{kg}$, $u_B = 0$; after: $v_A = 0.20\,\text{m s}^{-1}$, $v_B = 0.80\,\text{m s}^{-1}$. (a) From $p = m v$ (8A):

$$p_{\text{before}} = 0.40 \times 0.60 + 0 = 0.24\,\text{kg m s}^{-1}$$

$$p_{\text{after}} = 0.40 \times 0.20 + 0.20 \times 0.80 = 0.08 + 0.16 = 0.24\,\text{kg m s}^{-1}.$$

(b) The totals are equal, so the data **support** the hypothesis that momentum is conserved in this collision. (c) From $E_k = \frac{1}{2} m v^2$ (9C):

$$E_{k,\text{before}} = 1/2 \times 0.40 \times 0.60^2 = 0.072\,\text{J}$$

$$E_{k,\text{after}} = 1/2 \times 0.40 \times 0.20^2 + 1/2 \times 0.20 \times 0.80^2 = 0.008 + 0.064 = 0.072\,\text{J}.$$

The total kinetic energy is the same before and after. This is consistent with the momentum result — and shows that momentum conservation does not require kinetic energy to be lost; in other collisions (such as the one in Example 3) momentum is conserved while kinetic energy is transferred to other forms.

Question 12 A full-mark answer would include: (a) The headline treats a theory and a law as rungs on one ladder, with the law higher. They are different kinds of knowledge: a theory is a broad, well-supported explanation; a law is a concise statement of an observed pattern. More confirming observations strengthen a theory; they do not convert it into a law. ("Confirm" is also doing too much work — observations are consistent with a theory; they do not make it certain.) (b) Any rewrite using both ideas correctly, for example: *"New observations add further support to the Big Bang theory"* or *"New observations are consistent with the predictions of the Big Bang theory."*

Question 13 A full-mark answer would include: (a) Any two from Chapter 1, for example: refraction obeying Snell's Law, $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ (1C); colour dispersion in prisms and lenses, where the component colours of white light refract by different amounts (1D); total internal reflection and the critical angle (1C); the formation of rainbows or mirages (1D). (b) It means the observations match what the model predicts. Being consistent with the model supports the model — but it is not proof, since no set of observations can rule out a future observation that conflicts. (c) First check the observation and the method behind it; if it is reliable and repeatable, the theory must be revised, restricted to a narrower domain, or replaced. That is how physics develops — a scientific idea changes when the evidence changes (10A).

Question 14 Data: the four (f, λ) pairs. (a) The products λf are: $0.20 \times 2.0 = 0.40$, $0.10 \times 4.0 = 0.40$, $0.08 \times 5.0 = 0.40$, $0.05 \times 8.0 = 0.40\,\text{m s}^{-1}$ — the wave speed $v = f\lambda$ (1A). (b) The data **support** the hypothesis exactly: if λ is inversely proportional to f, the product λf must be constant, and it is the same ($0.40\,\text{m s}^{-1}$) for every reading. (c) From $\lambda = \frac{v}{f}$:

$$\lambda = \frac{0.40}{10} = 0.040\,\text{m}.$$

Question 15 A full-mark answer would include: (a) For example: *"To investigate how the colour of a surface affects the amount of infrared radiation it absorbs."* The aim names what is changed and what is being compared. (b) For example: *"Darker, matt surfaces absorb more infrared radiation than lighter, shiny surfaces, because dark surfaces are observed to warm more quickly in sunlight."* The hypothesis is testable, states the expected relationship, and gives grounds from prior observation. (The reverse hypothesis, stated with grounds, would also be acceptable — marking rewards a clear, testable, grounded hypothesis, not the conclusion reached.) (c) For example: *"When identical surfaces are placed the same distance from the same infrared source for the same time, the temperature of the blackened surface will rise more than the temperature of the shiny surface."* The prediction must follow from the hypothesis and be checkable.

Question 16 A full-mark answer would include: (a) A refuted hypothesis is still an evidence-based result: the investigation set out to test an idea, and the data answered. Refutations are how ideas get revised — a clear refutation tells the next investigator something a vague result cannot, and it contributes exactly what the investigation was for.

(b) Editing readings is dishonest reporting: the conclusion is no longer drawn from the data that were actually generated, so the report misrepresents the evidence. Ethical conduct in undertaking and reporting investigations is required (14C), and data must be analysed and accounted for as they genuinely are — the study design calls honesty about data *"an ethical approach"* (VCE Physics Study Design, Terms used in this study). (c) The student should report the readings as measured, state that the evidence refutes the hypothesis, and discuss what the refutation suggests — for example, that the hypothesis should be revised, or that the method limited the test.

Question 17 $V = 6.0\ \text{V}$ throughout. (a) The products $I\,R$ are: $0.60 \times 10 = 6.0$, $0.31 \times 20 = 6.2$, $0.19 \times 30 = 5.7$, $0.10 \times 60 = 6.0\ \text{V}$. (b) The data **support** the hypothesis. From $I = \frac{V}{R}$ (5A), if I is inversely proportional to R at fixed V, the product $I\,R$ must equal the constant potential difference; the four products all lie within about $\pm 5\,\%$ of $6.0\ \text{V}$, and the small scatter is normal in measured data. (c) From $I = \frac{V}{R}$:

$$I = \frac{6.0}{40} = 0.15\ \text{A}.$$

Question 18 A full-mark answer would include: (a) Aim: *"I wanted to find out how the length of a wire affects its resistance."* Hypothesis: *"the longer the wire, the greater its resistance, because the charge carriers have further to travel"* — a proposed, testable explanation with grounds. Prediction: *"doubling the length would double the resistance"* — the checkable consequence of the hypothesis. Model: *"I modelled the wire as a perfect resistor"* — a simplification of the real wire used for reasoning. (b) The final sentence misuses two words. The student's idea was a hypothesis, not a theory — and one investigation whose results are consistent with a hypothesis *supports* it; it cannot turn anything into a law. A law is a pattern observed widely and repeatedly, not a hypothesis that did well once. Rewrite: for example, *"My results support my hypothesis; further investigations with other wires and longer lengths would test whether the pattern holds."*

Theory

By this point in Chapter 14 an investigation has been designed (Section 14A), its data have been generated (Section 14B), the work has been carried out safely and ethically (Section 14C), and the aim, hypothesis and prediction have been stated (Section 14D). What exists now is a set of raw results — readings in a table, or observations in a logbook. Raw results do not yet answer the investigation question. This section is about turning them into findings: organising the data, analysing them to identify patterns and relationships, and then evaluating the analysis itself — its errors, its uncertainty and its limitations — before any conclusion is drawn.

Primary data and its characteristics. Primary data are the measurements and observations that the investigator generates first-hand while carrying out the investigation. They stand apart from **secondary data**, which other people have already published and which the investigator collects from sources such as books, databases and reputable websites — the material of a literature review. Because you generated the primary data yourself, you also know exactly how they came about, and the **characteristics of the data** can be described in full. To describe the characteristics of a primary data set, state:

- whether the data are **quantitative** (numerical readings, such as a potential difference in volts) or **qualitative** (non-numerical observations, such as “the lamp glows more brightly”);
- which variables were measured, with their symbols and units;
- the instruments used and their **resolution** — the smallest change the instrument can display (Section 14B);
- the number of **repeat measurements** taken at each setting of the independent variable;
- the **range** of the independent variable (its lowest and highest values) and the **increments** (the steps between values);
- the **spread** of the repeat readings — how close they sit to one another;
- how uncertainty is recorded, for example as mean ± uncertainty or as uncertainty bars.

Reporting these characteristics is not decoration. It is what lets a reader judge the quality of the evidence for themselves, and it is the first step of the evaluation in this section.

Organising data into tables. The study design’s guidelines for data tables (VCE Physics Study Design, © VCAA) require: a title; similar data arranged in columns rather than rows; units in the column header; powers of 10 in the column header for very large or very small numbers; consistent decimal places within each data column (unless the measuring method changed); and replicate measurements with their calculated average in separate columns or rows. You first organised data this way with the current–potential difference tables of Section 5D. A well-made table is not just tidy — inconsistent decimal places, for instance, hide the resolution of the instrument, and a missing unit makes a number meaningless.

Identifying patterns and relationships. The aim of the analysis is to find what the data are doing: the **pattern** (the repeated behaviour the readings show) and the **relationship** between the variables (how one quantity changes as the other changes). Graphs are the main tool, and the study design’s graphing guidelines (VCE Physics Study Design, © VCAA) require: a title; axis labels with units (and powers of ten if relevant); the independent variable on the horizontal axis (unless other conventions or usefulness override this); uncertainty bars on data points when the uncertainty is given numerically; and a smooth trend line, straight or curved, through the data points. Two further rules bind on every graph in this course, and were stated in Section 7B: *“not all graphs will necessarily pass through the origin (0,0)”* and *“the origin may only be included as a data point if authentically measured”*. Extrapolation beyond the measured data is drawn with dashed lines.

The trend line is a **line of best fit**: a single smooth line drawn as close as possible to all the points, with the points scattered evenly on either side where the scatter is random. It is not a dot-to-dot join. Where two quantities are directly proportional, the study design notes that the graphed result is expected to be a linear relationship passing through the origin — but only the plotted data can show whether that expectation is met.

Linearising a graph, and the significance of the gradient. Many relationships in physics are not linear in the raw variables. A curved graph is hard to test and hard to read, so the data are **linearised**: one or both variables are transformed so that the predicted relationship becomes a straight line. The method is always the same:

1. Write down the mathematical relationship the investigation is testing.
2. Rearrange it into the form $y = \text{gradient} \times x$ (plus an intercept, if one is expected).
3. Plot y against the transformed x-quantity.
4. If the points fall on the expected straight line, the relationship is supported; if not, the relationship — or the data — needs closer inspection.
5. Read the **gradient** of the line and interpret it: the gradient of a linear graph carries direct physical meaning.

The study design's treatment of data (VCE Physics Study Design, © VCAA) states that when interpreting graphs students should consider *"the physical meaning of the gradient of linear graphs"*. The gradient is found from two well-separated points on the line of best fit (not from two data points, and never from a single point and the origin), and its units are the units of the vertical axis divided by the units of the horizontal axis. Those units usually name the physical quantity the gradient represents. Relationships from this course that are commonly linearised include:

Relationship (from)	Plot	Expected line	Gradient represents
$s=\frac{1}{2}at^2$ from rest (7C)	s against t^2	straight, through the origin	$\frac{1}{2}a$
$v=f\lambda$ with λ constant (1A)	v against f	straight, through the origin	λ
$Q=mc\Delta T$, with energy E supplied (2B)	ΔT against E	straight, through the origin	$\frac{1}{mc}$
$V=IR$ for a fixed resistor (5A)	V against I	straight, through the origin	R
$F=kx$ within the elastic limit (9B)	F against x	straight, through the origin	k
$E_k=\frac{1}{2}mv^2$ (9C)	E_k against v^2	straight, through the origin	$\frac{1}{2}m$

Intercepts matter too: Section 7B showed how extrapolating a line to an axis gives an intercept with physical meaning (an initial velocity, a stopping time). In an evaluation, an intercept where none is expected is a clue that something in the method shifted every reading.

Uncertainty in the analysis. Section 14B introduced uncertainty as an interval around a measured value. At Units 1 & 2 there are three things you are asked to do with it. The study design (VCE Physics Study Design, © VCAA) states that students should be able to:

- recognise the representation of uncertainty as mean ± uncertainty (for example, "the temperature is $20 \pm 2^{\circ}\text{C}$") or graphically as uncertainty bars;
- draw uncertainty bars given a numerical representation of the uncertainty;
- state the numerical value for uncertainty given a graphical representation of an uncertainty bar.

On a graph, an uncertainty bar is a short line through the plotted point, centred on the mean value, stretching from (mean − uncertainty) to (mean + uncertainty), often with small caps at each end. Uncertainty bars are used to judge the trend: if a straight line of best fit can be drawn that passes inside every uncertainty bar, the linear relationship is well supported by the data. The wider the bars, the weaker the support.

There is also a ceiling to respect. The study design states that *"determining uncertainty for a set of measurements is beyond the scope of VCE Physics"* — you will not be asked to calculate the uncertainty of a data set from the scatter of its readings. The uncertainty you work with is always given to you.

Outliers and other difficult data. The study design defines an outlier: *"Outliers are data points or observations that differ significantly from other data points or observations."* An outlier is not simply an inconvenient number. The study design's guidance is explicit: *"Outliers in data must be further analysed and accounted for, rather than being automatically dismissed, as an ethical approach to dealing with data."* In practice that means: keep the point on the graph; repeat the reading to see whether it reproduces; if the repeat shows the outlier was a mistake (a misread scale, a wrongly copied number), redo that reading correctly — the study design states that mistakes *"should not be included in reporting and analysis"* — and record what was done in the logbook (Section 14F). If no cause is found, the point stays plotted, the line of best fit is drawn from the other points, and the decision is stated and justified in the analysis.

Three further kinds of difficult data are named in the key science skills. The study design uses these terms without defining them; in this section they are treated as follows, and every question here is answerable on these definitions alone. **Contradictory data** are readings or results from different trials, groups or sources that disagree with each other beyond what their uncertainties can explain — they signal that at least one method, instrument or assumption differs between the sources. **Provisional data** are preliminary results — from a trial run, or from measurements not yet repeated or confirmed — that are reported as standing only until better data replace them. **Incomplete data** are data with a gap: missing readings, a variable changed in steps too coarse to show the trend, or a range that stops short of the region a conclusion is claimed for. Identifying any of these is part of an honest analysis; quietly filling the gap with a guessed value is not.

Scientific error and its signatures in the analysis. Section 14B defined the three classes of error; here the concern is what each one *does to the analysis*.

- **Random errors** are unpredictable variations from one reading to the next. On a graph they appear as scatter, with points spread on both sides of the line of best fit. They affect **precision** (the closeness of repeat readings to one another). Taking repeat measurements and averaging them, and drawing a line of best fit through many points, reduces their effect on the result.
- **Systematic errors** shift every reading in the same way by the same amount or proportion. On a graph they appear as a whole line displaced from where it should be — a vertical-axis intercept where none is expected, or a gradient that is consistently too large or too small — while the points may still sit tightly on the line. They affect **accuracy** (the closeness of a reading to the true value). Repeating readings does not reduce a systematic error: every repeat carries the same shift. Removing it requires fixing the cause — recalibrating or zeroing the instrument, correcting the method, or accounting for the missing effect.
- **Mistakes** (sometimes called personal errors), such as misreading a scale, are not part of the error analysis at all. The reading is excluded and the experiment repeated correctly.

Common causes of systematic error in school investigations include a zero offset on a meter, a ruler whose zero is not aligned with the start of the measurement, friction that has not been compensated for on a moving trolley, and energy lost to the surroundings in a heating experiment. Each one leaves the characteristic signature above, and recognising the signature is the core skill of evaluating an analysis.

Limitations of the data, the methodology and the methods. Every investigation has limits, and an evaluation names them and says what each one does to the findings. The study design's key knowledge for this section asks for limitations of three things:

- the **data** — for example, too few points, a narrow range of the independent variable, large scatter, or no repeat measurements. A narrow range limits how far any relationship can be claimed to hold; large scatter weakens every value read from the line;
- the **methodology** — the general approach chosen (experiment, modelling, simulation, and so on; Section 14A). A simulation, for instance, is only as good as the assumptions built into it;
- the **methods** — the specific procedure, equipment and instruments: their resolution, the variables that were not controlled, and effects that were ignored (heat loss, air resistance, friction).

A limitation is not an apology and not a list. Each named limitation must be linked to its effect on the result: which part of the analysis it weakens, and in which direction.

Improving precision and reducing uncertainty. An evaluation ends with recommendations, and the study design's key science skills ask you to suggest how precision can be improved and how uncertainty can be reduced. Recommendations must match the error they address:

- to reduce the effect of **random errors** — take more repeat measurements and average them; average the repeats at every setting of the independent variable, not just one;
- to reduce the effect of **systematic errors** — zero and calibrate instruments before use, check alignments (a ruler zero, a level track), control the variables that drift (temperature, supply voltage), or change the method to remove the effect (for example, compensating for friction, or insulating a heated block);
- to reduce uncertainty in the reading — use an instrument of higher resolution, or automate the measurement (a light gate or data logger instead of hand timing);
- to strengthen the relationship found — widen the range of the independent variable, take more points, and use smaller increments, especially where the trend changes.

Evaluating the evidence against the aim. The final judgement of the analysis is the degree to which the evidence supports the aim of the investigation. Work through the same questions every time:

1. Is there a clear pattern in the data, and does it have the predicted shape — linear or curved, through the origin or not?
2. Does the gradient (and any intercept) agree with the value physics predicts, once the uncertainty in the readings is allowed for?
3. How strong is the evidence — how many points, over what range, with how little scatter, and with how many repeats?
4. Which limitations weaken the conclusion, and in which direction?

The answer is then stated with the right strength: the evidence **supports** the aim, **partially supports** it (and which part), or **does not support** it — never more strongly than the data justify. Where the support is partial, or the data are incomplete, the evaluation makes recommendations for modifying or extending the investigation: the new range to cover, the variable to control, the measurement to repeat, the increment to make smaller. Section 14D looked at whether evidence supports or refutes the hypothesis; Section 14G takes the conclusion the rest of the way, where the limitations of the conclusion itself are drawn out in full.

Units 3 & 4 preview. The skills of this section — linearising data, reading the physical meaning of a gradient, handling uncertainty bars, identifying outliers and evaluating methods — are examinable content in Units 3 & 4 (Unit 4, Area of Study 2), and the Units 3 & 4 skills chapter treats them as consolidation rather than first teaching. Content under this banner is not assessed in this book's topic tests or practice examinations.

Worked examples

Example 1 — scaffolded

A student investigates the current in a $10\,\Omega$ resistor held at a constant potential difference of $6.0\,\text{V}$. The current is measured five times, with the ammeter reconnected each time. The readings are:

Reading	1	2	3	4	5
Current I (A)	0.59	0.60	0.61	0.60	0.85

(a) Identify the outlier in the data.
(b) Describe how the outlier should be dealt with.
(c) Calculate the mean current from the remaining readings, and check it against the value V / R predicts.
(d) State one characteristic of these data, other than the mean, that should be reported.

Working	Comment
(a) The reading $0.85\,\text{A}$ differs significantly from the other four readings, which sit between 0.59 and $0.61\,\text{A}$.	An outlier is a data point that differs significantly from the others.
(b) It must not be automatically dismissed. The reading should be repeated to see whether it reproduces; if the repeat shows it was a mistake (for example, a misread meter scale), that reading is redone correctly and the	The study design requires outliers to be further analysed and accounted for, as an ethical approach to data.

Working	Comment
mistake is not included in the analysis. The decision is recorded in the logbook.	
(c) $I_{\text{mean}} = \frac{0.59+0.60+0.61+0.60}{4} = \frac{2.40}{4} = 0.60\ \text{A}$.	The mean of the four consistent readings.
Predicted: $I = \frac{V}{R} = \frac{6.0}{10} = 0.60\ \text{A}$. The mean agrees with the predicted value.	The expected current from $V = I\,R$.
(d) For example: four repeat readings were taken at the one setting, and their spread is small (0.59–$0.61\ \text{A}$).	A characteristic of the data: the number of repeats and the spread of the readings.

Example 2 — scaffolded

A dynamics cart is released from rest at the top of a straight ramp and rolls down with constant acceleration. Its displacement from the start is measured at several instants. Each displacement reading has an uncertainty of $\pm 0.02\ \text{m}$.

Time t (s)	Displacement s (m)
0.0	0.00
0.5	0.05
1.0	0.20
1.5	0.45
2.0	0.80
2.5	1.25
3.0	1.80

(a) Add a column of t^2 values to the table.

(b) Explain why plotting s against t^2 tests the relationship expected for this motion.

(c) Calculate the gradient of the line of best fit and hence the acceleration of the cart.

(d) Describe how the uncertainty of each reading is shown on the graph, and state how the uncertainty bars are used to judge the trend.

Working	Comment
(a) t^2 (s^2): 0.00, 0.25, 1.00, 2.25, 4.00, 6.25, 9.00.	Square each time reading.
(b) From rest, the expected relationship is $s = \frac{1}{2} a t^2$. This is linear in s and t^2: plotting s against t^2 should give a straight line through the origin with gradient $\frac{1}{2} a$.	The data are linearised: the transformed variable t^2 is chosen so the predicted curve becomes a straight line.
(c) The points lie on a straight line through the origin. Using the first and last readings: $\text{gradient} = \frac{\Delta s}{\Delta(t^2)} = \frac{1.80-0.00}{9.00-0.00} = 0.20\ \text{m s}^{-2}$.	The gradient is read from two well-separated points on the line of best fit.
$\text{gradient} = 1/2\,a$, so $a = 2 \times 0.20 = 0.40\ \text{m s}^{-2}$.	The gradient of the linearised graph has direct physical meaning.
(d) Each point carries a vertical uncertainty bar centred on the reading, stretching $0.02\ \text{m}$ above and below it (a total length of $0.04\ \text{m}$), drawn because the uncertainty was given numerically.	Uncertainty bars are drawn from the numerical representation of the uncertainty.
If a straight line can be drawn that passes inside every bar, the linear trend is well supported; the bars here are small compared with the values, so the support is strong.	Uncertainty bars are used to judge whether the trend holds within the uncertainty of the readings.

Example 3 — unscaffolded

A group of students investigates the extension of a spring when different loads are hung from it. For each load, the force stretching the spring is the force due to gravity on the hanging mass, and the extension x is measured once the spring has settled. Their results are:

Force F (N)	Extension x (cm)
1.0	2.0
2.0	4.1
3.0	6.0
4.0	7.9
5.0	10.1
6.0	12.0

(a) Describe the graph of F against x and state the relationship between force and extension that the data support.
(b) Calculate the gradient of the line of best fit and state what it represents.
(c) A second group, using the same spring, finds that their line of best fit meets the extension axis at $0.4\,\mathrm{cm}$ instead of passing through the origin. Identify the most likely class of error and suggest a specific cause. Explain why repeating every reading would not fix it.
(d) Use the first group's line to predict the extension of the spring under an $8.0\,\mathrm{N}$ load, and state the assumption this prediction relies on.

The relationship expected is Hooke's law, $F = k\,x$, which is linear in F and x with gradient k, so no transformation is needed.

(a) The plotted points lie close to a straight line that passes through the origin (the extension is zero when the force is zero). Within the range measured, the extension is directly proportional to the force: the data support Hooke's law for this spring up to $6.0\,\mathrm{N}$.

(b) Using the first and last readings,

$$\text{gradient} = \frac{\Delta F}{\Delta x} = \frac{6.0 - 1.0}{12.0 - 2.0} = \frac{5.0\,\mathrm{N}}{10.0\,\mathrm{cm}} = 0.50\,\mathrm{N\ cm^{-1}} = 50\,\mathrm{N\ m^{-1}}.$$

The gradient of the force–extension graph is the spring constant k, so $k = 50\,\mathrm{N\ m^{-1}}$.

(c) A line displaced from the origin while the points still sit tightly on it is the signature of a **systematic error**: every reading is shifted the same way. The most likely cause is that every extension reading is $0.4\,\mathrm{cm}$ too large — for example, the ruler's zero was not aligned with the position of the spring's end before loading began, so the $0.4\,\mathrm{cm}$ offset was counted into every reading. Repeating the readings would not fix it, because the same offset enters every repeat: a systematic error is removed by fixing the cause (re-aligning the ruler, or subtracting the offset), not by averaging.

(d) From $F = k\,x$,

$$x = \frac{F}{k} = \frac{8.0}{50} = 0.16\,\mathrm{m} = 16\,\mathrm{cm}.$$

The $8.0\,\mathrm{N}$ load lies beyond the measured range, so this is an extrapolation: it assumes the spring still obeys Hooke's law at $8.0\,\mathrm{N}$, which the data cannot confirm.

$\therefore$ the spring constant is $50\,\mathrm{N\ m^{-1}}$, the second group's result is best explained by a systematic error of $0.4\,\mathrm{cm}$ in every extension reading, and the predicted extension at $8.0\,\mathrm{N}$ is $16\,\mathrm{cm}$.

Example 4 — unscaffolded

A student's aim is to determine the specific heat capacity of an aluminium block. The block has mass $1.0\,\mathrm{kg}$ and contains an electric heater connected to a $12.5\,\mathrm{V}$ supply drawing $2.0\,\mathrm{A}$. The student assumes that all of the energy supplied by the heater is transferred to the block. The temperature rise ΔT is measured as energy is supplied. (The accepted specific heat capacity of aluminium is $900\,\mathrm{J\,kg^{-1}K^{-1}}$.)

Energy supplied E (kJ)	Temperature rise ΔT (K)
0.0	0.0
2.5	2.4
5.0	4.9
7.5	7.6
10.0	9.9
12.5	12.4

(a) State the relationship between ΔT and E that $Q = mc\Delta T$ predicts, and say whether the graph of ΔT against E supports it.

(b) Calculate the gradient of the line of best fit.

(c) Calculate the specific heat capacity the student obtains.

(d) Compare the result with the accepted value and evaluate the degree to which the evidence supports the aim, identifying the most likely cause of any disagreement.

(e) Recommend one modification to the method that would reduce the disagreement.

(f) The energy supplied E plays the role of Q in $Q = mc\Delta T$, so $\Delta T = \frac{1}{mc}E$: a straight line through the origin with gradient $\frac{1}{mc}$. The plotted points lie close to such a line, so the data support the predicted relationship.

(g) The heater's power is $P = VI = 12.5 \times 2.0 = 25\,\mathrm{W}$, consistent with the energy column. Using the first and last readings:

$$\text{gradient} = \frac{\Delta(\Delta T)}{\Delta E} = \frac{12.4 - 0.0}{12500 - 0} = 9.9 \times 10^{-4}\,\mathrm{K\,J^{-1}}.$$

(c) Since $\text{gradient} = \frac{1}{mc}$,

$$c = \frac{1}{m \times \text{gradient}} = \frac{1}{1.0 \times 9.9 \times 10^{-4}} \approx 1.0 \times 10^{3}\,\mathrm{J\,kg^{-1}K^{-1}}$$

to two significant figures, set by the mass $1.0\,\mathrm{kg}$.

(d) The measured value, $1.0 \times 10^{3}\,\mathrm{J\,kg^{-1}K^{-1}}$, is about 12% above the accepted value of $900\,\mathrm{J\,kg^{-1}K^{-1}}$. The evidence therefore **partially supports** the aim: the method returns a value of the right order, from data that follow the predicted straight line, but the value is consistently too high. The direction of the disagreement points to the cause: with energy escaping to the surroundings, a larger E is needed for each kelvin of rise, the gradient $\frac{1}{mc}$ is smaller than it should be, and the calculated c comes out too large. The assumption that all of the heater's energy reaches the block is the limitation of the method responsible.

(e) Insulate the block (and cover its exposed surfaces) so that less energy escapes to the surroundings. This addresses the systematic energy loss directly; repeating the readings without insulation would reproduce the same shifted line.

∴ the student obtains $c \approx 1.0 \times 10^{3}\,\mathrm{J\,kg^{-1}K^{-1}}$, about 12% above the accepted value, most likely because energy was lost to the surroundings.

Practice questions

Question 1 *(scaffolded)* A student releases a cart from the same point on a ramp and measures the time taken to travel between two markers $1.0\,\mathrm{m}$ apart. The measurement is repeated five times with a stopwatch. The readings are 1.9, 2.0, 2.0, 2.1 and 2.0 seconds. (a) State whether these data are primary or secondary, and quantitative or qualitative. (b) Calculate the mean time. (c) State two characteristics of this data set, other than the mean, that the student should report in the analysis.

Question 2 *(scaffolded)* A student records measurements of the potential difference across, and the current in, a length of wire in the following rough table.

Reading	Voltage	Current
1	1.5	0.10
2	3.0	0.21
3	4.50	0.29
4	6.0	0.41

(a) Identify two ways in which this table does not follow the study design's guidelines for data tables.
(b) Rewrite the two column headings correctly.

Question 3 *(scaffolded)* A student reports the time for a ball to fall a fixed distance as $t = 0.64 \pm 0.03\,\mathrm{s}$. (a) Name the form of this representation, and state the mean value and the uncertainty. (b) State the range of values within which the true time is represented as lying. (c) Describe how this uncertainty would be shown on a graph of the results. (d) A second student's result is shown on the graph as a point at $0.62\,\mathrm{s}$ with an uncertainty bar stretching from $0.57\,\mathrm{s}$ to $0.67\,\mathrm{s}$. State the numerical value of the uncertainty in the second student's result.

Question 4 *(scaffolded)* A student measures the time for a ball to roll $2.0\,\mathrm{m}$ along a level track. The six readings are 2.3, 2.4, 2.4, 2.3, 3.1 and 2.4 seconds. (a) Identify the outlier. (b) Describe how the outlier should be dealt with, referring to the study design's guidance. (c) Calculate the mean of all six readings, and the mean of the five consistent readings, and state the effect the outlier has on the mean.

Question 5 *(scaffolded)* In a ripple tank, straight water waves of constant speed are generated at different frequencies, and the wavelength is measured each time.

Frequency f (Hz)	Wavelength λ (m)
5.0	0.060
10.0	0.030
15.0	0.020
20.0	0.015
25.0	0.012

(a) Add a column of values of $1/f$ to the table, with its unit.
(b) Explain why plotting λ against $1/f$ gives a straight line, and state what the gradient represents.
(c) Calculate the gradient using the first and last readings, and state the speed of the waves.

Question 6 *(scaffolded)* In an investigation, three things go wrong: (i) students using a stopwatch press the start and stop buttons a little early or a little late, differently on each trial; (ii) the needle of a voltmeter sits at $0.1\,\mathrm{V}$ when nothing is connected, so every reading is $0.1\,\mathrm{V}$ too high; (iii) one student writes $6.2\,\mathrm{V}$ in the table when the meter displayed $2.6\,\mathrm{V}$. (a) Classify each of (i), (ii) and (iii) as a random error, a systematic error or a mistake. (b) For each, state whether taking repeat measurements would reduce its effect on the result.

Question 7 A spring is stretched by hanging loads from it, and the extension is measured for each load.

Force F (N)	Extension x (cm)
2.0	4.9

Force F (N)	Extension x (cm)
4.0	10.1
6.0	15.0
8.0	19.9

(a) Plot F against x (describe the axes and the line) and state the relationship the data support.
(b) Calculate the gradient of the line of best fit and state what it represents. Give the spring constant in $N\ m^{-1}$.
(c) Predict the extension of the spring under a $10.0\,N$ load, and state what this prediction assumes.

Question 8 Two students plot the same six data points, which include one clear outlier. Student A joins each point to the next with straight line segments. Student B draws a single straight line of best fit through the cluster of five points, leaves the sixth point plotted but off the line, and records in the logbook why the point was excluded from the fit. Evaluate the two approaches with reference to the study design's graphing guidelines and its guidance on outliers.

Question 9 A dynamics cart is set moving along a level track, and its kinetic energy is calculated from its measured speed.

Speed v ($m\ s^{-1}$)	Kinetic energy E_k (J)
0.40	0.064
0.60	0.144
0.80	0.256
1.00	0.400
1.20	0.576

(a) Explain why the data should be plotted as E_k against v^2 rather than E_k against v, and state what the gradient of the resulting line represents.
(b) Calculate the gradient of the line of best fit, including its unit.
(c) Calculate the mass of the cart.

Question 10 Three groups investigate the same spring and report the following values for its spring constant: group A $24\,N\ m^{-1}$, group B $25\,N\ m^{-1}$, group C $61\,N\ m^{-1}$. (a) Identify which group's result contradicts the others, and suggest one possible cause. (b) Group C labels its value "provisional". Explain what provisional data are and why the label is appropriate here. (c) Group B measured extensions only up to a load of $4\,N$ but claims the spring obeys Hooke's law up to $20\,N$. Explain why the group's data are incomplete for this claim.

Question 11 Explain why taking repeat measurements and averaging them reduces the effect of random errors on a result but does not reduce the effect of systematic errors. Use the terms precision and accuracy in your answer.

Question 12 Two students investigate a relationship expected to be directly proportional. Graph A shows points scattered evenly on both sides of a straight line that passes through the origin. Graph B shows points sitting tightly on a straight line that crosses the vertical axis above the origin. (a) For each graph, identify the class of error most consistent with the pattern shown, and justify your identification. (b) State which data set shows the better precision and which shows the more accurate relationship, giving a reason for each.

Question 13 A cart on a horizontal track is pulled by a measured force F and its acceleration a is determined for each force.

Acceleration a ($m\ s^{-2}$)	Force F (N)
0.50	0.60
1.00	1.00
1.50	1.40
2.00	1.80
2.50	2.20

(a) Calculate the gradient of the line of best fit of F against a, and state what it represents.
(b) The line does not pass through the origin: extrapolated back, it meets the force axis at $0.20\,\mathrm{N}$. Explain this intercept and identify what in the method caused it.
(c) Suggest one way to remove this error from the investigation.

Question 14 A student measures the current in a filament lamp at three potential differences — 0.5, 1.0 and $1.5\,\mathrm{V}$ — taking one reading at each. The student draws a straight line through the three points and uses it to predict the current in the lamp at $6.0\,\mathrm{V}$. Identify three limitations of the data or the method, and evaluate the reliability of the prediction.

Question 15 A cart of mass $0.50\,\mathrm{kg}$ rests against a compressed spring on a level bench. The spring is released and the cart's launch speed v is measured for each compression x.

Compression x (m)	v^2 ($\mathrm{m^2\,s^{-2}}$)
0.020	0.16
0.030	0.36
0.040	0.65
0.050	1.00

(a) If the elastic potential energy of the spring is transferred to the cart as kinetic energy, $\frac{1}{2}kx^2=\frac{1}{2}mv^2$. Explain why v^2 is plotted against x^2, and state what the gradient of the line represents in terms of k and m.
(b) Calculate the gradient of the line of best fit.
(c) Calculate the spring constant k.

Question 16 A student measures the current in a length of metal wire for potential differences from $0.5\,\mathrm{V}$ to $3.0\,\mathrm{V}$. The points lie on a straight line through the origin, and the largest current measured is $0.30\,\mathrm{A}$. The student concludes: "The wire is ohmic, so the potential difference across it is always proportional to the current in it." (a) Evaluate this conclusion as stated, referring to the range of the data. (b) State what further evidence would be needed before the claim could be made for all currents, and why the wire's behaviour at larger currents cannot simply be assumed.

Question 17 A steel ball is dropped from a height of $2.0\,\mathrm{m}$ and its fall is timed with a stopwatch. (a) Using $s=\frac{1}{2}gt^2$ with $g=9.8\,\mathrm{m\,s^{-2}}$, calculate the expected fall time. (b) The student's reaction time makes the uncertainty in the stopwatch measurement about $0.2\,\mathrm{s}$. State this uncertainty as a fraction of the fall time you calculated in (a). (c) A light gate and data logger measure the same fall with an uncertainty a hundred times smaller. Classify the stopwatch error, and explain why the light gate reduces the uncertainty so much.

Question 18 A student heats $0.25\,\mathrm{kg}$ of water and measures the temperature rise as energy is supplied.

Energy supplied E (kJ)	Temperature rise ΔT (K)
0.0	0.0
1.05	0.9
2.10	2.1
3.15	2.9
4.20	4.1
5.25	5.0

(a) Describe the graph of ΔT against E and the relationship it shows.
(b) Calculate the gradient of the line of best fit in $\mathrm{K\,kJ^{-1}}$.
(c) Use $Q=mc\Delta T$ to calculate the specific heat capacity of water from the gradient. (The accepted value is $4200\,\mathrm{J\,kg^{-1}\,K^{-1}}$.)
(d) State two characteristics of this data set that make the calculated value a reliable one.

Answers

Question 1 (a) primary, quantitative; (b) $2.0\,\text{s}$; (c) any two of: five repeat measurements; instrument (stopwatch) and its resolution; spread $1.9–2.1\,\text{s}$; unit (s) — see solution. **Question 2** (a) no title, units missing from the column headers, inconsistent decimal places in the voltage column; (b) "Potential difference V (V)", "Current I (A)". **Question 3** (a) mean ± uncertainty; mean $0.64\,\text{s}$, uncertainty $0.03\,\text{s}$; (b) $0.61–0.67\,\text{s}$; (c) an uncertainty bar centred on the point — see solution; (d) $\pm 0.05\,\text{s}$. **Question 4** (a) $3.1\,\text{s}$; (b) see solution — further analyse, repeat, do not dismiss; (c) all six: $2.5\,\text{s}$; five: $2.4\,\text{s}$; the outlier pulls the mean up. **Question 5** (a) $1/f$ (s): 0.200, 0.100, 0.067, 0.050, 0.040 ; (b) $\lambda = v/f = v \times (1/f)$, so the gradient is the wave speed v; (c) $0.30\,\text{m s}^{-1}$. **Question 6** (a) (i) random, (ii) systematic, (iii) mistake; (b) (i) yes, (ii) no, (iii) no — the reading is redone correctly. **Question 7** (a) straight line through the origin — $F \propto x$; (b) $0.40\,\text{N cm}^{-1} = 40\,\text{N m}^{-1}$, the spring constant k; (c) $25\,\text{cm}$, assuming Hooke's law still holds at $10.0\,\text{N}$. **Question 8** Student B — see solution. **Question 9** (a) $E_k = \frac{1}{2} m v^2$ is linear in v^2; gradient $= \frac{1}{2} m$; (b) $0.40\,\text{kg}$; (c) $0.80\,\text{kg}$. **Question 10** (a) group C; e.g. readings taken beyond the elastic limit, or a misread extension; (b) see solution; (c) see solution. **Question 11** See solution — averaging cancels random scatter (precision) but every repeat carries the same systematic shift (accuracy). **Question 12** (a) A: random error; B: systematic error; (b) precision: B; accuracy: A — see solution. **Question 13** (a) $0.80\,\text{kg}$, the mass of the moving system; (b) an unaccounted friction force of about $0.20\,\text{N}$; (c) see solution. **Question 14** See solution — three readings only, narrow range, no repeats, straight line assumed although the lamp is non-ohmic, long extrapolation: the prediction is not reliable. **Question 15** (a) $v^2 = (k/m) x^2$; gradient $= k/m$; (b) $400\,\text{s}^{-2}$; (c) $200\,\text{N m}^{-1}$. **Question 16** See solution — supported only up to $0.30\,\text{A}$; at larger currents heating may change the wire's resistance. **Question 17** (a) $0.64\,\text{s}$; (b) about 0.3 (roughly one third); (c) random error; see solution. **Question 18** (a) straight line through the origin: $\Delta T \propto E$; (b) $0.95\,\text{K kJ}^{-1}$; (c) $\approx 4.2 \times 10^3\,\text{J kg}^{-1}\text{K}^{-1}$; (d) see solution.

Fully-worked solutions

Question 1 Readings: 1.9, 2.0, 2.0, 2.1, 2.0 seconds. (a) The data are **primary** — the student generated them first-hand while carrying out the investigation — and **quantitative**, because they are numerical readings with a unit. (b) $\text{mean} = \frac{1.9 + 2.0 + 2.0 + 2.1 + 2.0}{5} = \frac{10.0}{5} = 2.0\,\text{s}$. (c) Model answer. Any two of: the number of repeat measurements (five); the instrument used (stopwatch) and its resolution; the spread of the readings ($1.9–2.1\,\text{s}$, a range of $0.2\,\text{s}$); the unit of the measured quantity (seconds); the fixed distance the cart travelled ($1.0\,\text{m}$). These are characteristics of the data that a reader needs in order to judge the quality of the evidence.

Question 2 (a) Model answer. The table has no title; the column headings carry no units; and the voltage column is not recorded to a consistent number of decimal places (1.5 and 3.0 to one decimal place, 4.50 to two). Each of these is required by the study design's guidelines for data tables. (b) "Potential difference V (V)" and "Current I (A)" — each heading carries the quantity, its symbol and its unit.

Question 3 (a) The representation is **mean ± uncertainty**: the mean is $0.64\,\text{s}$ and the uncertainty is $0.03\,\text{s}$. (b) The true time is represented as lying between $0.64 - 0.03 = 0.61\,\text{s}$ and $0.64 + 0.03 = 0.67\,\text{s}$. (c) Model answer. On the graph, the point is plotted at $0.64\,\text{s}$ and a vertical **uncertainty bar** is drawn through it, centred on the point, stretching from $0.61\,\text{s}$ to $0.67\,\text{s}$, usually with a small horizontal cap at each end. (d) The bar stretches $0.05\,\text{s}$ each side of the mean of $0.62\,\text{s}$, so the uncertainty is $\pm 0.05\,\text{s}$.

Question 4 Readings: 2.3, 2.4, 2.4, 2.3, 3.1, 2.4 seconds. (a) The reading $3.1\,\text{s}$ differs significantly from the other five, which sit between 2.3 and $2.4\,\text{s}$. (b) Model answer. The study design states that outliers must be further analysed and accounted for, rather than automatically dismissed — this is the ethical approach to data. The student should repeat the measurement to check whether the $3.1\,\text{s}$ reading reproduces. If the repeat shows it was a mistake (for example, the ball was obstructed, or the stopwatch was stopped late), that reading is redone correctly and the mistake is not included in the reporting or analysis. If no cause is found, the point stays in the data set and its treatment is recorded in the logbook. (c) Mean of all six: $\frac{2.3 + 2.4 + 2.4 + 2.3 + 3.1 + 2.4}{6} = \frac{14.9}{6} = 2.5\,\text{s}$ (2 significant figures).

Mean of the five consistent readings: $\frac{11.8}{5}=2.4\,\text{s}$. The outlier pulls the mean of all six upward, away from the value the consistent readings indicate — one reason a single outlier must be examined before any average is trusted.

Question 5 (a) $1/f$ is calculated for each reading; the column heading is "$1/f$ (s)":

f (Hz)	λ (m)	$1/f$ (s)
5.0	0.060	0.200
10.0	0.030	0.100
15.0	0.020	0.067
20.0	0.015	0.050
25.0	0.012	0.040

(b) Model answer. The relationship is $v=f\lambda$, which rearranges to $\lambda=v\times\frac{1}{f}$. This is linear in λ and $1/f$: plotting λ against $1/f$ gives a straight line through the origin, and the gradient is the wave speed v.

(c) $\text{gradient}=\frac{\Delta\lambda}{\Delta(1/f)}=\frac{0.060-0.012}{0.200-0.040}=\frac{0.048}{0.160}=0.30\,\text{m s}^{-1}$. The wave speed is $0.30\,\text{m s}^{-1}$.

Question 6 (a) (i) **Random error** — the timing varies unpredictably from trial to trial, producing a spread of readings. (ii) **Systematic error** — the zero offset makes every reading differ from the true value in the same way ($0.1\,\text{V}$ too high). (iii) **Mistake** (personal error) — a misreading recorded incorrectly. (b) (i) Repeat measurements reduce its effect: the early and late presses scatter either side of the true value, and averaging many trials reduces the effect of the scatter. (ii) Repeat measurements do not reduce it: every repeat carries the same $0.1\,\text{V}$ offset, and the average is shifted by $0.1\,\text{V}$ too. The meter must be zeroed or the readings corrected. (iii) Repeats in the ordinary sense do not apply — the study design states that mistakes should not be included in reporting and analysis; the experiment is repeated correctly and the corrected reading used.

Question 7 Readings: $F=2.0$, 4.0, 6.0, 8.0 N; $x=4.9$, 10.1, 15.0, 19.9 cm. (a) Model answer. The graph has force F (N) on the vertical axis and extension x (cm or m) on the horizontal axis, each labelled with its quantity and unit, and the points plotted with a single straight line of best fit through them. The points lie on a straight line through the origin: within the range measured, the extension is directly proportional to the force, and the data support Hooke's law. (b) $\text{gradient}=\frac{\Delta F}{\Delta x}=\frac{8.0-2.0}{19.9-4.9}=\frac{6.0}{15.0}=0.40\,\text{N cm}^{-1}=40\,\text{N m}^{-1}$. The gradient of the force–extension graph is the spring constant k: $k=40\,\text{N m}^{-1}$. (c) $x=\frac{F}{k}=\frac{10.0}{40}=0.25\,\text{m}=25\,\text{cm}$. The load of $10.0\,\text{N}$ is beyond the measured range, so this is an extrapolation: it assumes the spring continues to obey Hooke's law at $10.0\,\text{N}$.

Question 8 Model answer. Student B's approach is the better one, for two reasons. First, the study design's graphing guidelines require a smooth trend line through the data points — a single line of best fit, not a dot-to-dot join. Student A's line segments connect every reading in order, so the outlier kinks the line and the random scatter of the good readings is built into the "trend" instead of being averaged out by it. Second, the study design's guidance on outliers requires them to be further analysed and accounted for, not automatically dismissed. Student B does exactly this: the outlier stays plotted, so any reader can see it; the fit is drawn from the other points; and the reason for leaving it off the line is recorded in the logbook, where the authentication of the data lives. Student A neither identifies the outlier nor justifies any treatment of it. The one thing Student B must not do is delete the outlier from the graph: a point that is plotted off the line, with the decision explained, is honest analysis; a point that disappears is not.

Question 9 Readings as tabulated; v^2: 0.16, 0.36, 0.64, 1.00, $1.44\,\text{m}^2\,\text{s}^{-2}$. (a) Model answer. The relationship is $E_k=\frac{1}{2}mv^2$, which is linear in E_k and v^2: plotting E_k against v^2 should give a straight line through the origin. Plotting E_k against v instead would give a curve, from which the mass could not be read directly. The gradient of the linearised graph is $\frac{1}{2}m$. (b) $\text{gradient} = \frac{\Delta E_k}{\Delta(v^2)} = \frac{0.576 - 0.064}{1.44 - 0.16} = \frac{0.512}{1.28} = 0.40$. The unit is $\text{J} \div \text{m}^2\,\text{s}^{-2}$, which is the kilogram: the gradient is $0.40\,\text{kg}$. (c) $\frac{1}{2}m = 0.40\,\text{kg}$, so $m = 0.80\,\text{kg}$.

Question 10 (a) Group C's value, $61\,\text{N m}^{-1}$, contradicts groups A and B, which agree within the uncertainty of such a measurement. A possible cause is that group C loaded the spring beyond its elastic limit, where the extension is no longer proportional to the force; another is a misread extension or a different spring. Identifying the cause needs the groups' methods, which is why contradictory results are investigated rather than averaged together. (b) Model answer. Provisional data are preliminary results — from a trial run, or from measurements not yet repeated or confirmed — that stand only until better data replace them. The label is appropriate because group C's value disagrees strongly with two other groups: reporting it as provisional says honestly that the result is not yet reliable and must be checked (for example, by repeating the measurements and reviewing the method) before it is used. (c) Model answer. The data are incomplete because they cover only part of the range the claim is made about. The group measured extensions up to $4\,\text{N}$, so it has evidence about the spring's behaviour only up to $4\,\text{N}$; the claim extends to $20\,\text{N}$, where no measurements exist. The spring may well stop obeying Hooke's law at some load between $4\,\text{N}$ and $20\,\text{N}$ — the data cannot say. To support the claim, the group would need to take readings across the whole range.

Question 11 Model answer. Random errors are unpredictable variations that differ from one reading to the next, sometimes high and sometimes low. When readings are repeated and averaged, the high and low variations tend to cancel, so the average settles closer to the true value and the effect of the scatter is reduced: repeat measurements improve the **precision** of the result. Systematic errors are different: they shift every reading in the same way by the same amount or proportion, so every repeat carries exactly the same shift, and the average is shifted by it too. Averaging cannot cancel a shift that never changes sign; the **accuracy** of the result stays just as poor however many readings are taken. A systematic error is reduced only by removing its cause — recalibrating or zeroing the instrument, or correcting the method.

Question 12 (a) Graph A: **random error**. The points scatter on both sides of the line, which is the signature of unpredictable variations from reading to reading; the line itself sits where the relationship predicts (through the origin), so there is no sign of a consistent shift. Graph B: **systematic error**. The points sit tightly on their line, so random scatter is small, but the whole line is displaced — it crosses the vertical axis above the origin where a directly proportional relationship should pass through $(0, 0)$. Every reading has been shifted in the same way, for example by a zero offset on the instrument or an offset in the quantity being measured. (b) Precision describes the closeness of readings to one another: graph B shows the better precision, because its points sit tightly on the line with little scatter. Accuracy describes the closeness of readings to the true value: graph A shows the more accurate relationship, because its line passes through the origin as the physics predicts, while graph B's line — precise though it is — is displaced from the true relationship.

Question 13 (a) $\text{gradient} = \frac{\Delta F}{\Delta a} = \frac{2.20 - 0.60}{2.50 - 0.50} = \frac{1.60}{2.00} = 0.80$. The unit is $\text{N} \div \text{m s}^{-2} = \text{kg}$. From $\Sigma F = ma$, force against acceleration is linear with gradient m, so the gradient is the mass of the moving system: $0.80\,\text{kg}$. (b) Model answer. The intercept means that when the applied force is $0.20\,\text{N}$ the acceleration is still zero: the first $0.20\,\text{N}$ of every applied force is used up overcoming friction before the cart can accelerate. The applied force F plotted in the table is therefore not the net force on the cart; the net force is $F - 0.20\,\text{N}$. This is a systematic error: friction acts on every reading in the same way, shifting the whole line off the origin. (c) Model answer. Any one of: compensate for friction by raising one end of the track slightly until the cart moves at constant velocity with no pull; measure the friction force separately and subtract it from each applied force, so the net force is plotted; or use a lower-friction track and wheels so the effect is small enough to neglect — stating that it has been neglected.

Question 14 Model answer. Three limitations: (1) the data set is very small — three readings in total, with no repeats at any potential difference, so there is no measure of the scatter and no averaging of random error; (2) the range is narrow (0.5–$1.5\,\text{V}$), so even the straight line drawn is weakly supported — three points always look linear; (3) the prediction at $6.0\,\text{V}$ is a long extrapolation, far beyond the measured range, and the straight-line fit is itself an assumption that physics says will fail here: a filament lamp is non-ohmic (Section 6C), and as the filament heats up its resistance increases, so the current–potential difference graph curves away from the straight line fitted at the low voltages — the line will overestimate the current at $6.0\,\text{V}$. The prediction is therefore **not reliable**: it rests on a line fitted to three points over a 1.0 V span, extended 4.5 V beyond them into a region where the lamp's behaviour is known to change. To make it reliable, the student should take more readings at smaller increments, repeat each one, and extend the measurements to higher voltages (within the lamp's rating) so that the actual curve is mapped.

Question 15 (a) Model answer. From $\frac{1}{2}kx^2=\frac{1}{2}mv^2$, cancelling the factor $\frac{1}{2}$ gives $v^2=\frac{k}{m}x^2$, which is linear in v^2 and x^2. Plotting v^2 against x^2 should give a straight line through the origin with gradient k/m. (b) x^2 (m^2): 0.00040, 0.00090, 0.0016, 0.0025. $\text{gradient}=\frac{\Delta(v^2)}{\Delta(x^2)}=\frac{1.00-0.16}{0.0025-0.00040}=\frac{0.84}{0.0021}=400\,\text{s}^{-2}$. (c) $\frac{k}{m}=400\,\text{s}^{-2}$, so $k=400\times0.50=200\,\text{N m}^{-1}$.

Question 16 (a) Model answer. The conclusion is too strong as stated. The data support a proportional relationship between potential difference and current — that is, ohmic behaviour — only over the range actually measured, 0.5–3.0 V and currents up to 0.30 A. The word "always" claims the relationship for every current, including currents far beyond anything in the data. A valid conclusion is limited to the range of the evidence: "the wire behaved as an ohmic conductor for currents up to 0.30 A". (b) Model answer. The student would need measurements at larger currents to show the line continues straight through the origin. This matters because at larger currents the wire heats up (energy is transferred to the wire as thermal energy), and a change of temperature can change the wire's resistance — the behaviour at 1 A cannot be assumed from the behaviour at 0.30 A. This is the same reason a filament lamp, which gets much hotter, is not ohmic: heating is the physical effect that the further measurements would test for.

Question 17 (a) From rest, $s=\frac{1}{2}gt^2$, so $t=\sqrt{\frac{2s}{g}}=\sqrt{\frac{2\times2.0}{9.8}}=\sqrt{0.408}=0.64\,\text{s}$. (b) $\frac{0.2}{0.64}\approx0.3$: the uncertainty is about one third of the whole fall time. Any result from this measurement is uncertain by roughly a third. (c) Model answer. The stopwatch error is a **random error**: the student's press is sometimes a little early and sometimes a little late, varying unpredictably from trial to trial. The light gate reduces the uncertainty because it removes the person from the measurement entirely: the gate triggers the timing electronically as the ball passes, with no reaction time involved, and the data logger's timing has a far higher resolution than a stopwatch read by eye. Automating the measurement both shrinks the random scatter and improves the resolution of the instrument — two of the standard ways to reduce uncertainty in a result.

Question 18 (a) Model answer. The graph has ΔT (K) on the vertical axis and E (kJ) on the horizontal axis; the points lie close to a straight line through the origin. The temperature rise is directly proportional to the energy supplied, as $Q=mc\Delta T$ predicts with $Q=E$. (b) $\text{gradient}=\frac{\Delta(\Delta T)}{\Delta E}=\frac{5.0-0.0}{5.25-0.0}=0.95\,\text{K kJ}^{-1}$. (c) With $\Delta T=\frac{1}{mc}E$, the gradient is $\frac{1}{mc}$. Converting the gradient to SI units: $0.95\,\text{K kJ}^{-1}=9.5\times10^{-4}\,\text{K J}^{-1}$. Then

$$c=\frac{1}{m\times\text{gradient}}=\frac{1}{0.25\times9.5\times10^{-4}}=4.2\times10^{3}\,\text{J kg}^{-1}\text{K}^{-1}$$

to two significant figures, consistent with the accepted value of $4200\,\text{J kg}^{-1}\text{K}^{-1}$. (d) Model answer. Any two of: the data set has six points, giving the line of best fit a real basis; the readings cover a wide range of energies (0–5.25 kJ), so the gradient is determined by a long line rather than a short one; and the scatter of the points about the line is small compared with the values, so the relationship is well supported. (Energy lost to the surroundings would make the calculated c come out a little high; the agreement with the accepted value suggests the loss here was small.)

Chapter 14 Scientific investigation — 14F The logbook and authentication of primary data

Scope. This section is set out in the *VCE Physics Study Design*, Unit 2, Area of Study 3 — *How do physicists investigate questions?* — key knowledge block *Scientific evidence*. The key knowledge dot point owned here is quoted verbatim below.

ID	Key knowledge (verbatim)
`U2.3.10`	"model the scientific practice of using a logbook to authenticate generated primary data"

This section also gives first teaching of two of the study design's key science skills:

ID	Key science skill (verbatim)
`KSS.2.3`	"work independently and collaboratively as appropriate and within identified research constraints, adapting or extending processes as required and recording such modifications in a logbook"
`KSS.4.2`	"record and summarise both qualitative and quantitative data, including use of a logbook as an authentication of generated or collated data"

What is deliberately not taught here: techniques of generating primary data, and accuracy, precision, repeatability, reproducibility, resolution and validity of data, belong to Section 14B; health, safety and ethical guidelines belong to Section 14C; the organisation, analysis and evaluation of primary data — patterns, outliers, error, uncertainty and linearised graphs — belong to Section 14E; the conventions of scientific report writing belong to Section 14G. Those sections build the investigation around the data; this section builds the record that proves the data are genuine.

Theory

What a logbook is, and why science keeps one. Every investigation you have done in this course so far produced numbers, observations and decisions that mattered only because they were written down. A reading that is not recorded might as well not have been taken; a change of method that is not remembered a week later might as well not have been made. The tool that solves both problems is the **logbook**.

The study design requires a logbook but does not define the format, so this section states the operational definition it uses throughout: in this section, a **logbook** is a dated record, kept by the student in write-once form — a bound notebook, or a digital record that preserves every entry in the order it was made — that documents, as the work happens, what was planned, what was done, what was observed, and what was changed. Other formats exist, and a teacher may specify the format for a class; what matters is the set of features taught below, because they are what make the record do its job.

This is not a school invention. It is the scientific practice the dot point asks you to **model** — to do the way it is genuinely done. Practising scientists keep laboratory notebooks with exactly these features: dated, ordered, written at the time of the work. A result reported in a paper must be traceable back to the original notebook record, because other scientists accept a result only when they can see how it was produced and repeat it for themselves. A claim with no record behind it has nothing to support it. Your logbook is the same instrument at the scale of one student's investigation: it is where the investigation *lives* between sessions, and it is the record your conclusion will stand on.

The planning framework of 14A gives the logbook one row of its own: *Logbook record — how is the primary data dated, documented and authenticated?* This section fills in that row.

The VCAA requirement. Most decisions about assessment at Units 1 & 2 are made by your school: the study design lists suitable task types but fixes no marks (14A). The logbook is the exception. The study design states that students *“maintain a logbook of practical activities in each of Units 1 to 4 for recording, authentication and assessment purposes”*, and that the logbook *“is submitted as a requirement for satisfactory completion in each of Units 1 to 4”* (*VCE Physics Study Design*). It is the one Units 1 & 2 artefact with a VCAA-level submission requirement attached.

That sentence names three purposes, and each is a different job:

Purpose	The job it does	Built in
Recording	The logbook holds the primary data and the observations, as generated, so nothing is lost between sessions.	14B generates; this section records.
Authentication	The logbook lets your teacher see that the data are genuinely yours — generated by you, when and how you say they were.	This section.
Assessment	The logbook is source material for assessed work: *“reflective annotations related to one or more practical activities from a logbook”* is one of the study design’s own listed assessment task types, and the Unit 2 Outcome 3 report of your investigation (14A, 14G) is built from the record it contains.	14G writes; this section supplies.

Two consequences follow. First, the logbook is not a fair copy produced after the fact — it is the working record, kept as the work happens, because that is the only form that can do the authentication job. Second, the habit matters beyond this unit: satisfactory completion is what is reported to the VCAA for Units 1 & 2 — a student’s result for each unit is reported as **S** (satisfactory) or **N** (not satisfactory) — and the same logbook requirement continues through Units 3 & 4.

What authentication means. The study design uses the word *authenticate* but does not define it. This section therefore treats it as an operational definition, and every question in this section is answerable on that definition alone: to **authenticate** primary data is to be able to show, from the record itself, that the data are what they are claimed to be — generated (or collated) by the student named, at the times and places stated, by the method described — and not copied from someone else, invented, or altered afterwards. Other definitions exist; this is the one used here.

Authentication matters because of what the data are: they are the **evidence** of the investigation (10A). Section 14E organises and evaluates the data, and 14G builds the conclusion from them — but evaluation and conclusion are only as strong as the evidence is trustworthy. Data that cannot be traced cannot support a conclusion, no matter how good the graph looks. The logbook is the trace.

The practical test is a reader test: *could someone else — your teacher, or a student repeating your investigation — follow your record and see exactly what you did, in what order, with what result?* A logbook answers the reader’s questions before they are asked: when was this measured? with what equipment? by whom? was the method changed part-way? what happened to the reading that looked wrong? Where the record answers those questions, the data are authenticated; where it leaves them open, they are not.

What goes into a logbook entry. A logbook entry is everything one session of the investigation produces. The anatomy below follows the planning framework of 14A — each planning element leaves its trace in the logbook.

Element	What the entry shows	Where it was built
Date (and time, where it matters)	When the work was done	This section
Investigation question and aim	What the session was for	14A

Element	What the entry shows	Where it was built
Equipment list	What was used, in enough detail to be repeated	14B
Method and variables	What was done, in order; what was changed, measured and controlled	14A, 14B
Safety notes	The hazards identified and how they were managed	14C
Hypothesis or prediction, if one was made	What was expected before measuring	14D
Raw data	The readings themselves, with units, as they came from the instrument	14B, this section
Qualitative observations	What was noticed: behaviour, appearances, sounds, surprises	This section
Modifications	Any change or extension to the process, with its reason	This section
Summary	Means and calculated values worked out from the raw data, kept beside it	This section, 14E
Secondary data collated	The data, with organisation, document and retrieval date	10A, this section
Reflection	What worked, what did not, what to do next — the raw material of the evaluation and of reflective annotations	14E, 14G
Sign-off	Your initials (and your teacher's countersignature, where used) at the end of the session	This section

No entry needs every element every time — a planning session records the plan, a data session records the data — but over the whole investigation every element appears, and each one is dated.

Recording and summarising qualitative and quantitative data. The second key science skill of this section is to *"record and summarise both qualitative and quantitative data, including use of a logbook as an authentication of generated or collated data"*. Each word in that skill is a practice.

Record. Write the readings down as they are taken, not afterwards from memory. Record them in a table whose column headings name the quantity and its unit — potential difference (V), current (A) — exactly as graphs label their axes (1A, 7B). Record every reading with the significant figures the instrument supports (1A) and do not round readings to tidier numbers: a thermometer that reads $46^{\circ}\mathrm{C}$ is recorded as $46^{\circ}\mathrm{C}$, not "about $50^{\circ}\mathrm{C}$". And record *every* reading, including the ones that look wrong — a strange value is written down with a note of what seemed odd at the time; whether it is an outlier is decided later, by the analysis of 14E, not by the bin at the bench.

Qualitative and quantitative. Quantitative data are numbers — times, distances, temperatures, currents. Qualitative data are observations in words — what you saw, heard or noticed: "the filament globe glowed brighter as the potential difference increased", "the cart clicked against the end stop on every run", "the spring returned to its starting length each time the masses were removed". Qualitative observations are data too (14B): they are evidence, and they often explain the numbers — the observation that a spring returns to its starting length is evidence that it is behaving elastically (9B), which is what allows extension to be used as a measure of force.

Summarise. After the raw data are recorded, work out the summaries: the mean of a set of repeat readings, a calculated value such as $R = V / I$ (5A). The summary goes *beside* the raw data, never in place of them — the raw readings stay in the logbook, because the summary is only one step of processing applied to them, and 14E may need to look behind it.

Collated. The skill names *collated* data as well as generated data. If your investigation uses a secondary data set — data someone else produced, which you collect (10A) — the logbook records it with its full source: the organisation that published it, the document or data-set title, and the retrieval date, in the same Source-line form this book itself uses (10A). A collated data set with no source is in the same position as a reading with no record: it cannot be traced, so it cannot be authenticated.

Working independently and collaboratively, and recording modifications. The first key science skill of this section is to *"work independently and collaboratively as appropriate and within identified research constraints, adapting or extending processes as required and recording such modifications in a logbook"*. It contains three practices.

Within constraints. Every investigation works inside constraints: the equipment available, the time allowed, the safety rules of 14C, and the scope the question was given in 14A. Working within constraints is not a failure of ambition — it is the normal condition of real science, and the logbook is where the constraints, and what they forced, are written down.

Adapting and extending. A modification is a change to the process made while the work is under way. An **adaptation** changes how something is done; an **extension** adds to it. Modifications are expected — equipment misbehaves, readings turn out smaller than planned, a better way of measuring appears mid-session — and a modification is not something to hide. It is recorded, in four parts:

1. **What** changed;
2. **Why** it changed;
3. **From when** it applied (which trial onward);
4. **What effect** it may have on the data — in particular, whether readings taken before the change are directly comparable with readings taken after it.

That fourth part matters most. If the instrument or the method changes mid-investigation, the data on the two sides of the change may not be comparable, and the record must say so — the analysis of 14E then treats the two sets accordingly, instead of joining them as though nothing happened.

Independently and collaboratively. Scientific investigations may be undertaken in groups, but the study design is explicit: *all work for assessment must be completed individually* (14A). The two halves of that rule sit together with the logbook between them. Group work is normal and valuable: a group can share apparatus, take readings together, and discuss method. But the logbook is an individual record, because authentication is about *whose* work it is. Each student keeps their own logbook. Where readings are taken together, the standard practice is that one student reads the instrument aloud and **every** student writes the reading into their own logbook at that moment, each also noting their own role in the session. Copying a page from another student's logbook — by photograph, photocopy or transcription — does not authenticate anything, because the copy cannot show who wrote it, when, or what part of the work was theirs.

The logbook rules. The practices above compress into eight rules. They are the habits the rest of this section's questions test.

1. **Date every entry**, and add the time where the timing of the session matters.
2. **Write as you go.** Entries are made during the work, not reconstructed afterwards from memory — memory of which value went in which column does not survive the week.
3. **Keep the order.** Entries follow one another in sequence; leave no blank gaps, and do not remove pages. In a digital logbook, entries are added, never silently deleted or rewritten.
4. **The original stays.** When a value is written wrong or misread, correct it by drawing a single line through it, writing the corrected value beside it, and initialling the change. Never overwrite, erase or blank it out — the original value is still evidence of what actually happened at the bench, and overwriting destroys exactly the trace authentication needs.
5. **Every number carries its unit**, and every table names the quantity and unit in its heading (1A).

6. **Attachments are labelled.** Printouts, photographs and screenshots from data loggers or video analysis are fixed into the logbook with a caption, a date and your initials, so each one says what it shows and where it came from.
7. **Failed attempts are recorded too.** A run that did not work, with the reason it did not work, is part of the record — it explains the gaps in the data and feeds the evaluation (14E). A logbook containing only clean successes describes an investigation that never happened.
8. **Sign off.** Initial the end of each session's entry; your teacher may countersign entries as the work progresses.

How a logbook fails to authenticate. Each rule above exists because a real logbook can fail in that way. The failures to watch for — in your own logbook and when judging anyone else's — are:

- **Undated entries**, which cannot be matched against the class schedule and could have been written at any time;
- **Entries written after the event**, reconstructed from memory or from another student's record;
- **Overwritten or erased values**, which hide the original reading instead of preserving it;
- **Identical entries across students**, word for word, which show copying rather than individual records;
- **Data with no scatter at all.** Real repeat measurements differ from one another by small amounts (14B); a set of repeats that comes out identical, or that lands exactly on the expected line with no deviation, raises the question of whether the values were measured or filled in to fit;
- **Silent gaps.** Where data are lost or a run fails, the honest record says so — "the file from run 3 would not open; the run was repeated". A gap quietly filled is the opposite of authentication; a gap honestly named leaves the rest of the record trustworthy. This is the ethical side of the logbook, and it belongs with the ethical conduct of 14C.

Notice what all six failures have in common: each one breaks the trace between the claim ("this is my data") and the evidence for the claim. Authentication is the trace, kept in writing.

A logbook template for your investigation. The template below gathers every element of this section onto one page. It supports the practical hours of your investigation — the hours themselves belong in the laboratory and are planned by your teacher (14A); the template is what you write in while you work.

Entry	What to write
Name; date; time; session number	Who is writing, and when
Investigation question and aim	In one sentence each (14A)
Plan for this session	The method step to be done, the variables, the equipment (14A, 14B)
Safety check	The hazards of this session and the precautions taken (14C)
Prediction, if one is made	What you expect to happen, before measuring (14D)
Raw data	Table with quantity and unit headings; every reading as taken (1A, 14B)
Observations	What was noticed, in words
Modifications	What changed, why, from when, and the effect on the data
Summary	Means and calculated values, beside the raw data
Secondary data collated	With organisation, document title and retrieval date (10A)
Reflection	What worked, what did not, what to change next session (14E, 14G)
Sign-off	Your initials; teacher's countersignature where used

Units 3 & 4 preview. The logbook requirement does not end with Unit 2: the logbook is maintained and submitted in each of Units 1 to 4, and the student investigation of Unit 4, Area of Study 2 — an examinable outcome at Units 3 & 4 — is built on the same practice this section teaches. The investigation skills of this chapter are assumed there without revision, which is why the habit is built now. Content under this banner is not assessed in this book's topic tests or practice examinations.

Worked examples

Example 1 — scaffolded

A student investigating how the extension of a spring depends on the applied force (the investigation of Hooke's Law, 9B) writes the following entry in her logbook.

12 March 2026 — Session 3 — Spring and forces

Aim: to investigate how the extension of the spring depends on the force applied to it.

Equipment: spring on stand, set of slotted masses, millimetre ruler.

Method: hang masses from the spring; measure the extension for each force, $F_g = mg$, with $g = 9.8\ \text{N kg}^{-1}$.

Trial 1 note: held the metre rule by hand to read the $0.98\ \text{N}$ extension; hard to read to the nearest mm.
From trial 2, clamped the mm ruler to the stand and read it at eye level.

Force (N)	Extension (cm)
0.98	1.3
1.96	2.7
2.94	3.9
3.92	5.3
4.90	6.5

Observation: the spring returned to its starting length each time the masses were removed.

(a) Identify two features of this entry that help authenticate the data.
(b) Identify the modification recorded in the entry, and explain why recording it matters for the analysis.
(c) Identify one feature that would strengthen the entry if added.

Working	Comment
The entry is dated (12 March 2026) and labelled as session 3 of a named investigation.	The date places the work in the sequence of class sessions; the data can be matched against when the work was actually done.
The readings are recorded as raw data, in a table whose headings name the quantity and its unit, with realistic small differences between points — the extensions do not land on perfectly even values.	Readings as taken, with units (rule 5), are the trace of what was measured; real repeat measurements scatter slightly (14B), and this set does.
The modification: from trial 2 onward the ruler was clamped to the stand and read at eye level, replacing the hand-held rule of trial 1, because the hand-held rule was hard to read to the nearest mm.	The entry states what changed, why, and from when — three of the four parts of a modification record.
It matters because the trial-1 reading was taken by a different method from the rest. If the trial-1 extension is less reliable, the analysis (14E) must treat it accordingly rather than joining all five points as though they were measured the same way.	A recorded modification protects the analysis: the data either side of a method change are only comparable if the record says they are.
One missing feature (any one): the entry is not signed or initialled at the end (rule 8); no time is given; no safety note is recorded for the hanging masses (14C).	Sign-off, timing and safety notes each strengthen the record; their absence is an omission, not a failure of honesty.

Example 2 — scaffolded

A student is investigating how the drop height of a basketball affects its rebound height (14A). After two heights have been measured by watching the top of the bounce against a metre stick, the student finds the rebound too quick to read reliably, and decides to film each drop in slow motion on a phone and read the rebound height from the video frame by frame, against a ruler fixed behind the bounce.

Write the logbook entry that records this modification.

Working	Comment
What changed: rebound heights are now measured from slow-motion video, frame by frame, against a ruler fixed behind the bounce — replacing reading the top of the bounce by eye against a hand-held metre stick.	The modification is stated precisely: the old method and the new.
Why: the rebound reaches its top too quickly to read reliably by eye; the video can be paused and replayed, so the height can be read to the nearest centimetre.	The reason shows the change was made for the quality of the data (14B), not for convenience alone.
From when: from trial 3 onward (drop heights $0.60\,\text{m}$ and above); trials 1–2 ($0.20\,\text{m}$, $0.40\,\text{m}$) were measured by eye.	The record says exactly which data were taken by which method.
Effect on the data: the two methods may not give identical heights, so heights at $0.20\,\text{m}$ and $0.40\,\text{m}$ will be repeated with the video method next session to check whether the two methods agree before the data sets are joined.	The effect is named and a response is planned: data either side of the change are not assumed comparable (14E).
Initials and date at the end of the entry.	Rules 2 and 8: the entry is written at the time of the work and signed off.

Example 3 — unscaffolded

Three students run an investigation of the motion of a cart down a ramp as a group: one student releases the cart, one operates the stopwatch, and one calls the readings out. At the end of the session, only the student calling the readings has written the data table in her logbook. The other two students photograph her page and put the photograph into their own logbooks.

Evaluate whether the two photographs authenticate those students' data, and state what the group should do instead.

The photographs do not authenticate the two students' data. Authentication requires each student's logbook to be their own dated record of the work, showing what they did and what they recorded at the time it happened. A photograph of another student's page is a copy: it cannot show who wrote it, it was not written as the readings were taken, and it is identical to the original by construction — the very pattern the rules of this section identify as the sign of copying rather than recording. It also leaves no trace of either student's own role in the session.

This does not mean the group did anything wrong in working together. Investigations may be undertaken in groups, and sharing the work — releasing, timing, calling readings — is collaboration of exactly the kind the key science skill describes. What must be individual is the record, because all work for assessment must be completed individually.

What the group should do instead: as each reading is called out, **every** student writes it into their own logbook at that moment, so that each logbook holds the data as an original, dated record, written as the readings were taken. Each student also records their own role in the session — who released, who timed, who called — so that the part of the work that was theirs is visible in their own book. Where the school uses teacher countersigning, the entries can be countersigned as the session progresses. The group work stays shared; the evidence stays individual.

∴ the photographs fail to authenticate — they are copies, not individual records made at the time; each student must record the readings in their own logbook as they are taken, with their own role noted.

Example 4 — unscaffolded

Two students investigated the same spring as in Example 1. Their logbooks contain the following extracts.

Student P.

> **12 March 2026, 2:10 pm — Session 3.** Same aim and equipment as sessions 1–2. Reading taken at eye level with the ruler clamped to the stand.

Force (N)	Extension (cm)
0.98	1.4
1.96	2.6
2.94	4.0
3.92	5.3
4.90	6.5

> The 1.96 N reading was first read as 3.1 cm; re-checked and corrected — I had read the ruler from the wrong end. ~~3.1~~ 2.6 (initialled).
>
> Signed: A.P.

Student Q.

> Spring practical — results.

Force (N)	Extension (cm)
0.98	1.3
1.96	2.6
2.94	3.9
3.92	5.2
4.90	6.5

> Results were as expected.

Evaluate which student's logbook better authenticates its primary data. In your answer, use the features of this section.

Student P's logbook authenticates its data; Student Q's does not, and each difference between the two extracts is one of the features this section teaches.

Date and place in the work. Student P's entry carries a date, a time and a session number, and links back to earlier sessions; the work can be matched against the class schedule. Student Q's extract is undated and could have been written at any time, including after the event.

The record of error. Student P's entry preserves a misread value: the original 3.1 cm is struck through with a single line, the corrected value sits beside it with the reason for the correction, and the change is initialled — rule 4 of this section, applied exactly. This is strong evidence of authenticity, because it shows a real reading process, including a real mistake handled honestly. Student Q's extract contains no trace of the work at all — no method, no observation, no difficulty.

The scatter. Student P's extensions carry the small irregularities of real measurement (1.4, 2.6, 4.0, 5.3, 6.5). Student Q's values sit almost exactly on an even pattern, 1.3 cm per 0.98 N with almost no departure: a set this regular raises the question of whether the values were measured or adjusted to fit, which is exactly the suspicion authentication exists to remove.

Sign-off. Student P signs the entry; Student Q does not.

None of this proves anything about Student Q's honesty — the extract alone simply cannot do the authentication job, which is the point of the rules: a logbook is written so that no one has to ask whether the data are genuine, because the record shows it.

∴ Student P's logbook authenticates its data — dated, ordered, signed, with a corrected reading preserved and realistic scatter; Student Q's extract fails: undated, unsigned, without method or modification notes, and with data too regular to show a real measurement process.

Practice questions

Question 1 *(scaffolded)* Define each of the following as the term is used in this section: (a) logbook; (b) authenticate, as applied to primary data; (c) primary data.

Question 2 *(scaffolded)* (a) State the three purposes for which the study design requires students to maintain a logbook. (b) Identify in which units of VCE Physics the logbook must be maintained and submitted. (c) State what the study design's logbook requirement makes the logbook the one example of, at Units 1 & 2.

Question 3 *(scaffolded)* Classify each of the following as **qualitative** or **quantitative** data: (i) the time taken for a cart to roll down a ramp, $2.3\,\mathrm{s}$; (ii) "the filament globe glowed brighter as the potential difference increased"; (iii) the temperature of the water, $46\,^{\circ}\mathrm{C}$; (iv) "bubbles formed on the surface of the water as it was heated"; (v) the current in the circuit, $0.42\,\mathrm{A}$; (vi) "the cart clicked against the end stop on every run".

Question 4 *(scaffolded)* A student's investigation uses four items of information: (i) rebound heights the student measured and recorded during the investigation; (ii) a table of Melbourne's daily maximum temperatures downloaded from the Bureau of Meteorology website; (iii) a table of refractive indices printed in a reference book; (iv) observations of wave behaviour written in the student's logbook during a practical session. (a) Classify each item as **primary** or **secondary** data (10A). (b) For each secondary item, state the three details the student must record in the logbook alongside it.

Question 5 *(scaffolded)* Identify five features of a logbook entry that help it authenticate the data it contains.

Question 6 *(scaffolded)* A student is absent on the day of a practical session and writes up the entry a week later, from memory and from notes sent by a friend. (a) Identify two reasons this entry does not authenticate the data. (b) State the practice the student should follow instead.

Question 7 While recording readings, a student realises she has written $3.4\,\mathrm{cm}$ for a reading that was actually $4.3\,\mathrm{cm}$. (a) Describe the correct way to fix the entry. (b) Explain why overwriting the value, or erasing it, must not be done.

Question 8 A student investigating how the force on a spring affects its extension finds the extensions produced by $10\,\mathrm{g}$ mass steps too small to read reliably, and switches to $50\,\mathrm{g}$ steps from the fourth trial onward. Write the four parts of the logbook entry that records this modification: what changed, why, from when, and the effect on the data.

Question 9 Three students plan to investigate the motion of a cart down a ramp together. (a) Quote the study design's statement about group investigations and work for assessment. (b) Explain how each student keeping their own logbook allows the group to collaborate while still authenticating each student's work.

Question 10 A student measures the current in a resistor at three potential differences, and records the readings in her logbook as: *"1.0 V — 0.20 A; 2.0 V — 0.40 A; 3.0 V — 0.59 A"*. (a) Rewrite the data as a correctly headed logbook table. (b) The student calculates the resistance from $R = V / I$ (5A) for each row. Calculate the three resistance values, each to two significant figures. (c) Explain whether the table of calculated resistance values replaces the raw readings in the logbook, or is added beside them.

Question 11 A student times a cart rolling down a ramp five times and records: $2.2\,\mathrm{s}$, $2.4\,\mathrm{s}$, $2.2\,\mathrm{s}$, $2.3\,\mathrm{s}$, $2.4\,\mathrm{s}$. (a) Calculate the mean time, and write the sentence the student should add to the logbook as the summary. (b) Explain why the five raw readings must remain in the logbook alongside the mean. (c) If one of the readings looked far from the others, identify which section of this chapter decides whether it is an outlier, and state what the logbook entry should record in the meantime.

Question 12 (a) Name the assessment task type from the study design's own list that is built directly from a logbook, quoting the task type. (b) Explain how dated logbook entries support that task.

Question 13 Two students in the same class hand in logbooks whose entries for the same practical session are word-for-word identical, including the same shortened phrases and the same spelling mistakes. (a) Identify the feature of authentic logbooks that this pattern breaks. (b) State two things the teacher can no longer tell from these entries.

Question 14 A student investigating the period of a pendulum records five repeat measurements: $1.4\,\text{s}$, $1.4\,\text{s}$, $1.4\,\text{s}$, $1.4\,\text{s}$, $1.4\,\text{s}$, measured with a stopwatch reading to $0.1\,\text{s}$. (a) Explain why a set of repeat measurements this regular should prompt a question about how the data were recorded. (b) State what realistic repeat measurements would look like, using the ideas of 14B.

Question 15 A student undertakes a fieldwork investigation at a local site (14A). (a) State what the study design requires to be done with the site-specific data generated during fieldwork. (b) Identify two things the fieldwork entry should contain, besides the readings themselves.

Question 16 A student using a data logger prints out a temperature–time graph of her cooling-water investigation and wants to put it into her logbook. Identify three things she must do to the printout so that it becomes part of the authenticated record.

Question 17 A student's logbook entry for a session on circuits reads:

> Measured current for different voltages. Results in the table. The globe got hotter as the voltage went up.

V	I
1	0.2
2	0.4
3	0.6

(a) Identify two strengths of this entry.
(b) Identify three omissions that weaken the authentication of the data.

Question 18 Write a complete model logbook entry for the first data session of an investigation with the aim *"to investigate how the drop height of a basketball affects its rebound height"* (14A). Your entry must include: a date; the aim; an equipment list; a raw data table with correctly headed columns containing at least three rows of readings; one qualitative observation; one modification recorded in full (what, why, from when, effect); and a sign-off.

Answers

Question 1 (a) see solution — dated, ordered, write-once record kept as the work happens; (b) showing from the record itself that the data are what they are claimed to be; (c) data generated by the student and recorded in their logbook (10A). **Question 2** (a) recording, authentication and assessment; (b) each of Units 1 to 4; (c) the one Units 1 & 2 artefact with a VCAA-level submission requirement. **Question 3** (i), (iii), (v) quantitative; (ii), (iv), (vi) qualitative. **Question 4** (a) (i) primary; (ii) secondary; (iii) secondary; (iv) primary; (b) organisation, document or data-set title, retrieval date. **Question 5** Any five from the solution — e.g. dated entries, entries written at the time, units on every number, corrections by single-line strike-through, sign-off. **Question 6** (a) not written at the time of the work; based on another student's notes rather than the student's own record; (b) record the data in their own logbook as the work happens, or repeat the work and record that. **Question 7** (a) single line through the wrong value, corrected value beside it, initialled; (b) see solution — the original value is evidence and must stay visible. **Question 8** See solution — what: $50\,\text{g}$ steps replaced $10\,\text{g}$ steps; why: extensions too small to read reliably; from when: trial 4 onward; effect: trials 1–3 not directly comparable. **Question 9** (a) "all work for assessment must be completed individually"; (b) see solution. **Question 10** (a) table headed "Potential difference (V)" and "Current (A)"; (b) $5.0\,\Omega$, $5.0\,\Omega$, $5.1\,\Omega$; (c) added beside — the raw readings stay. **Question 11** (a) $2.3\,\text{s}$; (b) see solution; (c) 14E; the reading stays in the table with a note of what seemed odd. **Question 12** (a) "reflective annotations related to one or more practical activities from a logbook"; (b) see solution. **Question 13** (a) individual authorship — the entries show copying; (b) e.g. which student recorded which reading, and whether either student recorded anything at the time. **Question 14** (a) real repeat measurements scatter; five identical values to the stopwatch's resolution suggest the values were filled in rather than measured; (b) see solution. **Question 15** (a) recorded in the student's logbook; (b) e.g. the context of the site, and the relevance of the site to the investigation (14A). **Question 16** Any three: label/caption stating what it shows; date it; initial it; reference which session and data set it belongs to. **Question 17** (a) e.g. a data table is present, and a qualitative observation is recorded; (b) e.g. no date, no units in the table headings, no sign-off — see solution. **Question 18** Rubric-style model entry in the fully-worked solutions.

Fully-worked solutions

Question 1 (a) A **logbook** is a dated record, kept by the student in write-once form — a bound notebook or a digital record that preserves every entry in the order made — that documents, as the work happens, what was planned, what was done, what was observed, and what was changed. (b) To **authenticate** primary data is to be able to show, from the record itself, that the data are what they are claimed to be — generated (or collated) by the student named, at the times and places stated, by the method described — and not copied, invented or altered afterwards. (c) **Primary data** are the data the student generates in an investigation and records in their logbook (10A). Data produced by someone else and collected by the student are secondary.

Question 2 (a) The study design requires the logbook to be maintained *"for recording, authentication and assessment purposes"*. (b) In each of Units 1 to 4 — the logbook is submitted as a requirement for satisfactory completion in each of Units 1 to 4. (c) It is the one Units 1 & 2 artefact with a VCAA-level submission requirement attached: task types and marks at Units 1 & 2 are matters for school decision, but the logbook itself is a named requirement of satisfactory completion.

Question 3 Quantitative data are numbers with units: (i) $2.3\,\text{s}$, (iii) $46\,^{\circ}\text{C}$, (v) $0.42\,\text{A}$. Qualitative data are observations in words: (ii) the globe glowing brighter, (iv) bubbles forming, (vi) the cart clicking against the stop. Both kinds are data; the qualitative observations often explain the quantitative ones.

Question 4 (a) (i) primary — measured and recorded by the student; (iv) primary — observations written by the student during the practical session. (ii) and (iii) are secondary — produced by someone else (the Bureau of Meteorology; the reference book's authors) and collected by the student (10A). (b) For each secondary item: the **organisation** that published it (Bureau of Meteorology; the publisher of the reference book), the **document or data-set title**, and the **retrieval date** — the same Source-line form used throughout this book (10A). Without these details a collated data set cannot be traced, and what cannot be traced cannot be authenticated.

Question 5 Any five of the following, each stated as a feature of the entry: - the entry is **dated** (and timed where it matters), so the work can be matched against the class schedule; - the entry was **written at the time of the work**, not reconstructed afterwards; - entries sit **in order**, with no gaps and no removed pages; - **every number carries its unit**, and tables name quantity and unit in their headings; - **corrections are made by a single-line strike-through**, with the corrected value beside the original and the change initialled — the original stays visible; - attachments are **labelled, dated and initialled**; - the entry is **signed off** at the end of the session, with a teacher countersignature where used; - **modifications are recorded** — what changed, why, from when, and the effect on the data.

Question 6 (a) Any two reasons: the entry was not written at the time of the work, so it cannot be a record of the work as it happened — it is a reconstruction from memory a week later; and it is built from another student's notes, so it cannot show what *this* student recorded or did — it is a copy at one remove. Both break the trace between the student's claim and the evidence for it. (b) The student should record data in their own logbook as the work happens. Having missed the session, the honest options are to repeat the practical (or join another group's run, recording their own role and their own readings) and record that work in their own logbook, noting that it was done later and why.

Question 7 (a) Draw a single line through $3.4\,\mathrm{cm}$ so that it remains readable, write $4.3\,\mathrm{cm}$ beside it, and initial the correction. (b) The original value is evidence of what actually happened at the bench — including the fact that a misread occurred and was caught. Overwriting or erasing destroys that trace, and a record in which values can be silently changed cannot authenticate anything: there is no way to tell a corrected error from a value quietly adjusted to fit.

Question 8 A full entry would contain all four parts: - **What:** $50\,\mathrm{g}$ mass steps replaced the $10\,\mathrm{g}$ steps. - **Why:** the extensions produced by $10\,\mathrm{g}$ steps were too small to read reliably with the ruler in use (a matter of resolution — 14B). - **From when:** from trial 4 onward; trials 1–3 used $10\,\mathrm{g}$ steps. - **Effect:** the trials on the two sides of the change used different force steps and may not be directly comparable — for example, the $10\,\mathrm{g}$-step readings may be less reliable — so the analysis (14E) must treat the two sets accordingly, or the early trials must be repeated with $50\,\mathrm{g}$ steps before the sets are joined.

Question 9 (a) The study design states that scientific investigations may be undertaken in groups, *"but all work for assessment must be completed individually"* (14A). (b) Collaboration happens in the shared work — the apparatus, the readings, the discussion of method — and each student's logbook keeps the evidence individual: as readings are called out, every student writes them into their own logbook at that moment, and each student records their own role in the session. The group's data are the same readings; the records are three original, dated, individual accounts of the one session, each showing what that student did — which is what authentication requires.

Question 10 (a) The table headings must name the quantity and its unit:

Potential difference (V)	Current (A)
1.0	0.20
2.0	0.40
3.0	0.59

(b) $R = V / I$ (5A): $R = 1.0 / 0.20 = 5.0\,\Omega$; $R = 2.0 / 0.40 = 5.0\,\Omega$; $R = 3.0 / 0.59 = 5.08\ldots = 5.1\,\Omega$, each to two significant figures.

(c) The calculated values are added beside the raw readings, never in place of them. The raw table is the record of what was measured; the resistance values are one step of processing applied to it, and 14E may need to look behind the summary — for example, to see that the third reading departs slightly from the pattern the first two suggest.

Question 11 (a) Mean $= (2.2 + 2.4 + 2.2 + 2.3 + 2.4) / 5 = 11.5 / 5 = 2.3\,\mathrm{s}$. Summary sentence: *"Mean of five runs: $2.3\,\mathrm{s}$."* (b) The mean is a summary — one number standing for five. If the five readings are erased or overwritten, nothing behind the mean remains: the scatter of the runs, which shows the precision of the timing (14B), is lost, and 14E cannot check the summary or judge any one reading. The summary is worked out *from* the raw data and sits beside it. (c) Section 14E decides whether a reading is an outlier, as part of analysing and evaluating the data. Meanwhile the logbook does not remove the reading: it stays in the table, with a note of what seemed odd at the time — for example, "cart bumped the guide rail on this run".

Question 12 (a) *"Reflective annotations related to one or more practical activities from a logbook"* — one of the study design's listed task types for assessment at Units 1 & 2. (b) Reflective annotations are notes added to the record that look back on the activity — what worked, what did not, what would be done differently and why. Dated entries give the annotations something to reflect *on*: the annotation can point to the exact session, the exact readings and the exact modification it refers to, and the dates show the reflection follows the work rather than preceding it. Without the dated record, the annotation has no anchor.

Question 13 (a) Individual authorship. Two entries word-for-word identical, mistakes included, show that one was copied from the other (or both from a third source) rather than each written as the work happened. A genuine individual record would differ at least in phrasing, and the mistakes would not match. (b) Any two of: which student actually recorded which readings; whether either student was recording at the time of the work; what either student's own role in the session was. The teacher can no longer see either student's work as their own — which is the question the logbook exists to answer.

Question 14 (a) Real repeat measurements of the same quantity differ from one another by small amounts — the reaction time of the person with the stopwatch, the exact release, the reading of the stopwatch itself all vary (14B). Five repeats identical to the stopwatch's $0.1\,\mathrm{s}$ resolution are more regular than the measuring process can produce, which raises the question of whether the values were measured each time or written once and repeated. Suspiciously perfect data weaken authentication for exactly the same reason as an overwritten value: they do not show a real measurement process. (b) Realistic repeats would cluster around a central value with small differences between them — for example, $1.3\,\mathrm{s}$, $1.4\,\mathrm{s}$, $1.4\,\mathrm{s}$, $1.5\,\mathrm{s}$, $1.4\,\mathrm{s}$ — and the spread itself is useful information about the precision of the timing (14B).

Question 15 (a) The study design states that the generation of site-specific data during fieldwork *"should be recorded in the student's logbook"* (14A). (b) Any two, following the study design's description of fieldwork (14A): the context of the site — what the place was like and what was happening there; the relevance of the site to the investigation, prediction and/or hypothesis — why this location answers this question; and the practical conditions of the measurements — where and how each reading was taken.

Question 16 Any three of the following: give the printout a **caption** stating what it shows (a temperature–time graph of the cooling water, from the data logger); **date** it, and write the session it belongs to; **initial** it, so it is tied to the student's own record; and note in the entry what was done to the data before printing, if anything (for example, nothing — the logger's own readings plotted directly). An unlabelled printout fixed into a logbook proves nothing: it could be anyone's, from any session.

Question 17 (a) Any two strengths: a table of readings is present, with one row per measurement; and a qualitative observation is recorded ("the globe got hotter as the voltage went up") — the entry holds both kinds of data. (b) Any three omissions, each weakening authentication in a specific way: **no date** — the entry cannot be matched against when the work was done; **no units in the table headings** — "1" and "0.2" name no quantity (the units are presumably V and A, but "presumably" is exactly what authentication removes); **no equipment or method note** — a reader cannot see how the data were generated; **no sign-off** — nothing shows the entry is complete and the student's own. The clean $0.2\,\mathrm{A}$ steps of the current column would also be worth a note of how the values were read.

Question 18 Marks are awarded for the features, not for the exact numbers. A full-mark entry would include every required element, correctly formed. For example:

24 August 2026 — Session 2 — Data session 1

Aim: to investigate how the drop height of a basketball affects its rebound height.

Equipment: basketball (same ball throughout), metre ruler fixed vertically to the wall, wooden floor, marker for drop heights.

Method: drop the ball from rest at each marked height; read the top of the rebound against the ruler; repeat each height three times.

Drop height (m)	Rebound height, trial 1 (m)	Rebound height, trial 2 (m)	Rebound height, trial 3 (m)
0.20	0.12	0.13	0.12
0.40	0.24	0.25	0.24
0.60	0.38	0.36	0.37

Observation: the rebound was straight up each time; the ball's bounce sounded unchanged across the session.

Modification: from the $0.80\,\mathrm{m}$ height onward, a second student will call the top of the rebound while I read the ruler, because at the higher drops the top of the bounce is too quick for one person to drop and read. Reason: reliability of the reading (14B). Effect: all heights up to $0.60\,\mathrm{m}$ were read by me alone, so if the two-person readings look different, the $0.60\,\mathrm{m}$ height will be repeated both ways to check.

Signed: J.L. — teacher countersigned.

The required features and their check: a date; the aim in one sentence (14A); an equipment list specific enough to repeat; a table with quantity-and-unit headings and realistic small scatter between trials (14B); one qualitative observation; one modification recorded in all four parts — what, why, from when, effect; and a sign-off.

Chapter 14 Scientific investigation — 14G Communicating findings: report conventions and key findings

Scope. This section is set out in the *VCE Physics Study Design*, Unit 2, Area of Study 3 — *How do physicists investigate questions?* — key knowledge block *Science communication*. The two key knowledge dot points owned here are quoted verbatim below.

ID	Key knowledge (verbatim)
`U2.3.11`	"apply the conventions of scientific report writing including scientific terminology and representations, standard abbreviations, units of measurement, significant figures and acknowledgement of references"
`U2.3.12`	"apply the key findings of the selected investigation and their relationship to key physics concepts."

This section also gives first teaching of five of the study design's key science skills:

ID	Key science skill (verbatim)
`KSS.6.4`	"use reasoning to construct scientific arguments, and to draw and justify conclusions consistent with evidence and relevant to the question under investigation"
`KSS.6.5`	"identify, describe and explain the limitations of conclusions, including identification of further evidence required"
`KSS.7.1`	"use appropriate physics terminology, representations and conventions, including standard abbreviations, graphing conventions, vector diagrams, algebraic equations, significant figures, uncertainty bars and units of measurement"
`KSS.7.6`	"use clear, coherent and concise expression to communicate to specific audiences and for specific purposes in appropriate scientific genres, including scientific reports and posters"
`KSS.7.7`	"acknowledge sources of information and assistance, and use standard scientific referencing conventions"

What is deliberately not taught here: evaluating the validity of sources belongs to Section 10A; constructing and linearising graphs belongs to Sections 7B and 14E; accuracy, precision and the handling of random and systematic error belong to Sections 14B and 14E; formulating a hypothesis, and judging whether evidence supports or refutes it, belong to Section 14D; the logbook authentication of primary data belongs to Section 14F. This section gathers those skills into the finished report: it teaches the conventions of scientific report writing, and how to state the key findings of the investigation in relation to the physics behind it.

Theory

The last stage of an investigation. An investigation is not finished when the last measurement is taken. Its outcome is a claim about how the world behaves, and a claim that has not been communicated — with its evidence, its method and its limits — cannot be checked, repeated or used by anyone else. Communication is the stage at which your work becomes science other people can build on. It is also the stage the outcome of this area of study asks for, verbatim: *"On completion of this unit the student should be able to draw an evidence-based conclusion from primary data generated from a student-adapted or student-designed scientific investigation related to a selected physics question."* (*VCE Physics Study Design*, Unit 2, Area of Study 3).

The study design names the assessed task for this outcome: *"a report of a practical investigation (student-designed or adapted) using an appropriate format, for example a scientific poster, practical report, oral communication or digital presentation."* Four formats are offered, and — verbatim again — *"Where teachers allow students to choose between tasks they must ensure that the tasks they set are of comparable scope and demand."* The formats look different, but the conventions of this section apply to all of them: the same terminology, the same units and significant figures, the same acknowledgement of sources, and the same requirement to state the key findings in relation to the physics.

This section closes the planning framework of Section 14A. Every earlier section filled one row of that framework: the question, aim and concepts (14A), the method and data quality (14B), the safety and ethical guidelines (14C), the hypothesis and prediction (14D), the analysis and evaluation of the data (14E), and the logbook record that dates and authenticates the primary data (14F). The final row is this one:

Planning element	The question it answers	Built in
Report and key findings	How is the conclusion communicated, and how does it relate to the physics?	14G

One rule applies to the report as it applied to everything before it: scientific investigations may be undertaken in groups, but the study design is explicit that *all work for assessment must be completed individually*. Your report is your own writing, your own analysis and your own conclusions — and that is exactly why acknowledging every source and every assistance is not politeness but part of the honesty of the document (14F).

The shape of a practical report. A scientific report is a genre — a kind of writing with its own settled conventions — and the conventions exist so that any reader can find any part of the work quickly and check it. Different schools order the parts slightly differently, and your teacher's structure always wins; the structure below is the one this book uses. Each part answers one question, and each is built from an earlier section of this chapter.

Part of the report	The question it answers	Built from
Title	What is this report about?	Names the variables and the system (14A)
Aim and investigation question	What was the purpose, and what was asked?	14A
Background physics	What concepts, key terms and published information is the investigation built on?	14A, with sources evaluated as in 10A
Hypothesis and prediction	What was expected to happen, and why?	14D
Method	What was done, with what, and how were the variables controlled?	14B, including the safety and ethical guidelines of 14C
Results	What did the data show?	Tables, graphs and uncertainty bars, organised as in 14E
Discussion	What do the data mean, and how good were the method and the data?	14E: patterns, outliers, error, uncertainty, limitations
Conclusion: the key findings	What is the answer to the question, in relation to the physics and the hypothesis?	This section
References and acknowledgements	Whose information and assistance did the work use?	This section

Two notes on the shape. First, the logbook is not a part of the report — it is the dated record that authenticates the primary data the report is built on (14F) — but a report may point the reader to it, for example by noting where the raw readings are recorded. Second, the same structure serves the other formats the study design names: a scientific poster lays these parts out as titled panels around the page, with more emphasis on figures and less on prose; an oral or digital presentation orders the same parts in time rather than on a page. Whatever the format, the conventions of this section apply unchanged.

Terminology. The study design's terminology rules bind every report in this course (1A, 8C). Three of them are the ones most often broken in first drafts.

- The force due to gravity is F_{g}. The words "weight" and "weightlessness" are not used.
- The force in the normal direction between two surfaces in contact is the **normal force** — never "reaction force" or "normal reaction force".
- Forces are labelled for the two bodies involved: $F_{\text{on A by B}}$, with $F_{\text{on A by B}} = -F_{\text{on B by A}}$ for a Newton's third-law pair (8C).

Beyond those rules: define each key term at first use, as it applies in *this* investigation (14A), and then use the same term the same way throughout. A report that calls the same quantity "speed", "velocity" and "rate" in turn forces the reader to guess whether one idea or three are being discussed. Speed and velocity are not the same idea — one is a scalar and the other a vector (7A) — and a report must not use one word where the other is meant.

Representations. Physics representations — tables, graphs, force diagrams, circuit diagrams, ray diagrams, energy-transfer diagrams and algebraic equations — carry the argument of a report as much as its sentences do. The conventions for each have been built since 1A and 7B; in the report they are applied with three additions.

1. Number and caption every figure and every table — *Figure 1: Energy-transfer diagram for the cart on the ramp* — so the reader can refer to it and so it can be checked.
2. Refer to every representation in the text. A figure the report never mentions is a figure the reader cannot be told how to read.
3. Give each representation the conventions of its kind: graphs carry labelled axes with units, an appropriate scale, and uncertainty bars where the data have them, and need not pass through the origin (7B); vector diagrams draw each force as an arrow from its point of application, labelled $F_{\text{on A by B}}$ (8C); energy-transfer diagrams show the stores and the transfers between them (9C).

Standard abbreviations and units. A report's quantities and units follow fixed conventions, most of which you have been applying since 1A. Gathered in one place for the report:

- Quantity symbols are italic (m, v, F, λ); unit symbols are upright and never pluralised: $5\,\mathrm{kg}$, not 5 kgs; $12\,\mathrm{N}$, not 12 Ns.
- A space sits between the value and the unit: $2.4\,\mathrm{m\ s^{-1}}$, not $2.4\,m/s$.
- Unit symbols named after a person are capital letters (N, J, W, V, A, Hz, K); written-out unit names are common nouns: *newton*, *joule*, *watt*. The prefixes are lower case where the prefix itself is lower case: kJ, mA, nm — not KJ or mj.
- Compound units use the study design's form with negative indices: $\mathrm{m\ s^{-1}}$, $\mathrm{N\ kg^{-1}}$, $\mathrm{W\ m^{-2}}$; the kilowatt-hour is written kW h, with a space and no hyphen, as the study design writes it.
- The kilogram is the SI unit of mass. Report masses in kilograms ($1200\,\mathrm{g} = 1.2\,\mathrm{kg}$) unless there is a stated reason not to, and convert before calculating, so every quantity in a calculation is in SI units (1A).
- A bare number is not a measurement. Every measured or calculated quantity in a report carries its unit — in running text, in every table column heading, and on every graph axis.
- Time is written in seconds in calculations: $90\,\mathrm{s}$, not 1.5 min. Where a reading was taken in minutes, show the conversion once.

Standard abbreviations beyond the units — DC and AC (5A), the RCD (6B), the LDR and the LED (6C), for example — are written in full at first use, with the abbreviation in brackets, and as the abbreviation thereafter: *"a residual current device (RCD) … the RCD …"*. Do not invent abbreviations a reader would have to decode, and do not begin a sentence with a symbol or a numeral.

Significant figures. The seven significant-figure rules are stated, verbatim from the study design, in Section 1A, and they apply to a report exactly as they apply to a calculation. Three report-specific habits sit on top of them.

1. Record a measured value to the resolution of the instrument that measured it (14B) — a metre ruler read to the millimetre gives $0.425\,\mathrm{m}$, three significant figures — and keep every reading at that same precision in the results table.
2. Give a calculated result no more significant figures than the least precisely known value it was built from (1A). A calculation from two-significant-figure data reported to five figures claims a precision the measurement never had.
3. Keep a column of a table internally consistent: the same number of decimal places, or the same number of significant figures, throughout. A column reading 1.2, 1.35, 1.412 mixes three different claims about the same instrument.

Show the unrounded working, then round once at the end, and do not round intermediate values that feed the next step (1A).

Acknowledging references. A report is built from two kinds of material: your own work — the primary data in your logbook and the analysis you performed on it — and material that came from elsewhere: published numbers, quoted or paraphrased sentences, a method adapted from a demonstration, an image or table redrawn from someone else's. The first kind needs no reference — the logbook authenticates it (14F). The second kind must always be acknowledged. To use another person's words, data or ideas without acknowledgement is to present their work as your own, and no report in this course may do that.

The acknowledgement has two parts. At the point of use, in the text, the report names the source briefly; at the end, the reference list gives the full details, so a reader can find and check the source for themselves. This book uses one source-line form throughout, and your reports can use the same:

> *Source: ,
>
> , retrieved .*

For example, the statement in Section 10A that Australia's average temperature has risen by more than $1.5\,°\mathrm{C}$ since national records began in 1910 carries the line

> *Source: Bureau of Meteorology and CSIRO, State of the Climate 2024, retrieved 2026-08-18.*

and the same report appears, in full, in that section's reference list. Every real number you quote from outside your logbook needs such a line. (Your school may prescribe a named referencing style, such as an author–date system; if it does, follow it — the principle is identical, and every entry still answers *who produced it, what it is, where it is, and when you accessed it*.)

Assistance is acknowledged differently from sources. A teacher who checked your circuit, or a classmate who held the metre ruler, is thanked in an acknowledgements sentence — *"the author thanks ..."* — but does not enter the reference list and is never listed as an author of the work. The study design's individual-work requirement stands: the report remains your own.

Key findings. The key findings of an investigation are statements of what the data showed, and they are the heart of the conclusion. A key finding is quantitative — it carries numbers and units — and it answers the investigation question, not a different one. *"The rebound height increased"* is an impression; *"the rebound height increased with drop height, with a rebound ratio of 0.76 across the range* 0.50–$1.50\,\mathrm{m}$*"* is a finding. State the pattern the data showed, give its size, and give the range over which it was shown.

The second dot point of this section asks for the findings **and their relationship to key physics concepts**. That means the conclusion names the concepts of the investigation — the ones identified in the plan (14A) — and says how the findings sit against them:

- the findings are **consistent with** the concept, and here is the numerical agreement;

- the findings **differ from** the concept's prediction, and here is the size of the difference and the most likely cause, from the discussion of error and uncertainty (14E);
- the findings are **inconclusive** for the concept, because the data could not distinguish the prediction from the alternatives.

The same care applies to the hypothesis. The data can **support** a hypothesis or **refute** it (14D); they never *prove* it. A hypothesis that survived one investigation has not been shown true for all systems, all ranges and all times — it has been shown consistent with this evidence. Physics does not work by proof; it works by evidence that has so far held up.

Arguments and limitations. A conclusion is an argument, and a scientific argument has three parts that can always be seen: the **claim** — the position taken on the question; the **evidence** — the specific data, with their numbers and units, that the position rests on; and the **reasoning** — the physics that connects the evidence to the claim. A reader should be able to underline the claim, circle the evidence and follow the reasoning in between. If any of the three is missing, the conclusion is an assertion, not an argument.

Every conclusion also carries its **limitations** — the respects in which it claims less than it might appear to. A limitation can be about scope (this system, this range of the independent variable, these conditions), about the data (their uncertainty, the errors identified in 14E), or about the method (what it could not control). Stating limitations is not a weakness of the report — it is the report showing exactly how far its evidence reaches. The matching skill is to say what **further evidence** would be required to extend the conclusion: more trials, a wider range, a different system, a method with less uncertainty.

Clear, coherent and concise. The study design's final communication skill asks for *clear, coherent and concise expression to communicate to specific audiences and for specific purposes*. In a scientific report that means:

- **Clear**: short, direct sentences, each making one point; every quantity with its unit; every figure and table referred to in the text.
- **Coherent**: the parts in the order the reader needs them, with each part building on the last — the aim reappears in the conclusion, the hypothesis in the discussion, every symbol defined before it is used.
- **Concise**: no word that is not working. Vague descriptions are replaced by the number itself: not *"the speed increased a lot"* but *"the speed increased from* $1.4\ \mathrm{m\ s^{-1}}$ *to* $2.7\ \mathrm{m\ s^{-1}}$*"*.

Two genre habits complete it. Write about what you did in the past tense (*"the cart was released from rest"*) and about established physics in the present tense (*"kinetic energy is proportional to the square of the speed"*). And write for your reader: the report is read by your teacher, who knows the physics and wants to see your evidence and your reasoning — not by a general audience, who would first need the physics explained. The same finding, written for Year 8 students, would use different words and more context; the skill is matching the expression to the audience and the purpose.

Units 3 & 4 preview. The report conventions of this section are assumed, without revision, when you communicate the Unit 4, Area of Study 2 student investigation: the same terminology rules, the same units and significant figures, the same acknowledgement of sources, and the same claim–evidence–reasoning structure. Content under this banner is not assessed in this book's topic tests or practice examinations.

Before you submit: the conventions checklist.

- ☐ The title names the variables and the system.
- ☐ The aim, question, hypothesis, method and conclusion are all present and agree with each other.
- ☐ Key terms are defined at first use, and used one way throughout.
- ☐ The study design's terminology is followed: F_{g}, the normal force, $F_{\text{on A by B}}$.
- ☐ Every figure and table is numbered, captioned and referred to in the text.
- ☐ Graphs: labelled axes with units, appropriate scale, uncertainty bars where the data have them; the origin included only if authentically measured (7B).

- ☐ Every quantity carries its unit; units in the study design's form ($m\ s^{-1}$, $N\ kg^{-1}$, kW h); abbreviations defined at first use.
- ☐ Measurements recorded to the instrument's resolution; calculated results to the least number of significant figures in the data they came from (1A).
- ☐ Every source of information is acknowledged at its point of use and listed at the end; assistance is acknowledged, not cited as authorship.
- ☐ The key findings are stated with numbers and units, and related to the named physics concepts; the hypothesis is supported or refuted, never proven.
- ☐ The limitations of the conclusion are stated, with the further evidence that would extend it.

Worked examples

Example 1 — scaffolded

A student submits this paragraph from the results section of a report on a falling mass:

> *"The mass's weight pulled it down and the reaction force of the air pushed up a bit. It fell from 1.5 M and hit the floor at 5.42216 m/s after 0.5566 seconds. We looked up g on the internet and it was 9.8."*

(a) Identify four breaches of the report conventions of this section.
(b) Rewrite the paragraph so that it follows them.

Working	Comment
Breach 1: "weight" and "reaction force".	The study design's terminology: the force due to gravity is F_g; the upward force of the air is a resistance force, and no force here is a "reaction force" (8C).
Breach 2: "1.5 M" — a capital M is not the symbol for metre.	Unit symbols are standard abbreviations: metre is m, lower case.
Breach 3: "5.42216 m/s" — six significant figures, and the form m/s.	The height was recorded to two significant figures, so the speed cannot support six (1A); the unit takes the study design's form $m\ s^{-1}$.
Breach 4: "g … was 9.8" with no unit and no acknowledgement.	A constant carries its unit, $9.8\ m\ s^{-2}$ (this book's formula-sheet value); anything looked up is secondary information and needs a named source (10A).
Rewritten: *The force due to gravity, F_g, on the mass by the Earth accelerated it downward while air resistance opposed the motion. The mass fell from rest through* $1.5\ m$ *and reached the floor with a speed of* $5.4\ m\ s^{-1}$ *after* $0.55\ s$. *The value* $g = 9.8\ m\ s^{-2}$ *was taken from the formula sheet.*	Terminology, unit symbols, significant figures and acknowledgement corrected in one rewrite.

Example 2 — scaffolded

A student investigates how the release height of a cart on a ramp affects the cart's speed at the bottom (the investigation of Example 2 in Section 14A), with the hypothesis that v^2 is proportional to h. Energy conservation (9C) predicts $1/2\, m v^2 = m g \Delta h$, so $v^2 = 2 g h$: a graph of v^2 against h should be linear with gradient $2g$. The data:

Release height h (m)	0.100	0.200	0.300	0.400	0.500
Speed at the bottom v ($m\ s^{-1}$)	1.36	1.92	2.36	2.73	3.05

(a) Calculate v^2 for each height, to an appropriate number of significant figures.

(b) The line of best fit passes through $(0.100\,\mathrm{m}, 1.85\,\mathrm{m^2\,s^{-2}})$ and $(0.500\,\mathrm{m}, 9.30\,\mathrm{m^2\,s^{-2}})$. Calculate the gradient of the line, with its unit.

(c) Write the key finding of the investigation, and state its relationship to the physics concept being tested and to the hypothesis.

Working	Comment
v^2: $1.36^2 = 1.85$; $1.92^2 = 3.69$; $2.36^2 = 5.57$; $2.73^2 = 7.45$; $3.05^2 = 9.30$ — all in $\mathrm{m^2\,s^{-2}}$.	Three significant figures throughout, matching the three figures of the measurements (1A).
$\text{gradient} = \frac{9.30 - 1.85}{0.500 - 0.100} = \frac{7.45}{0.400} = 18.6\,\mathrm{m\,s^{-2}}$.	Gradient = $\Delta v^2 / \Delta h$, with units $(\mathrm{m^2\,s^{-2}})/\mathrm{m} = \mathrm{m\,s^{-2}}$. The physics relationship supplies the meaning of the gradient (14E).
Expected gradient: $2g = 2 \times 9.8 = 19.6\,\mathrm{m\,s^{-2}}$. Measured: $18.6\,\mathrm{m\,s^{-2}}$, about $5\,\%$ smaller.	The comparison with the prediction is part of the finding; the cause of the difference belongs in the discussion.
Key finding: *v^2 increased linearly with release height, with the line passing near the origin, and the gradient of the v^2–h graph was* $18.6\,\mathrm{m\,s^{-2}}$ *over the range* 0.100–$0.500\,\mathrm{m}$.	Quantitative; names the pattern, the gradient and its unit, and the range of the data.
Relationship: the linear relationship supports the energy-conservation model — v^2 is proportional to h, as $v^2 = 2gh$ predicts — and the hypothesis is supported in form. The measured gradient is $5\,\%$ below $2g$, consistent with some of the gravitational potential energy being transformed into thermal energy and sound by friction (9C).	The finding is stated against the named concept, with the size of the difference and its most likely cause. “Supports”, never “proves”.

Example 3 — unscaffolded

A student writing a report on the physics of climate change (Option 2.1) has used four things from outside their own logbook: one sentence quoted from the Bureau of Meteorology and CSIRO report *State of the Climate 2024*; a set of temperature figures taken from the same report; a method adapted from a class demonstration; and a labelled diagram redrawn from one on a science organisation’s web page. The teacher also checked the student’s measurement arrangement before data collection began.

State how each of these five items must be acknowledged in the report, and write the source line for the report’s data in the form this book uses.

Quoted words need two things: quotation marks at the point of use, so the reader can see exactly which words are not the student’s own, and a reference to the source. The temperature figures are secondary data: the report states them in the text and gives a source line at the point of use —

Source: Bureau of Meteorology and CSIRO, State of the Climate 2024, retrieved 2026-08-18.

— and the report appears again, in full, in the reference list at the end. The adapted method needs one sentence of acknowledgement where the method is described — *“the method was adapted from a class demonstration”* — because a reader must be able to tell which parts of the procedure are the student’s own design and which were taken from elsewhere. The redrawn diagram needs a caption that names its origin — *“Figure 2: … redrawn from , , retrieved ”* — with the full details in the reference list.

The teacher’s help is different in kind: it is assistance, not information. It is acknowledged in an acknowledgements sentence — *“the author thanks …”* — but it does not enter the reference list, and it does not make the teacher an author of the work. The report remains the student’s own, as the study design’s individual-work requirement states.

Example 4 — unscaffolded

A student’s conclusion reads:

> *"Our experiment proves that momentum is always conserved in every collision. There were no errors in our measurements. Newton's laws are true everywhere."*

The investigation was a collision between two trolleys on a straight track: total momentum $0.42\,\text{kg m s}^{-1}$ before the collision and $0.40\,\text{kg m s}^{-1}$ after, with an uncertainty of $\pm 0.03\,\text{kg m s}^{-1}$ on each value (8E).

Identify what is wrong with the conclusion as written, and rewrite it as a correctly limited conclusion for this investigation, including the further evidence that would extend it.

Three things are wrong. First, *proves* and *always* and *every*: one investigation of low-speed collisions between two laboratory trolleys cannot establish a universal claim — the evidence can support the idea, within the conditions tested, and that is all it can do. Second, *there were no errors*: every measurement has uncertainty (14B), and a report that denies its own uncertainty loses the reader's trust; the discussion is where the identified errors and their effects belong (14E). Third, the conclusion does not actually quote the data it rests on — it has a claim and no evidence.

Rewritten, for example:

∴ *The total momentum of the two trolleys was the same, within uncertainty, before and after the collision:* $0.42\,\text{kg m s}^{-1}$ *before and* $0.40\,\text{kg m s}^{-1}$ *after, each* $\pm 0.03\,\text{kg m s}^{-1}$*, so the two uncertainty bars overlap. The finding is consistent with conservation of momentum in an isolated system (8E) and supports the hypothesis. The conclusion applies to low-speed collisions between these trolleys on a level track; friction with the track means the system was not perfectly isolated, which is the most likely cause of the slightly smaller "after" value. To extend the conclusion, the investigation could be repeated with different trolley masses and speeds, and with a lower-friction track.*

The rewrite keeps the claim, adds the evidence with its units and uncertainty, gives the reasoning, states the scope and the limitation, and names the further evidence — every part of a scientific conclusion in about one hundred words.

Practice questions

Question 1 *(scaffolded)* A student writes in their report on a collision between two trolleys (8E):

> *"The first trolley had a weight of 500 grams and rolled at 0.8 M per second into the second trolley. After the collision the trolleys moved together at 0.35714 m/s. Momentum was definitely conserved."*

(a) Identify four breaches of the conventions of this section.
(b) Rewrite the passage so that it follows them.

Question 2 *(scaffolded)* Rewrite each of the following in the unit conventions of this section. (i) 1200 grams (ii) 60 km per hour, in m s^{-1} (iii) 9.8 m/s/s (iv) 4.5 KJ (v) 250 milliamps (vi) *"The Force acting on the block was 12N."*

Question 3 *(scaffolded)* A student measures the mass of a trolley as $0.52\,\text{kg}$ and its speed as $1.846\,\text{m s}^{-1}$, and calculates its kinetic energy from $E_\text{k} = 1/2\,m v^2$ (9C). (a) State the number of significant figures in each measured value. (b) Calculate the kinetic energy, giving your answer to the correct number of significant figures. (c) Explain why the answer should not be given to four significant figures.

Question 4 *(scaffolded)* A student investigating the physics of climate change (Option 2.1) quotes temperature figures from the Bureau of Meteorology and CSIRO report *State of the Climate 2024*, which they accessed on 2026-08-18. (a) Write the source line for this report in the form this book uses. (b) State where the acknowledgement appears in the report, and where the full details appear. (c) The student's measurement method was adapted from a class demonstration. State what the report must say about this, and where.

Question 5 *(scaffolded)* A student investigates whether a resistor is an ohmic device (5D). They plot potential difference V on the vertical axis against current I on the horizontal axis and obtain a straight line through the origin with gradient 4.7. (a) State what the gradient represents, with its unit. (b) Write the key finding of the investigation as one sentence. (c) The student's hypothesis was that the device is ohmic. State whether the finding supports or refutes the hypothesis, with the reason.

Question 6 *(scaffolded)* Rewrite each of the following sentences so that it is concise and quantitative, using the data given. (i) *"The cart went heaps faster when we let it go from higher up."* Data: the speed at the bottom of the ramp was $1.4\ \mathrm{m\ s^{-1}}$ at a release height of $0.100\ \mathrm{m}$ and $2.7\ \mathrm{m\ s^{-1}}$ at a release height of $0.400\ \mathrm{m}$. (ii) *"The globe used a fair bit of power."* Data: the potential difference across the globe was $6.0\ \mathrm{V}$, the current in it was $0.50\ \mathrm{A}$, and $P = V\,I$ (5A).

Question 7 The nine parts of a practical report are listed below in no order: *Discussion; Aim and investigation question; Method; Title; Results; Conclusion; Background physics; Hypothesis and prediction; References and acknowledgements*. Write them in the order this book uses, and state the question that the Discussion and the Conclusion each answer.

Question 8 A student times a cart over a fixed distance five times and records the result as $1.84 \pm 0.06\ \mathrm{s}$. (a) State the smallest and the largest values consistent with this record. (b) Describe how this uncertainty would be shown on a graph that includes this value. (c) The student's model predicted a time of $1.95\ \mathrm{s}$. State whether the prediction is consistent with the measurement within its uncertainty, with the reason.

Question 9 A student writes:

> *"The weight of the block pulled it into the bench and the bench's reaction force pushed back up. We pulled the block with a spring balance, and when our pull beat friction the block sped up."*

Rewrite the passage using the study design's terminology and the $F_{\text{on A by B}}$ labelling convention (8C).

Question 10 The student's ramp investigation of Example 2 found a gradient of $18.6\ \mathrm{m\ s^{-2}}$, below the predicted $2g = 19.6\ \mathrm{m\ s^{-2}}$. Their conclusion reads: *"No energy was lost in our investigation, and the conservation of energy is always true."* (a) Identify two ways this conclusion is inconsistent with the student's own finding. (b) State two further pieces of evidence that would be needed before the conclusion could be extended beyond this investigation.

Question 11 A student investigates the refraction of light entering a perspex block from air (1C), taking the refractive index of air as 1.00. Their hypothesis is that the refractive index of the perspex is 1.50. They plot $\sin\theta_1$ (in air) against $\sin\theta_2$ (in the block); the gradient of the line of best fit is 1.47, with an uncertainty of ± 0.05. Write a claim–evidence–reasoning paragraph stating whether the evidence supports or refutes the hypothesis. Your paragraph must include the calculation that decides the matter.

Question 12 The same investigation can be communicated as a practical report or as a scientific poster. (a) State three ways a poster differs from a report in how it presents the work. (b) State two things that must be the same in both formats.

Question 13 A student's results table is reproduced below.

Trial	mass of cart (g)	Speed (m/s)
1	500	1.2566
2	500	1.3
3	500	1.28

(a) Identify three breaches of the conventions of this section in the table.
(b) Rewrite the table so that it follows them.

Question 14 State whether each of the following must be referenced, acknowledged, or neither, and name the form the acknowledgement takes. (i) A sentence quoted directly from a textbook. (ii) A conclusion paraphrased from a published article. (iii) The student's own primary data, recorded in their logbook. (iv) A diagram downloaded from a website and included in the report. (v) A classmate who held the metre ruler during data collection.

Question 15 A student writes: *"It was found by us that when the release height was made to be bigger, the speed at the bottom also became bigger, and this was basically what we thought would happen before we started."* Rewrite the sentence so that it is clear, coherent and concise.

Question 16 In an investigation of an ohmic device (5D), a student plots V against I and writes: *"the gradient of the graph is 6.8"*. (a) State what is missing from this statement, and give the gradient with its unit. (b) Use the gradient to calculate the current in the device when the potential difference across it is $6.0\,\mathrm{V}$.

Question 17 A student investigates Hooke's Law for a spring (9B) with the hypothesis that *the extension of the spring is proportional to the applied force, for all forces*. The data are linear up to $4.0\,\mathrm{N}$, with a gradient corresponding to $k = 24\,\mathrm{N\ m^{-1}}$, but curve away from the line at larger forces. (a) Use $F = k\,x$ to calculate the extension the linear relationship predicts at a force of $3.0\,\mathrm{N}$. (b) State whether the hypothesis is supported, refuted or supported only within a range, justifying your answer and stating the range.

Question 18 A student investigates how the drop height of a basketball affects its rebound height (the investigation of Question 1 in Section 14A). Over the range $0.50–1.50\,\mathrm{m}$ they find rebound ratios (rebound height ÷ drop height) of 0.77, 0.76 and 0.75. (a) Calculate the mean rebound ratio. (b) Write the conclusion of the investigation in four to six sentences, containing the claim, the evidence, the reasoning (including the energy transformations of the bounce, 9C), one limitation of the conclusion, and one piece of further evidence that would extend it.

Answers

Question 1 (a) e.g. “weight” for a mass; grams; “M per second”; five-figure speed; “definitely conserved” — see solution; (b) see solution. **Question 2** (i) 1.2 kg; (ii) 17 m s^{-1}; (iii) 9.8 m s^{-2}; (iv) 4.5 kJ; (v) 250 mA; (vi) see solution. **Question 3** (a) 2 and 4; (b) 0.89 J; (c) see solution. **Question 4** (a) *Source: Bureau of Meteorology and CSIRO, State of the Climate 2024, retrieved 2026-08-18.*; (b) and (c) see solution. **Question 5** (a) resistance, 4.7 Ω; (b) and (c) see solution. **Question 6** See solution. **Question 7** Title; Aim and investigation question; Background physics; Hypothesis and prediction; Method; Results; Discussion; Conclusion; References and acknowledgements. Questions answered: see solution. **Question 8** (a) 1.78 s and 1.90 s; (b) an uncertainty bar; (c) no — see solution. **Question 9** See solution. **Question 10** (a) and (b) see solution. **Question 11** Rubric-style model paragraph in the fully-worked solutions. **Question 12** (a) and (b) see solution. **Question 13** (a) and (b) see solution. **Question 14** (i) referenced, with quotation marks; (ii) referenced; (iii) neither — authenticated by the logbook; (iv) referenced; (v) acknowledged. **Question 15** See solution. **Question 16** (a) the unit: 6.8 Ω; (b) 0.88 A. **Question 17** (a) 0.13 m; (b) supported only up to 4.0 N — see solution. **Question 18** (a) 0.76; (b) rubric-style model conclusion in the fully-worked solutions.

Fully-worked solutions

Question 1 (a) Any four breaches, for example: *“weight”* is used for what is actually the mass of the trolley — the study design does not use the word weight; the force due to gravity is F_g (8C). *500 grams* — the SI unit of mass is the kilogram: 0.50 kg. *“0.8 M per second”* — the unit symbol for metre is lower case m, and the unit takes the form m s^{-1}. *0.35714* — five significant figures from data given to two; the value must be rounded to two figures. *“definitely conserved”* — a claim of proof; the data can only be consistent with conservation within uncertainty. (b) For example: *The first trolley, of mass* 0.50 kg*, rolled at* 0.8 m s^{-1} *into the second trolley. After the collision the trolleys moved together at* 0.36 m s^{-1}. *The measured momenta are consistent with conservation of momentum within the uncertainty of the measurements (8E).*

Question 2 (i) 1200 g = 1.2 kg — masses are reported in kilograms. (ii) $60\text{ km per hour} = \frac{60 \times 1000}{3600} = 16.66\ldots = 17\text{ m s}^{-1}$ (to two significant figures). (iii) 9.8 m s^{-2} — negative indices, not repeated division. (iv) 4.5 kJ — the prefix kilo is lower case k; the unit symbol joule is capital J. (v) 250 mA. (vi) For example: *The force on the block was* 12 N. — the quantity name is a common noun (lower case), and a space sits between the value and the unit.

Question 3 (a) 0.52 kg has two significant figures; 1.846 m s^{-1} has four. (b) $E_k = 1/2\, m v^2 = 0.5 \times 0.52 \times 1.846^2 = 0.5 \times 0.52 \times 3.4077 = 0.886\text{ J}$, which to two significant figures is 0.89 J. (c) The mass is known to only two significant figures, so a kinetic energy reported to four figures would claim a precision the measurement never had (1A). The result can carry no more significant figures than the least precisely known value it was built from.

Question 4 (a) *Source: Bureau of Meteorology and CSIRO, State of the Climate 2024, retrieved 2026-08-18.* (b) The acknowledgement appears at the point of use — next to the temperature figures in the text — and the report appears in full in the reference list at the end of the report, so a reader can find and check the source. (c) The method section states in one sentence that the method was adapted from a class demonstration, so the reader can tell which parts of the procedure are the student’s own design and which were taken from elsewhere.

Question 5 (a) Since $V = I R$ (5D), the gradient of a V–I graph is the resistance: $4.7\text{ V A}^{-1} = 4.7\ \Omega$. (b) For example: *The potential difference across the resistor increased in proportion to the current in it, with a constant resistance of* 4.7 Ω. (c) Supports. An ohmic device has a constant resistance — R is the same at all currents — and its V–I graph is a straight line through the origin (5D). Both are observed, so the finding supports the hypothesis.

Question 6 (i) For example: *As the release height increased from* 0.100 m *to* 0.400 m*, the speed of the cart at the bottom of the ramp increased from* 1.4 m s^{-1} *to* 2.7 m s^{-1}. (ii) For example: *The globe transferred energy at a rate of* 3.0 W *($P = V I = 6.0 \times 0.50$).* The number replaces the vague description.

Question 7 Title; Aim and investigation question; Background physics; Hypothesis and prediction; Method; Results; Discussion; Conclusion; References and acknowledgements. The Discussion answers *what do the data mean, and how good were the method and the data?* — patterns, outliers, error, uncertainty and limitations (14E). The Conclusion answers *what is the answer to the question, in relation to the physics and the hypothesis?* — the key findings of this section.

Question 8 (a) Smallest: $1.84-0.06=1.78\,\mathrm{s}$. Largest: $1.84+0.06=1.90\,\mathrm{s}$. (b) As an uncertainty bar: a vertical bar centred on the plotted point at $1.84\,\mathrm{s}$, running from $1.78\,\mathrm{s}$ to $1.90\,\mathrm{s}$ (7B, 14E). (c) No. The predicted value $1.95\,\mathrm{s}$ lies above the top of the uncertainty bar ($1.90\,\mathrm{s}$), so it is not consistent with the measurement within its stated uncertainty; the prediction is not supported by this data.

Question 9 For example: *The force due to gravity, F_g — the force on the block by the Earth — acted downward, and the normal force on the block by the bench acted upward, perpendicular to the bench. The spring balance exerted a force on the block along the bench, and a friction force on the block by the bench opposed the motion. When the force of the spring balance exceeded the friction force, the net force on the block was non-zero and the block accelerated (8B).* There is no "reaction force" — the upward contact force is the normal force; and the force due to gravity is F_g, never "weight" (8C).

Question 10 (a) Any two, for example: the finding itself — a measured gradient of $18.6\,\mathrm{m\,s^{-2}}$ against the predicted $19.6\,\mathrm{m\,s^{-2}}$ — shows that some of the gravitational potential energy did not become kinetic energy, so the claim that no energy was lost contradicts the student's own data; and *"always true"* claims more than one ramp investigation can support — the data are consistent with energy conservation in this system, and that is all they can show. (b) Any two, for example: repeating the investigation with different carts and ramp surfaces, to see whether the same pattern holds for other systems; measurements with smaller uncertainty, to reduce the size of the effect that error alone could produce; or a wider range of release heights, to show the pattern holds beyond the range tested.

Question 11 A model paragraph, for example: *The evidence supports the hypothesis that the refractive index of the perspex is* 1.50. *The gradient of the* $\sin\theta_1$*–*$\sin\theta_2$ *graph is the refractive index of the block (1C): by Snell's Law,* $n_1\sin(\theta_1)=n_2\sin(\theta_2)$, *so with* $n_1=1.00$ *for air,* $\sin\theta_1=n_2\sin\theta_2$ *and the gradient equals* n_2. *The measured gradient was* 1.47 ± 0.05, *and the difference between the measured value and the hypothesis value is* $1.50-1.47=0.03$, *which is smaller than the stated uncertainty of* 0.05 *— the hypothesis value lies within the uncertainty bar. The hypothesis is therefore supported, within the uncertainty of the measurement; it is not proven, and values of* n_2 *from about* 1.42 *to* 1.52 *are also consistent with the data.* The paragraph shows all three parts: the claim (supported), the evidence (1.47 ± 0.05, and the 0.03 comparison), and the reasoning (Snell's Law makes the gradient the refractive index).

Question 12 (a) Any three, for example: a poster lays the parts of the report out as titled panels on one page rather than as numbered sections in sequence; it gives more space to figures and tables and less to prose, with the data carrying more of the argument; and it is built to be read standing up in a few minutes, so each panel makes one point and captions stand in for paragraphs. (b) Any two, for example: the conventions of this section apply unchanged — terminology, units, significant figures and acknowledgement of references; and the findings must still be stated in relation to the physics concepts, with the hypothesis supported or refuted and the limitations of the conclusion stated.

Question 13 (a) Any three, for example: the mass is in grams — the SI unit of mass is the kilogram; the Speed column mixes five, two and three significant figures, claiming three different precisions for the same instrument; and the unit is written m/s rather than $\mathrm{m\,s^{-1}}$. (The capital S in the column heading is also a breach: quantity names in headings are common nouns.) (b) For example, with the mass converted and the speeds consistent to three significant figures:

Trial	Mass of cart (kg)	Speed ($\mathrm{m\,s^{-1}}$)
1	0.500	1.26
2	0.500	1.30
3	0.500	1.28

Question 14 (i) Referenced — in quotation marks at the point of use, with the full details in the reference list. Quoted words must always be shown to be someone else's. (ii) Referenced — paraphrasing an idea does not make the idea yours; the source is acknowledged at the point of use and listed at the end. (iii) Neither — the student's own primary

data needs no reference; the dated logbook entry is what authenticates it (14F). (iv) Referenced — the caption names the source of the image, and the reference list gives the full details; an unacknowledged image is someone else's work presented as your own. (v) Acknowledged — in an acknowledgements sentence, not the reference list; assistance is thanked, never cited as authorship.

Question 15 For example: *The speed at the bottom of the ramp increased with release height, supporting the hypothesis.* — one claim, one reason to believe it, no words that are not working.

Question 16 (a) The unit. From $V = I\,R$ the gradient of a V–I graph is the resistance, so the statement should read: *the gradient of the graph is* $6.8\ \mathrm{V\,A^{-1}}$, that is, $6.8\ \Omega$. (b) $I = \frac{V}{R} = \frac{6.0}{6.8} = 0.88\ \mathrm{A}$, to two significant figures (5D).

Question 17 (a) From $F = k\,x$ (9B), $x = \frac{F}{k} = \frac{3.0}{24} = 0.125 = 0.13\ \mathrm{m}$, to two significant figures. (b) Supported only within a range. Up to $4.0\ \mathrm{N}$ the data are linear, which is the proportional relationship the hypothesis predicts — in that range the hypothesis is supported. Beyond $4.0\ \mathrm{N}$ the data curve away from the line, so extension is no longer proportional to force there, and the words *"for all forces"* are refuted by the student's own data. The correctly limited conclusion is: the spring obeys Hooke's Law up to $4.0\ \mathrm{N}$ — the limit of proportionality for this spring lies at about $4.0\ \mathrm{N}$.

Question 18 (a) Mean rebound ratio $= \frac{0.77 + 0.76 + 0.75}{3} = \frac{2.28}{3} = 0.76$. (b) A model conclusion, for example: *The rebound height of the basketball was proportional to its drop height over the range* 0.50–$1.50\ \mathrm{m}$*: the rebound ratio was* 0.77*,* 0.76 *and* 0.75 *at the three heights, a mean of* 0.76*, so about three quarters of the drop height was recovered as rebound height at every height tested. The constant ratio is consistent with a constant fraction of the ball's energy being returned each bounce: gravitational potential energy is transformed into kinetic energy during the fall, and at impact some of the energy is transformed into thermal energy and sound, so the rebound energy — and height — is the smaller (9C). The finding supports the hypothesis within the range tested. The conclusion is limited to this ball on this surface over the heights tested; whether the ratio stays constant at greater drop heights, where the ball deforms more, is not shown by these data. Further evidence — the same investigation with other balls and other surfaces — would show whether the constant ratio is a property of the bounce in general or of this ball and surface.*

Topic 5 Test A — Scientific investigation (multiple choice)

Time allowed: 25 minutes · 20 marks · One scientific calculator permitted · The Physics Units 1 & 2 formula sheet may be used.

Answer **all** questions. Choose the response that is **correct** or that **best answers** the question. A correct answer scores 1; an incorrect answer scores 0. Marks will **not** be deducted for incorrect answers.

Question 1

A student directs a ray of light from air into a rectangular glass block. She measures the angle of incidence and the angle of refraction for several rays, to answer the question: *how does the angle of refraction depend on the angle of incidence?* The independent variable in this investigation is:

A. the angle of refraction.

B. the refractive index of the glass block.

C. the width of the glass block.

D. the angle of incidence.

Question 2

A student investigates how the number of identical resistors connected in series affects the equivalent resistance of the combination. Which one of the following is a controlled variable in this investigation?

A. The number of resistors in the combination.

B. The equivalent resistance of the combination.

C. The potential difference of the power supply used for each measurement.

D. The current in the circuit for each combination.

Question 3

A student models the decay of a radioactive sample by repeatedly rolling one hundred dice and removing every die that shows a six, because the real sample decays too slowly to observe in class time. This methodology is best described as:

A. an experiment.

B. modelling.

C. a simulation.

D. a literature review.

Question 4

Which one of the following is a hypothesis for the investigation *how does the number of identical resistors in series affect the equivalent resistance of the combination?*

A. To measure the equivalent resistance of several series combinations of resistors.

B. The equivalent resistance will increase as more resistors are added, because resistances in series add.

C. How does adding resistors in series change the equivalent resistance of the combination?

D. The equivalent resistance is the single resistance that could replace the combination without changing the current.

Question 5

Which one of the following correctly distinguishes a scientific law from a scientific theory?

A. A law summarises a pattern observed repeatedly in nature, often as a mathematical statement; a theory explains why that pattern occurs.

B. A theory is an unproven law; once a theory is confirmed it is upgraded to a law.

C. A law explains why a pattern occurs; a theory only describes the pattern.

D. A law applies only in laboratories; a theory applies in everyday situations.

Question 6

A balance displays masses to $0.1\,\text{g}$. A student records the mass of a block as $34.65\,\text{g}$. What is wrong with this recording?

A. Nothing — recording extra digits is always good practice.

B. The final digit claims a resolution of $0.01\,\text{g}$ that the balance cannot display.

C. The mass must be recorded in kilograms, not grams.

D. The balance displays to $0.01\,\text{g}$, so one more digit should be recorded.

Question 7

Four students measure a length known to be $200\,\text{mm}$. Their readings, in millimetres, are 196, 197, 196 and 196. These readings are best described as:

A. precise but not accurate.

B. both precise and accurate.

C. accurate but not precise.

D. neither precise nor accurate.

Question 8

In a circuit investigation, every measured current is $0.05\,\text{A}$ greater than the true value. This pattern — the same difference, in the same direction, on every reading — is the signature of:

A. a random error, which affects precision.

B. a systematic error, which affects accuracy.

C. a mistake, which can be removed by averaging.

D. an uncertainty, which sets the resolution of the ammeter.

Question 9

Which one of the following is the best way to reduce the effect of random errors on the mean fall time of a ball?

A. Calibrate the stopwatch against a more accurate clock.

B. Use the largest recorded time, which is closest to the true value.

C. Repeat the measurement several times under the same conditions and average the readings.

D. Change the drop height between trials so that more values are obtained.

Question 10

Two groups determine the speed of water waves in a ripple tank. Group 1 calculates the speed from $v = f\lambda$ using a measured frequency and wavelength; Group 2 measures the time a crest takes to travel a measured distance. Both groups obtain the same speed within the uncertainty of their readings. This agreement is an example of:

A. repeatability.

B. reproducibility.

C. accuracy.

D. validity.

Question 11

A student compares how well two insulating materials keep water warm. She wraps cup A in material X and fills it with $100\,\text{mL}$ of hot water, and wraps cup B in material Y and fills it with $200\,\text{mL}$ of hot water. Cup B stays warmer, and she concludes that material Y is the better insulator. The main weakness of this conclusion is that:

A. the thermometer did not have enough resolution.

B. the cooling times were not repeatable.

C. the temperature readings were not precise.

D. the data are not valid for the question, because the volume of water — a controlled variable — was allowed to change.

Question 12

A student reports the mean fall time of a ball as $0.62\,\text{s}$, with an uncertainty of $0.03\,\text{s}$. Within which interval is the true value expected to lie?

A. $0.59\,\text{s}$ to $0.65\,\text{s}$

B. $0.56\,\text{s}$ to $0.68\,\text{s}$

C. $0.62\,\text{s}$ to $0.65\,\text{s}$

D. $0.59\,\text{s}$ to $0.62\,\text{s}$

Question 13

On a graph, an uncertainty bar stretches from $1.4\,\text{m}$ to $1.8\,\text{m}$, centred on the plotted point. The result is best written as:

A. $1.6 \pm 0.4\,\text{m}$

B. $1.4 \pm 0.4\,\text{m}$

C. $1.8 \pm 0.2\,\text{m}$

D. $1.6 \pm 0.2\,\text{m}$

Question 14

A student plots six points; five lie close to a straight line and one lies well away from it. The first thing the student should do with the point that lies away from the line is to:

A. delete it from the table so that the line fits the remaining points.

B. investigate it — check for a mistake, and repeat the reading if possible.

C. move it onto the line of best fit.

D. draw the line of best fit through that point only.

Question 15

To determine the gradient of a line of best fit, a student should use:

A. any two data points, however close together.

B. the first data point and the origin.

C. one data point and the relationship $y = m x$.

D. two well-separated points that lie on the line of best fit.

Question 16

A trolley moves along a straight track with constant acceleration a. Its speed v is measured at several displacements s from its starting point. To obtain a straight-line graph whose gradient is twice the acceleration, the student should plot:

A. v^2 against s.

B. v against s.

C. s against v^2.

D. v against s^2.

Question 17

A cart of fixed mass is pushed to different speeds v, and its momentum p is found for each speed. A graph of p against v is a straight line. The gradient of the line represents:

A. half the mass of the cart, $1/2\,m$.

B. the speed v of the cart.

C. the mass m of the cart.

D. the net force on the cart.

Question 18

How many significant figures are in the measured value $0.0040\,\text{m}$?

A. 1

B. 2

C. 3

D. 4

Question 19

Which one of the following is the correct practice for recording primary data in a logbook?

A. Copy the readings out neatly at home on the evening of the practical.

B. Record only the mean of each set of repeat readings.

C. Rewrite any messy page before the logbook is submitted.

D. Record the raw readings in the laboratory during the practical, in an entry that is dated and signed.

Question 20

Before beginning a new practical investigation, a student must first:

A. identify the hazards and complete a risk assessment, informed by the safety data sheets for any substances used.

B. write the conclusion, so that the expected result is clear.

C. decide which readings will support the hypothesis.

D. draw the final graph from the predicted results.

Topic 5 Test A — solutions

Question	Answer	Question	Answer
1	D	11	D
2	C	12	A
3	C	13	D
4	B	14	B
5	A	15	D
6	B	16	A
7	A	17	C
8	B	18	B
9	C	19	D
10	B	20	A

Question 1 — D. The independent variable is the quantity the investigator deliberately changes — here the angle of incidence. The angle of refraction is measured in response, so it is the dependent variable (A). The refractive index of the block (B) is fixed for the block, and the width of the block (C) is a controlled variable.

Question 2 — C. A controlled variable is held constant so that any change in the dependent variable can be attributed to the independent variable alone: the supply potential difference must be the same for every measurement. A is the independent variable and B the dependent variable; the current (D) changes as the equivalent resistance changes, so it is not held constant.

Question 3 — C. The dice are a model of the nuclei, and the student runs that model to study the behaviour of a real system that decays too slowly to observe directly — a simulation. An experiment (A) measures the real system itself; modelling (B) is the construction of the representation rather than running it to study the real system; a literature review (D) collates published results.

Question 4 — B. A hypothesis is a testable statement predicting how the variables are related, with the physics reason behind it: B predicts the direction of change and cites the series-resistance rule. A is an aim, C is the investigation question, and D is a definition — a statement of the model, not a prediction to test.

Question 5 — A. A law summarises a pattern observed repeatedly in nature (often as a mathematical statement); a theory explains why the pattern occurs. B is the common misconception that a theory is “upgraded” to a law — they are different kinds of statement; C reverses the roles; D is false.

Question 6 — B. The balance’s resolution is $0.1\,\text{g}$, so a recording of $34.65\,\text{g}$ claims a hundredth of a gram that the instrument cannot display — the final digit is not supported by the resolution, contrary to the significant-figure conventions. Extra digits are never “always good practice” (A); the unit (C) is not the issue; D reverses the resolution.

Question 7 — A. The readings lie within $1\,\text{mm}$ of one another, so they are precise; their mean (about $196\,\text{mm}$) sits about $4\,\text{mm}$ below the true $200\,\text{mm}$, so they are not accurate. The consistent offset is the signature of a systematic error.

Question 8 — B. The same shift, in the same direction, on every reading is the definition of a systematic error; it moves the mean away from the true value, so it affects accuracy. A describes a random error (scatter); C a one-off mistake; D confuses an error with the uncertainty or resolution of the instrument.

Question 9 — C. Random errors push readings unpredictably high and low, so averaging repeats lets the high and low readings cancel and the mean sits closer to the true value. Calibrating the instrument (A) addresses systematic errors; B and D do not reduce random errors.

Question 10 — B. The same quantity was measured under changed conditions — a different group, a different method and different equipment — and the results agree: reproducibility. Repeatability (A) requires the same conditions; accuracy (C) is closeness to the true value; validity (D) is whether the investigation tests what it claims to test.

Question 11 — D. Two things differed between the cups — the insulating material and the volume of water — so the different cooling cannot be attributed to the material alone: a controlled variable was allowed to change, and the data are not valid for the question. Resolution (A), repeatability (B) and precision (C) are properties of readings, not of the design.

Question 12 — A. The result $0.62 \pm 0.03\,\mathrm{s}$ means the true value is expected to lie in the interval from $0.62 - 0.03 = 0.59\,\mathrm{s}$ to $0.62 + 0.03 = 0.65\,\mathrm{s}$. B doubles the uncertainty; C and D apply the uncertainty to one side only.

Question 13 — D. The centre of the bar is the mean: $(1.4 + 1.8)/2 = 1.6\,\mathrm{m}$; the uncertainty is half the bar's length: $(1.8 - 1.4)/2 = 0.2\,\mathrm{m}$. The result is $1.6 \pm 0.2\,\mathrm{m}$. A uses the full length of the bar as the uncertainty; B and C centre the interval on the wrong value.

Question 14 — B. An outlier must be investigated and accounted for, not automatically dismissed: check it for a mistake and repeat the reading if possible. Deleting it (A) or moving it (C) falsifies the record; drawing the line through it alone (D) lets one suspect point control the whole analysis.

Question 15 — D. The gradient is determined from two well-separated points that lie on the line of best fit. Data points scatter about the line (A), and the origin may be used only if it is an authentically measured point (B); one point cannot fix a gradient (C).

Question 16 — A. For constant acceleration, $v^2 = u^2 + 2as$ is linear in v^2 and s, with gradient $2a$. Plotting v against s (B) gives a curve; C swaps the axes, giving a gradient of $1/(2a)$; D does not linearise the relationship.

Question 17 — C. Since $p = mv$ and m is constant, p is linear in v with gradient m. Half the mass (A) is the gradient of an E_k against v^2 graph; the speed (B) changes from point to point; the net force (D) is not part of this relationship.

Question 18 — B. Leading zeros are not significant; a trailing zero to the right of the decimal point is significant. In 0.0040, only the 4 and the final 0 are significant: two significant figures.

Question 19 — D. Primary data are recorded in the logbook during the practical, as they are taken, in an entry that is dated and signed — that is what lets the data be authenticated. Copying up later (A), recording means only (B) and rewriting pages (C) all weaken the record.

Question 20 — A. The risk assessment — informed by the safety data sheets for any substances in use — must be completed before practical work begins. Writing the conclusion first (B) invites bias, and C and D describe dishonest practice.

Topic 5 Test B — Scientific investigation (written responses)

Time allowed: 50 minutes · 40 marks · One scientific calculator permitted · The Physics Units 1 & 2 formula sheet may be used. In questions where more than one mark is available, appropriate working must be shown.

Answer **all** questions in the spaces provided. Give final answers to an appropriate number of significant figures.

Question 1 (5 marks)

A student has a set of identical resistors, each of resistance R. She plans to investigate how the number of resistors connected in series affects the equivalent resistance of the combination.

a. Write the aim of the investigation. 1 mark

b. Write a hypothesis for the investigation, including the physics reason on which it is based. 2 marks

c. Identify the independent variable and the dependent variable, and state two controlled variables for this investigation. 2 marks

Question 2 (6 marks)

Water boils freely in an open beaker at sea level. The accepted temperature of freely boiling water is $100\,^{\circ}\mathrm{C}$. Two groups of students each measure the temperature of the boiling water four times, using their own thermometer. Their readings, in °C, are:

Group	Readings (°C)
A	$97.6, 97.8, 97.6, 97.8$
B	$99.2, 100.8, 99.6, 100.4$

a. Calculate the mean temperature for each group. 2 marks

b. Identify, with reasons, which group's readings are precise but **not** accurate. Refer to both the spread of the readings and the accepted value in your answer. 2 marks

c. For each group, identify the kind of error — random or systematic — that best accounts for the pattern of the readings, and state which of accuracy and precision that kind of error affects. 2 marks

Question 3 (4 marks)

A micrometer allows readings to $0.01\,\mathrm{mm}$. A student uses it to measure the diameter of a length of resistance wire.

a. State the resolution of the micrometer, and explain why recording a diameter of $0.5125\,\mathrm{mm}$ is not justified. 2 marks

b. Classify each of the following as a test of **repeatability** or of **reproducibility**.

i. The student measures the same wire again, immediately, at the same bench, with the same micrometer.

ii. A student at another school measures the same wire with a different micrometer. 2 marks

Question 4 (6 marks)

A student investigates the decay of a radioactive source with a detector that records the count rate. Even with no source present, the detector records a background count rate of 20 counts per minute. The student's measured count rates are:

Time t (min)	0	2	4	6	8
Measured count rate (counts min^{-1})	822	418	221	118	70

a. After correcting for the background, determine the half-life of the source from the data. 1 mark

b. The readings scatter slightly about a smooth pattern even though the conditions did not change. Explain why this scatter is expected for radioactive decay. 1 mark

c. Suppose the student forgets to subtract the background count rate. Classify the effect on the readings as a random or a systematic error, and state which of accuracy and precision it affects. 2 marks

d. State one action that corrects for the background, and one action that reduces the scatter of the readings. Match each action to the problem it addresses. 2 marks

Question 5 (8 marks)

A cart is set moving along a straight, level track. It slows with constant acceleration as it moves because of friction. Its speed v is measured by video analysis at several displacements s from the starting point. Each displacement reading has an uncertainty of $\pm 0.02\,\text{m}$.

Displacement s (m)	0.00	0.40	0.80	1.20	1.60	2.00
Speed v (m s^{-1})	1.20	1.10	0.86	0.85	0.69	0.49

Five of the six points follow a straight-line pattern when v^2 is plotted against s; one point lies well away from the pattern.

a. The motion has constant acceleration a, so $v^2 = u^2 + 2as$, where u is the initial speed. Explain why a graph of v^2 against s is expected to be a straight line, and state what the gradient and the vertical intercept of the line represent. 2 marks

b. Copy the table and add a row of values of v^2 in $\text{m}^2\,\text{s}^{-2}$. 2 marks

c. Identify the outlying point and state how it should be treated in the analysis. Then, using two well-separated points on the line of best fit, determine the gradient of the line and hence the acceleration of the cart. 2 marks

d. Use the intercept of the line to determine the initial speed u of the cart. 1 mark

e. State how the uncertainty of $\pm 0.02\,\text{m}$ in each displacement reading is shown on the graph of v^2 against s. 1 mark

Question 6 (5 marks)

The logbook entry for the investigation of Question 5 contains the following:

- (i) the raw speed readings, recorded in the laboratory during the practical;
- (ii) the entry is dated and signed;
- (iii) one reading has been rubbed out and a different value written in its place;
- (iv) a note, written at the time, explains that the video camera was moved closer to the track for the last two trials.

a. Identify **two** of the numbered features that support the authentication of the primary data. 2 marks

b. Explain why feature (iii) weakens the authentication of the data, and state what the student should have done instead. 2 marks

c. State the requirement the study design makes of the logbook for satisfactory completion of Units 1–4. 1 mark

Question 7 (6 marks)

A group of students model the decay of a radioactive sample with 100 dice. They roll all the dice, remove every die that shows a six, and record the number N remaining. They repeat the process for six throws. The results are:

Throw number n	0	1	2	3	4	5	6
Number N remaining	100	84	69	58	49	41	34

a. A student writes: *"After 3 throws, 58 dice remain, so the half-life of the model is 3 throws."* Evaluate this claim using the data. 2 marks

b. State one limitation of the data or of the method, and state its effect on the half-life determined from these results. 2 marks

c. State one way in which this model represents real radioactive decay well, and one way in which it differs from the decay of a real radioactive sample. 2 marks

Topic 5 Test B — solutions

Question 1 (5 marks)

a. (1 mark) Aim: *to investigate how the number of identical resistors connected in series affects the equivalent resistance of the combination.* The aim names both variables and the system; it is not a method and not a hypothesis.

b. (2 marks) Hypothesis: *"If more identical resistors are added in series, then the equivalent resistance of the combination will increase, because resistances in series add —* $R_{\text{equivalent}} = R_1 + R_2 + \ldots$ *— so each resistor added contributes its own resistance to the total"* [1 for a testable prediction naming both variables; 1 for the physics reason based on the series-resistance relationship].

c. (2 marks) Independent variable: the number of resistors in the series combination; dependent variable: the equivalent resistance of the combination, measured as the ratio of potential difference to current ($R = V / I$) or with a multimeter [1]. Controlled variables — any two, for example: the same set of identical resistors (same value of R each); the same power supply, so the potential difference is the same for each measurement; the same meters; readings taken quickly so the temperature of the resistors does not change [1].

Question 2 (6 marks)

a. (2 marks) Mean of group A:

$$\frac{97.6+97.8+97.6+97.8}{4} = \frac{390.8}{4} = 97.7\,^{\circ}\text{C}[1].$$

Mean of group B:

$$\frac{99.2+100.8+99.6+100.4}{4} = \frac{400.0}{4} = 100.0\,^{\circ}\text{C}[1].$$

b. (2 marks) Group A's readings are precise but not accurate. The four readings lie within $0.2\,^{\circ}\text{C}$ of one another — a small spread about their mean, so they are precise [1]; but the mean, $97.7\,^{\circ}\text{C}$, is $2.3\,^{\circ}\text{C}$ below the accepted $100\,^{\circ}\text{C}$, so they are not close to the true value and are not accurate [1].

c. (2 marks) Group A: a **systematic error** — a consistent offset shifts every reading in the same direction by about the same amount; systematic errors affect **accuracy**, not precision [1]. Group B: **random error** — the readings scatter above and below the mean; random errors affect **precision**, not accuracy (the mean is on the accepted value) [1].

∴ group A is precise but not accurate (systematic error, affecting accuracy); group B is accurate on average but not precise (random error, affecting precision).

Question 3 (4 marks)

a. (2 marks) The resolution of the micrometer is $0.01\,\text{mm}$ [1]. Recording $0.5125\,\text{mm}$ is not justified because the final digit claims a ten-thousandth of a millimetre — one hundredth of the smallest change the instrument can display — so it pretends to more precision than the measurement has, contrary to the significant-figure conventions of 1A [1].

b. (2 marks) (i) **Repeatability** — the same observer measures the same quantity again with the same instrument, at the same location, over a short time: the conditions are unchanged [1]. (ii) **Reproducibility** — the measurement is carried out under changed conditions: a different observer and a different instrument [1].

Question 4 (6 marks)

a. (1 mark) Corrected count rates (measured -20), in counts min^{-1}: $802, 398, 201, 98, 50$. The count rate falls from about 800 to about 400 in the first $2\,\text{min}$, from about 400 to about 200 in the next $2\,\text{min}$, and again from about 200 to about 100 and from about 100 to about 50 every $2\,\text{min}$ after that: the count rate halves every $2\,\text{min}$, so the half-life is about $2.0\,\text{min}$.

b. (1 mark) Radioactive decay is random: which nucleus decays in any interval cannot be predicted. Even under unchanged conditions, the number of decays in each equal interval varies slightly, so the count rate scatters about the smooth decay pattern.

c. (2 marks) Without the subtraction, every reading is $20\,\text{counts min}^{-1}$ too high — the same shift, in the same direction, on every reading: a **systematic error** [1]. It affects **accuracy** (every reading, and any half-life read from the raw values, is shifted from the true value) but not **precision** (the scatter of the readings is unchanged) [1].

d. (2 marks) Subtract the background count rate — measured with the source removed — from every reading: this removes the systematic offset [1]. Repeat each reading and average, or count for a longer time at each point: this reduces the effect of the random scatter, because the random variations tend to cancel in the mean [1].

Question 5 (8 marks)

a. (2 marks) With constant acceleration, $v^2 = u^2 + 2as$ has the form of a straight-line relationship — $y = \text{intercept} + \text{gradient} \times x$ — with $y = v^2$ and $x = s$; since u and a are constants, a graph of v^2 against s is expected to be a straight line [1]. The gradient of the line is $2a$ (twice the acceleration), and the vertical intercept is u^2 (the square of the initial speed) [1].

b. (2 marks) Squaring each speed:

Displacement s (m)	0.00	0.40	0.80	1.20	1.60	2.00
v^2 ($m^2 s^{-2}$)	1.44	1.21	0.74	0.72	0.48	0.24

[2 for all six values correct; 1 for one error.] (The point at $s = 0.00\,\text{m}$ is an authentically measured reading — the speed at the start — so it may be plotted as a data point: the origin is included as a data point only if authentically measured.)

c. (2 marks) The point at $s = 0.80\,\text{m}$ ($v^2 = 0.74\,\text{m}^2\,\text{s}^{-2}$) is the outlier: the other points fall by about $0.24\,\text{m}^2\,\text{s}^{-2}$ for each $0.40\,\text{m}$ step, while this point breaks that pattern. It must not be quietly deleted: it should be investigated — checked for a mistake, and the reading repeated if possible; if the repeat shows a mistake, the reading is redone correctly and the change recorded in the logbook; if no cause is found, the point stays plotted, the line is drawn from the other points, and the decision is stated [1]. Using two well-separated points on the line of best fit — the remaining points lie on the line, so the end points $(0.00, 1.44)$ and $(2.00, 0.24)$ may be used:

$$\text{gradient} = \frac{\Delta v^2}{\Delta s} = \frac{0.24 - 1.44}{2.00 - 0.00} = \frac{-1.20}{2.00} = -0.60\,\text{m s}^{-2}.$$

Since gradient $= 2a$:

$$a = \frac{-0.60}{2} = -0.30\,\text{m s}^{-2} [1].$$

The negative sign shows the cart is slowing: its acceleration is $0.30\,\text{m s}^{-2}$ opposite to its motion.

d. (1 mark) The vertical intercept is $u^2 = 1.44\,\text{m}^2\,\text{s}^{-2}$, so

$$u = \sqrt{1.44} = 1.2\,\text{m s}^{-1}.$$

e. (1 mark) Each displacement uncertainty is shown as a **horizontal uncertainty bar** centred on the plotted point, stretching $0.02\,\text{m}$ either side of it — a total length of $0.04\,\text{m}$ along the displacement axis — drawn because the uncertainty is given numerically.

Question 6 (5 marks)

a. (2 marks) Any two of the following [1 each]:

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(i) the raw readings were recorded during the practical, as they were taken — not copied up or reconstructed afterwards;

•

(ii) the entry is dated and signed, fixing when it was made and who made it;

•

(iv) the change to the method (the camera position) was noted at the time it happened, so the record shows exactly what was done.

b. (2 marks) Rubbing out the reading destroys the original record: no one can see what was first written or check the change, so the data can no longer be audited or authenticated [1]. The student should have ruled a single line through the incorrect value so that it remained legible, written the corrected reading alongside it, and noted the reason for the change [1].

c. (1 mark) The logbook is submitted as a requirement for satisfactory completion in each of Units 1 to 4 (it is maintained for recording, authentication and assessment purposes).

Question 7 (6 marks)

a. (2 marks) The claim is not supported by the data [1]. After 3 throws, 58 of the original 100 dice remain — more than half — so fewer than half the dice have "decayed" and the sample has not yet halved. N passes 50 between throw 3 (58) and throw 4 (49), so the half-life of the model lies between 3 and 4 throws, not at 3 throws [1].

b. (2 marks) For example: only whole throws are recorded, so the half-life can be located only between two whole throws — the throw at which N reaches exactly 50 cannot be resolved, and the half-life determined from these data carries an uncertainty of about one throw [1 for the limitation, 1 for its effect]. Alternatively: this is a single run with 100 dice; decay is random, so a second run would pass $N = 50$ at a slightly different throw, and a single run is a weak estimate of the half-life [1 + 1].

c. (2 marks) One way the model represents real decay well: each die has a fixed probability (one in six) of "decaying" on every throw, and which dice go is random — like real nuclei, which decay randomly with a fixed probability per unit of time, so that the number remaining halves over equal intervals [1]. One way it differs: the model decays in discrete throws rather than continuously in time (the dice can also be reset and reused, unlike real nuclei; and the model's decay probability is chosen by the rules of the game, while a real isotope's is fixed) [1].