UNIVERSITY *of* CAMBRIDGE
International Examinations

Cambri
Pre-U

Teacher Guide

Cambridge Pre-U
Physics
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Cambridge Advanced

Contents

Introduction

The main purpose of this Teacher Guide is to support teachers in their delivery of the syllabus so that their students can achieve well and enjoy their learning.

The intention is not to instruct colleagues how to teach, more it is the case of sharing experiences so that teachers, especially those new to the profession, will have some indication of the timescale for the teaching of each section, will be made aware of opportunities for presentations, practical tasks and those occasions when, for example, the historical and philosophical dimensions can best be focused upon. Guidance on investigations, different styles of exam papers and suggested experiments, resources and booklist also feature.

The main thrust of this Teacher Guide is in the teaching and suggestion notes that appear alongside the syllabus details. They pinpoint the main pitfalls and common errors that students can make. Often these are mathematical in nature or arise from difficulties in understanding. It is hoped that highlighting these will help colleagues be forewarned and thus be better able to prepare more effective lessons. Students of physics also vary considerably in their mathematical skills and so the notes make particular reference to the application of those skills, and draw references to Appendix 1 of the syllabus.

It is hoped that you will find the Teacher Guide supportive, informative and useful.

Practical skills

Practical work throughout the year should develop the range of skills listed below as a minimum. We would expect Centres to extend beyond these skills according to the equipment they have available, for example, light gates, coulombmeters, joulemeters, sensors, etc.

1. Use of apparatus

- common circuit components
- data logger
- digital top-pan balance or other balance
- measuring cylinder
- metre rule
- micrometer screw gauge
- multimeter (to measure resistance, voltage or current)
- newton meter
- oscilloscope (to measure time or voltage)
- stopwatch
- thermometer
- variable resistor
- vernier callipers

2. Practical techniques

- assessing risks to themselves and others
- avoiding parallax
- calibration of a measuring instrument
- fiducial marker
- identifying and dealing with zero errors

3. Data processing

- data processing using a spreadsheet
- determining the uncertainty in a final result
- estimating uncertainties in measured quantities
- graph plotting
- identifying the physical significance of the gradient or y-intercept of a graph
- repetition and averaging of readings
- tabulating data (including units, decimal places and significant figures)

Suggested teaching order

Exemplar Teaching Order A – set shared by two teachers

Lower Sixth (Year 12)			
Taught by Teacher A	**Practical skills tasks**	**Taught by Teacher B**	**Practical skills tasks**
Term 1 (September – December)			
A1 Mechanics A2 Gravitational fields A4 Energy concepts 10 weeks	Measurements circus Spreadsheet modelling Datalogging	A5 Electricity 6 weeks	Electrical measurements Datalogging
A3 Deformation of solids 4 weeks	e.g. measuring Young Modulus/dealing with uncertainties	A6 Waves A7 Superposition 8 weeks	e.g. measuring wavelength of light/dealing with uncertainties
Interim examination (end of 1st term or start of 2nd term) 1 week			
Term 2 (January – March)			
A8 Atomic and nuclear A9 Quantum ideas 10 weeks		B11 Oscillations B10 Rotational mechanics 10 weeks	e.g. testing relationships/graphical work, video capture/motion sensing
Term 3 (April – July)			
B15 Special relativity 2 weeks		B19 Interpreting quantum theory 2 weeks	
Mini-investigations (preparation for Part B individual projects) 2 weeks			
Revision and interim examinations: Papers 1 and 2 (Part A material) 2 weeks			

Comments

- The timings given are approximate. The total time allocated in the first year of this scheme is 32 weeks.

- This exemplar order teaches significantly more than the Part A material in the Lower Sixth. This is recommended as Part B will be time-consuming.
- Section A8 could be expanded to include exponential decay, absorption and the inverse-square law from B17.
- The Practical skills tasks listed here are merely suggestions of the type of activity that could accompany each teaching topic. They are neither compulsory nor exhaustive.
- Students to undertake mini-investigations after being presented with open-ended research questions by their teachers. Use the mini-investigations to encourage an investigative approach throughout the course, in preparation for the practical Investigation in the Upper Sixth. Students write up their mini projects as if they were Practical Investigations, and receive a mark based on a reduced set of investigation criteria.

Upper Sixth (Year 13)	
Taught by Teacher A	**Taught by Teacher B**
Term 1 (September – December)	
B16 Molecular kinetic theory 6 weeks	B13 Gravitation 4 weeks
	B12 Electric fields 4 weeks
B17 Nuclear physics 6 weeks	B14 Electromagnetism 4 weeks
Personal Investigation Part 1 Preparation for investigation: proposal, pilot and planning. 1 week	
Term 2 (January – March)	
Personal Investigation Part 2 2 weeks	
B20 Astronomy and cosmology (and revisit B15) 6 weeks	B18 The Quantum atom (and revisit B19) 6 weeks
Studying pre-release material and carrying out relevant linked research 1 week	
Term 3 (April – July)	
Revision and trial papers 3 weeks	
Mock exams	

Comments

- The timings are approximate. The total time allocated in the second year of this scheme is 25 weeks.
- The planning for the Practical Investigation should take place early in the spring term.
- The Practical Investigations are marked 'blind' by both teachers, who then meet to compare marks and decide the final awarded mark.

Exemplar Teaching Order B – set taught by one teacher

Lower Sixth (Year 12)		
Time/ weeks	**Sequence**	**Outline of content**
Term 1 (September – December)		
3	1–5 in any order	A1 Mechanics
1		A2 Gravitational fields
1½		A3 Deformation of solids
1½		A4 Energy concepts
3		A5 Electricity
2		A6 Waves
2		A7 Superposition
Term 2 (January – March)		
2	9, 10, 15, 19 in any order	A9 Quantum ideas
1		B15 Special relativity
3		A8 Atomic and nuclear
3		B11 Oscillations
Term 3 (April – July)		
3		B10 Rotational mechanics
1		B19 Interpreting quantum theory
2		Mini-investigations
2		Revision + interim examination (Papers 1 + 2) + feedback
32 weeks total for Lower Sixth (Year 12)		

- Timings are approximate.

Upper Sixth (Year 13)		
Time/ weeks	**Sequence**	**Outline of content**
Term 1 (September – December)		
2	12 and 13 in any order	B12 Electric fields
2		B13 Gravitation
2	Electromagnetism before investigations as it may offer inspiration for projects	B14 Electromagnetism
4		B16 Molecular kinetic theory
1	Sensible to leave a gap (e.g. holiday) between Part 1 and Part 2	Personal Investigation Part 1 Preparation for investigation: proposal, pilot and planning
Term 2 (January – March)		
2		Personal Investigation Part 2 Two weeks of practical
3	17, 18, 20 in any order	B17 Nuclear physics
1½		B18 The quantom atom
2½		B20 Astronomy and cosmology
Term 3 (April – July)		
1		Pre-release material from exam board, Paper 2. The material will draw on physics concepts from Part A of the content but will expand to applications beyond the curriculum. The material will be made available electronically to schools that have submitted final Cambridge Pre-U Physics examination entries; teachers should then download the material and distribute to their pupils. Some lesson time should be devoted to data analysis and discussion work providing stimulus for pupils to explore the ideas further in their own time.
3		Trial/practice/mock papers, feedback and revision
24 weeks total for Upper Sixth (Year 13)		
Mock examinations at the end of Term 1 or the beginning of Term 2; a second mock at the end of the teaching time.		

Teaching notes and suggestions

Syllabus A1: Mechanics Topic: vectors and scalars/moments	
Learning objectives 1.1 distinguish between scalar and vector quantities and give examples of each 1.2 resolve a vector into two components at right angles to each other by drawing and by calculation 1.3 combine any number of coplanar vectors at any angle to each other by drawing 1.4 calculate the moment of a force and use the conditions for equilibrium to solve problems (restricted to coplanar forces)	**Notes** • Represent vectors as arrows. • Start with displacement but include velocity and force. • Sections 1.2 and 1.3 lead naturally into equilibrium of forces (1.4) and effects of resultant forces (1.12) and examples drawing on material in these sections could be introduced at this stage. • It is worth introducing *torque* since this will be used in Section 10 (Rotational dynamics 'mechanics'). • The idea of a couple as a moment with no resultant force is useful to illustrate the distinction between resultant force and resultant turning effect.
	Mathematical skills It may well be worth reviewing simple trigonometry (sine/cosine/tangent in particular) before starting to resolve vectors. [See Appendix 1. Mathematical Requirements Part A 11]* An object subject to **two** forces can only move in **one** direction. Vector addition finds the one force equivalent that would cause this motion. Competent mathematicians should be encouraged to **calculate** resultant vectors in 1.3 (but should also be able to use scale drawings) It is worth pointing out that equilibrium of coplanar forces and moments involves three independent simultaneous equations (resolving in two perpendicular directions and taking moments about one point) so up to three unknown quantities can be evaluated. Intelligent choice of axes (when resolving) and pivot (when taking moments) can simplify calculations. An object in equilibrium is not rotating about **any** point and so moments can be taken about any point at all.

* Subsequent references to the Appendix 1. Mathematical Requirements will be abbreviated to A1, B7, etc.

Syllabus A1: Mechanics

Topic: kinematics

Learning objectives

1.5 construct displacement/time and velocity/time graphs for uniformly accelerated motion

1.6 identify and use the physical quantities derived from the gradients of displacement/time and areas and gradients of velocity/time graphs, including cases of non-uniform acceleration

1.7 recall and use the expressions

$$v = \frac{\Delta x}{\Delta t}$$

$$a = \frac{\Delta v}{\Delta t}$$

1.8 recognise and use the kinematic equations for motion in one dimension with constant acceleration:

$$s = ut + \frac{1}{2}at^2$$

$$v^2 = u^2 + 2as$$

$$s = \left(\frac{u + v}{2}\right)t$$

Notes

Use a variety of experimental techniques to capture, display and analyse motion:

- metre rule and clock
- position sensor and datalogger
- video capture
- stroboscope

Simple iterative techniques (using Excel) could be introduced.

Mathematical skills

The approach and level of treatment here will depend on the ability of the students. For those who are less confident with the mathematics, a geometric approach is fine and the equations can be derived from simple velocity time graphs of constant acceleration.

Weaker students struggle with rates of change and it is worth investing time now to ensure they have a good grasp of this concept and of its link to gradients. (A24)

It is also worth reminding weaker students how to rearrange formulae.

This is a good place to introduce increments (Δx, Δt, etc.) and to consider the gradient (albeit qualitatively) as a limit.

More confident students will appreciate the early introduction of calculus, and gradients and areas give an ideal opportunity to use differential and integral calculus in a familiar context. (A24)

<table>
<tr><th colspan="2">Syllabus A1: Mechanics

Topic: projectiles</th></tr>
<tr><td rowspan="2">Learning objectives
1.9 recognise and make use of the independence of vertical and horizontal motion of a projectile moving freely under gravity</td><td>Notes
• This section could be delayed until Newton’s laws of motion have been introduced.
• Include a ‘monkey and hunter’ style demonstration.
• Model ideal projectile motion and compare it experimentally to real projectiles.
• An irregular plastic laminar with a lit LED at its centre of mass (CoM) can be thrown (in a dark room) to show that the path of the CoM can be treated as the path of a particle.
• The effects of drag are better left until Newton’s Laws have been discussed, but can then be modelled using an iterative approach or using software such as <i>Modellus</i>.</td></tr>
<tr><td>Mathematical skills
This work links to the addition and resolution of vectors in 1.2 and 1.3 and to the use of the ’suvat’ equations in 1.8.
It is important to emphasise that 2-D motion can be split into two separate 1-D problems because of the independence of perpendicular components of motion.
Algebraic manipulation and simple trigonometry may prove challenging for some and it is worth providing opportunities to practise these with plenty of problems. (A15, A16)
Most students ought to be able to handle a simple derivation of ideal parabolic motion in the absence of friction.</td></tr>
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Syllabus A1: Mechanics

Topic: Newton's laws of motion

Learning objectives

1.10 recognise that internal forces on a collection of objects sum to zero vectorially

1.11 recall and interpret statements of Newton's laws of motion

1.12 recall and use the relationship $F = ma$ in situations where mass is constant

1.13 recall and use the independent effects of perpendicular components of a force

Notes

1.10 can be linked to Newton's 3rd law and explains why it is impossible to 'pick yourself up by your bootlaces'. The idea of 'internal forces' also helps define 'resultant force' which is necessarily an 'external' force.

- Any accurate statements that capture the meaning of the laws of motion are acceptable.
- Students often find it difficult to accept that objects moving with constant velocity experience zero resultant force – this needs plenty of discussion.
- Newton's 2nd Law should used to define the Newton as the SI unit of force.
- Make sure that 'changing velocity' includes change of direction as well as magnitude.
- Newton's 3rd law is subtle and may be better expressed as: 'If A exerts a force on B then B exerts an equal and opposite force on A'. Action/reaction forces are two ends of an interaction and always act on different bodies. Consideration of Newton's 3rd law leads to conservation of momentum rules.
- Examples of vehicles on hills and the acceleration of pendulum bobs can be used to illustrate 1.13. A good simple experiment is to plot the acceleration of a trolley against the sine of the angle of slope of a runway and use this to make a graphical estimate for g.

Mathematical skills

Action and *reaction* are words to avoid. Beware of the word *reaction*. This is also used to describe the force from a surface on an object in contact with it (which is fine) but the action force producing this reaction is then the contact force acting on the surface from the body, **not** the weight of the body.

The words *action* and *reaction* in the context of physics should be reserved for Newton pairs where the pair contains forces of the same type and equal and opposite in size and direction; Newton pairs are pairs of forces arising from the same field.

Syllabus A1: Mechanics

Topic: conservation of linear momentum

Learning objectives

1.14 recall and use the expression $p = mv$ and apply the principle of conservation of linear momentum to problems in one dimension

1.15 distinguish between elastic and inelastic collisions

1.16 relate resultant force to rate of change of linear [not in syllabus] momentum in situations where mass is constant and recall and use

$$F = \frac{\Delta p}{\Delta t}$$

1.17 recall and use the relationship impulse = change in momentum

1.18 recall and use the fact that the area under a force-time graph is equal to the impulse

1.19 be able to apply the principle of conservation of linear momentum to problems in two dimensions

Notes

- It is important to distinguish momentum as a vector from kinetic energy as a scalar.
- Show how the law of conservation of linear momentum can be derived from Newton's laws (with the 3rd law crucial).
- Relate conservation of linear momentum to vehicle propulsion e.g. propellers, wheels, walking, jets and rockets (again linking to Newton's 3rd Law).
- Momentum is inevitably conserved in all collisions (elastic and inelastic) but KE may or may not be conserved (if it is, this then defines an elastic collision). An explosion can be thought of as a super-elastic collision – KE is injected into the situation.
- Plenty of examples from sport for impulse and momentum change.
- Rocket launches can be used to analyse the motion resulting from a specific initial impulse.
- Model rockets with digital altimeters are now available and can be used to check predictions of altitude etc. based on separate measurements of impulse when a model rocket motor is attached to a force sensor (using a suitable jig).

Mathematical skills

If increments and differentials were used before they can be reinforced here. Graphs of force vs time for bats hitting balls are interesting to interpret and can be investigated experimentally using force sensors. (A18, B10)*

2D momentum conservation should be used to revisit and reinforce ideas about resolution and addition of vectors. It also provides practise in algebra and trigonometry.

**Teachers may wish to use mathematical skills and concepts from Part B but students will only be examined on Part B in Paper 3.*

Syllabus A1: Mechanics

Topic: pressure

Learning objectives

1.20 recall and use the relationship $density = \frac{mass}{volume}$

1.21 recall and use the relationship $pressure = \frac{normal\ force}{area}$

1.22 recall and use the relationship $p = \rho gh$ for pressure due to a liquid

Notes

For many 1.19 will be revision.

- The equation for liquid pressure is useful and should be derived – this will involve ideas of density and weight.
- Pressure is a scalar whereas force is a vector; pupils often say things like ‘the direction in which the pressure acts’, which is incorrect.
- You might wish to consider simple ideas about liquid flow and to relate these to Newton’s laws – e.g. the need for a pressure difference where flow velocity increases (linked to $F = ma$) and therefore the drop in pressure inside the narrower parts of a tube.
- The change in flow rate from a leaking bucket can be considered qualitatively or experimentally and provides an early introduction to exponential change.
- A digression into how pressure is measured might be rewarding – including aneroid and mercury barometers, manometers, Bourdon Gauge and electronic pressure sensors linked to datalogging equipment.

Mathematical skills

Conversion of units can be practised here – e.g. converting N mm^{-2} to kPa. It is also a useful place to encourage the use of scientific notation. (A6, A4)

Don’t get bogged down with mathematical models of pressure variation in the Earth’s atmosphere – this is better left until the students are confident with exponentials and with the gas laws.

Syllabus A2: Gravitational fields

Topic: field strength and weight

Learning objectives

2.1 recall and use the fact that the gravitational field strength g is equal to the force per unit mass and hence that weight $W = mg$

2.2 recall that the weight of a body appears to act from its centre of gravity

2.3 sketch the field lines for a uniform gravitational field (such as near the surface of the Earth)

2.4 explain the distinction between field strength and force and explain the concept that a field has independent properties

Notes

- Relate $W = mg$ to $F = ma$ (1.12). Worth restating that weight is pull by Earth on mass m acting towards the centre of the Earth.
- 'Weight' might lead to a discussion of 'weightlessness'. Many students think that outside of Earth's atmosphere, gravity vanishes (They've all seen pictures from the shuttles). Apparent weightlessness should be explained at some point.
- $g = W/m$ yields alternative units to $\mathrm{m\ s^{-2}}$ of $\mathrm{N\ kg^{-1}}$ is a way of introducing the definition of gravitational field strength with g as its value.
- Emphasise vector nature of field strength with arrows on pattern giving direction.
- Emphasise that a uniform field pattern is a description, not the definition, of the uniform field. It requires the idea of constant force per unit mass.
- Worth considering mentioning here the general definition of a field as a link to later field theory (sections 12 and 13).
- The concept of a field allows a local explanation of interactions rather than action-at-a-distance.

Mathematical skills

Changing the subject of this simple formula (Part A15) with substitution of data for different planetary bodies can build confidence at this early stage.

Practise applying the SI base units (Part A2) to show the equivalence of the two sets of units for g.

Syllabus A3: Deformation of solids

Topic: materials terminology and definitions

Learning objectives

3.1 distinguish between elastic and plastic deformation of a material

3,2 explain what is meant by the terms brittle, ductile, hard, malleable, stiff, strong and tough; use these terms; and give examples of materials exhibiting such behaviour

3.3 explain the meaning of, use and calculate tensile/compressive stress, tensile/compressive strain, spring constant, strength, breaking stress, stiffness and the Young Modulus

Notes

It might be worth beginning this section with Hooke's law ($F = kx$) using steel springs including the effect on spring constant of connecting them in series and parallel. This will be helpful when discussing the use of stress and strain later (especially their dependence on dimensions). This also provides a good opportunity for some simple class practicals.

Students find it difficult to distinguish between these terms and will need practical experience handling materials, stretching them, scratching them, breaking them to fix the definitions in place.

It is worth defining stress and strain fairly early so that stress-strain graphs can be used from the outset to describe material properties and to compare different classes of material.

Emphasise the fact that the Young Modulus is an intrinsic property (of a material) unlike the spring constant (a property of material arranged in a particular way).

The experimental measurement of the Young Modulus should be done carefully with a full analysis of the inherent uncertainties.

Mathematical skills

Students often have difficulties with units and their conversion (e.g. mm^2 to m^2) in end up with values that are many orders of magnitude out! (A12)

Mathematicians tend to define a different spring constant: $F = \lambda x/l_o$. Mentioning this now might avoid confusion later

Syllabus A3: Deformation of solids Topic: materials terminology and definitions	
Learning objectives 3.4 draw force-extension, force-compression and tensile/compressive stress-strain graphs, and explain the meaning of the limit of proportionality, elastic limit, yield point, breaking force and breaking stress 3.5 state Hooke's law and identify situations in which it is obeyed 3.6 account for the stress-strain graphs of metals and polymers in terms of the microstructure of the material	**Notes** • It is important to put materials into context by using a range of examples drawn from engineering, sport, fashion, exploration etc. and asking the question 'how do the physical properties make it fit for purpose?' • Hooke's law here refers to the region of direct proportionality at the start of some stress-strain graphs. • Relating the macroscopic properties of Young Modulus, elastic and plastic behaviour, strength and hardness to microscopic structure is an example of the reductionist approach in physics (similar to that used in kinetic theory in Section 1).
	Mathematical skills • Link areas under force-extension graphs to work done and under stress-strain curves to work done per unit volume. This can be used to reinforce simple ideas about integration. (A24, A26)

Syllabus A4: Energy concepts

Topic: work, energy, power and potential

Learning objectives

4.1 understand and use the concept of work in terms of the product of a force and a displacement in the direction of that force, including situations where the force is not along the line of motion

4.2 calculate the work done in situations where the force is a function of displacement using the area under a force-displacement graph

4.3 calculate power from the rate at which work is done or energy is transferred

4.4 recall and use the relationship

$$P = Fv$$

4.5 recall and use the relationship

$$\Delta E = mg\Delta h$$

for the gravitational potential energy transferred near the Earth's surface

4.6 recall and use the expression

$$g\Delta h$$

as change in gravitational potential

Notes

- Energy is a subtle and abstract concept; and is fundamentally the basis for the whole of physics. However, students meet the word from a very early age and will arrive in many cases with the assumption that they understand it – this may need to be challenged!
- It is worth discussing the origins of the idea of conservation of energy and trying to begin by distinguishing terms such as energy, power (and even force) that students tend to confuse with one another.
- The idea of gravitational potential is subtle and prepares the way for the field theory of Part B. It is worth drawing simple diagrams showing equipotentials near the surface of Earth and using these to discuss energy changes as masses are moved around in the field.
- The equation $\Delta V_g = g\Delta h$ can be used to link potential gradients to field strength and to show the link between forces and energy changes in a field.
- Interesting philosophical discussions centre on the location of energy in a field.

Mathematical skills

- Integration – area under curves. This is a recurring idea and should be reinforced each time it is met.
- Weaker students will struggle with 'rates of change' so the concept of power (and its distinction from work or energy) can be used to reinforce this idea. (B4)

Syllabus A4: Energy concepts

Topic: energy equations and conservation

Learning objectives

4.7 recall and use the expression

$$E = \tfrac{1}{2} Fx$$

for the elastic strain energy in a deformed material sample obeying Hooke's law

4.8 use the area under a force-extension graph to determine elastic strain energy

4.9 derive, recall and use the expression

$$E = \tfrac{1}{2} kx^2$$

4.10 derive, recall and use the relationship

$$E = 1/2\ mv^2$$

for the kinetic energy of a body

4.11 apply the principle of conservation of energy solve problems

4.12 recall and use the expression

$$\%\ \text{efficiency} = \frac{\text{useful energy (or power) out}}{\text{total energy (or power) in}} \times 100\%$$

Notes

- It is important to show how the different energy expressions derive from the definition of work done.
- Experiments measuring energy transfer (e.g. from a catapult to a trolley) give good scope for interesting practical investigations.
- The derivation of KE can be done at different levels – e.g. from '*suvat*' under constant acceleration or using calculus.
- One of the points about the KE equation is that the final KE at any velocity is independent of the way that velocity was reached (e.g. rapid or slow acceleration).

Mathematical skills

- Area under graphs. (A24)
- Derivation of KE equation using integration. (B4)

Syllabus A4: Energy concepts

Topic: specific heat capacity and specific latent heat

Learning objectives	Notes
4.13 recognise and use the expression $\Delta E = mc\Delta\theta$, where c is the specific heat capacity 4.14 recognise and use the expression $\Delta E = mL$ where L is the specific latent heat of fusion or of vaporisation	• Specific heat capacity, c, and specific latent heat, L, are very commonly confused; it is sometimes best not to teach them one after the other. c refers to the temperature change in a given phase, and L refers to the phase change at a given temperature. There are typically (but not always) three specific heat capacities and two specific latent heats for any given substance. • While these are macroscopic equations, it is worth relating c and L to the microscopic properties of particles i.e. c is related to the energy per particle and number of particles, and L is related to the energy required to break bonds and the number of bonds. • Freezing experiments involving the release of latent heat lead to interesting discussions about energy transfer. The *Mpemba effect* and the story of Erasto Mpemba are worth mentioning and may lead into a discussion on how science creates new knowledge.
	Mathematical skills • Setting up equations – e.g. for final temperature of a mixture. (A17) • The mathematics behind the various types of cooling corrections that can be used experimentally supports and reinforces several useful and relevant practical and mathematical skills.

Syllabus A5: Electricity

Topic: electric current

Learning objectives

5.1 discuss electrical phenomena in terms of electric charge

5.2 describe electric current as the rate of flow of charge and recall and use the expression $I = \frac{\Delta Q}{\Delta t}$

5.3 understand potential difference in terms of energy transfer and recall and use the expression $V = \frac{W}{Q}$

Notes

- Charge is a fundamental property of matter possessed by all quarks and some leptons. Its existence cannot be explained, merely described.
- $V = W/Q$ and $V = P/I$ are, of course, equivalent definitions of p.d. It is worth pointing this out to weaker students.
- Worth discussing a wide variety of moving charge, not just electrons in metallic lattices e.g. lightning, cathode rays, electrolysis etc.
- Emphasise the 'rate' of flow in 5.2
- Worth mentioning $Q = ne$ where n is number of charged particles, too.
- Invest time in applying the definition of p.d. to determining the total p.d. across several components in a simple series circuit in preparation for development of concept of e.m.f.
- The definition of p.d. may be more easily understood in electrostatic terms and it might be best to leave the full treatment until then.

Mathematical skills

The base units of the volt and the coulomb can be derived at this stage. (A3)

The definition of p.d. may be more easily understood in electrostatic terms and it might be best to leave the full treatment until then.

Some scope for practising scientific notation provided teaching of 5.1 is imaginative. (A4 and 5)

Syllabus A5: Electricity

Topics: potential difference and electromotive force

Learning objectives

5.4 recall and use the fact that resistance is defined by $R = \frac{V}{I}$ and use this to calculate resistance variation for a variety of voltage-current characteristics

5.5 define and use the concepts of emf and internal resistance and distinguish between emf and terminal potential difference

5.6 derive, recall and use the equations $E = I(R + r)$ and $E = V + Ir$

5.7 deduce using numerical methods that maximum power transfer from a source of emf is achieved when the load resistance is equal to the internal resistance

5.8 recall and use the expressions $P = VI$ and $W = VIt$ and derive and use the related expression $P = I^2R$

Notes

This section offers numerous opportunities for practical work.

- Ammeter/voltmeter method for a length of nichrome wire readily yields data to support $V \propto I$. Students should appreciate the conditions under which R remains constant.
- V-I characteristics for various components (lamp, diode, etc.) can be plotted from experimental data and resistance calculated for different current values.
- Reinforce the fact that resistance is the gradient or inverse gradient of a *chord* of a V-I or I-V graph for components not following Ohm's law.
- Stress that most graphs showing the V-I characteristics for different components actually show the curves on an I-V graph. Make students practise noticing which way the axes are labelled.
- Emf is the property of a source of electrical energy; the energy is 'given' to the current. P.d. is the property of something that used electrical energy; the energy is 'taken' from the current. The sum of the emf and the p.d. in a circuit should be zero.
- Internal resistance is the resistance of the material from which the cell (or other power source) is made and through which a current flows.
- The teaching of Kirchhoff's laws can be challenging, and a demonstration to show that there is a 'lost' p.d. across the internal resistance can be helpful – the students will use this observation when they come to Kirchhoff in more detail.
- A practical exercise to determine the internal resistance of a cell helps the students understand the concept of internal resistance and is an excellent platform for practising graphical experimental skills.
- Numerous practice circuit questions are advised to drive home equations in 5.6. and 5.8. It might make more sense to teach 5.8 before 5.7.

Mathematical skills

Intercepts and gradients of straight line graphs have physical meaning (A:26), such as emf and internal resistance and these concepts can be a challenge to some.

Worth rearranging equations in 5.6 with the more able so that a variety of straight line graphs can yield internal resistance and/or emf.

Consider the effect on the gradient and intercept of a graph of having two or more cells in series.

Syllabus A 5: Electricity

Topics: resistance and resistivity

Learning objectives

5.9 recall and use the relationship $R = \frac{\rho L}{A}$

5.10 recall the formula for the combined resistance of two or more resistors in series and use it to solve problems $R_T = R_1 + R_2 + \ldots$

5.11 recall the formula for the combined resistance of two or more resistors in parallel and use it to solve problems $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$

Notes

- Students have difficulty with the units of resistivity – 'ohms per metre' being the standard error. Again, a practical introduction to resistivity helps secure understanding.
- Less able students often forget to invert $\frac{1}{R_T}$ to find total resistance when fractions are used.
- Emphasise the voltage and current properties of series and parallel combinations.
- Numerous practice problems needed before integrating networks into complete circuits.
- It is worth mentioning the resistance offered by an ideal voltmeter and ammeter and why these ideals have these values.
- More able students will appreciate the effect on current in a circuit which has a voltmeter with resistance comparable to the load.
- More able students will also appreciate that for a measuring instrument not to disturb a measurement, that measuring instrument will only alter the resistance of the component or circuit it is measuring by an amount less than the uncertainty of the measurement involved. Practise selecting the right measuring instrument for situations with different current and voltage levels

Mathematical skills

Substitution of numerical values into algebraic equations and the use of calculators to determine $1/R$. into (A10, A16, A17)

For the weaker students it is again worth reminding them how to manipulate equations, especially where the addition of fractions with different denominators is involved.

Note that the total resistance of a series resistances is larger than the largest, and that the total resistance of parallel resistors is smaller than the smallest.

Syllabus A 5: Electricity **Topics: conservation of charge and energy**	
Learning objectives 5.12 recall Kirchhoff's first and second laws and apply them to circuits containing no more than two supply components and no more than two linked loops 5.13 appreciate that Kirchhoff's first and second laws are a consequence of the conservation of charge and energy respectively 5.14 use the idea of the potential divider to calculate potential differences and resistances	**Notes** • The concept of potential divider should evolve naturally from study of 5.2, 5.3 and 5.10. Taking direct measurements of two series resistors and their relative pd.s will support 5.14 Extension work would come from using variable resistors or devices used for 5.4. • For more able students demonstrate a wheatstone bridge and point out that the measurement is taken when the measuring instrument has no current flowing through it. **Mathematical skills** Substitution of numerical values into algebraic equations and the use of calculators to determine 1/*R*. into (A10, A16, A17)

Syllabus A6: Waves

Topic: describing waves

Learning objectives

6.1 understand and use the terms *displacement*, *amplitude*, *intensity*, *frequency*, *period*, *speed* and *wavelength*

6.2 recall and apply the equation

$$f = \frac{1}{T}$$

to a variety of situations not limited to waves

6.3 recall and use the wave equation

$$v = f\lambda$$

6.4 recall that a sound wave is a Longitudinal wave which can be described in terms of the displacement of molecules or changes in pressure

6.5 recall that light waves are transverse electromagnetic waves, and that all electromagnetic waves travel at the same speed in vacuum

6.6 recall the major divisions of the electromagnetic spectrum in order of wavelength, and the range of wavelengths of the visible spectrum

6.7 recall that the intensity of a wave is directly proportional to the square of its amplitude

Notes

- Most of this is necessary revision from GCSE so try to inject some interest by using a wide range of examples and contexts and revisit a range of different types of wave (both mechanical and electromagnetic).
- One way might be to consider how different kinds of wave are used in different kinds of imaging systems – e.g. sonar, ultrasound, IR, visible, gamma. Even a very general discussion of these different systems will involve the nature of the waves used.
- Contrast the energy transfer by waves, where the energy moves **through** the medium with energy transfer by e.g. pile driver or petrol tanker – where the energy moves **with** the medium.
- Introduce the idea of a spectrum for both sound and light.
- Spend time on graphical descriptions of waves – distinguish carefully between plots of displacement versus time and displacement versus position.
- Emphasise that the transverse vibrations in an EM wave are not mechanical vibrations but varying field strengths in particular directions.
- It might be worth introducing the idea of phase and a phasor representation (7.4) even at this early stage in order to bring some new material into play and to prepare the way for work on superposition later.
- If you have the apparatus measure the speed of sound and light in the laboratory and discuss the precision and accuracy of the measurements.
- Note that a water wave of twice the amplitude raises twice the mass of water through twice the height, and so it must be carrying four times the energy in support of 6.7.

Mathematical skills

Able students will enjoy a derivation of the 1-D wave equation.

Syllabus A6: Waves

Topic: polarisation and refraction

Learning objectives

6.8 use graphs to represent transverse and longitudinal waves, including standing waves

6.9 explain what is meant by a plane polarised wave

6.10 use the components of amplitude perpendicular and parallel to the axis of a polarizing filter to determine the amplitude and intensity of transmission through a filter

6.11 recognise and use the expression for refractive index

$$n = \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

6.12 derive the equation

$$\sin c = \frac{1}{n}$$

recall it, and use it to solve problems

6.13 recall that optical fibres use total internal reflection to transmit signals

6.14 recall that, in general, waves are partially transmitted and partially reflected at an interface between media

Notes

- The formation of standing waves involves superposition so you might prefer to leave this until you teach Section 7. On the other hand it provides some useful experimental methods for measuring wavelengths (e.g. of microwaves or sound).
- Make every effort to let students play with two sheets of Polaroid; it is one of the few things which they still find genuinely astonishing. Rotate a third Polaroid sheet in the gap between two crossed Polaroids. Double resolution of vectors explains why light is transmitted – most notably when the middle sheet is at 45°.
- Polarisation should be demonstrated using microwaves and/or radio waves.
- Calculations of transmitted amplitudes and intensities through two or more polarising filters will help to reinforce the link between amplitude and intensity (as well as giving practice in resolving vectors).
- Optical activity can be used to carry out experimental measurements of sugar concentrations.
- Examples of the use of polarisation in photography, communications systems and 3-D cinema are all interesting.
- Faraday was convinced that light was electromagnetic in nature and demonstrated the link by rotating the plane of polarisation of a beam of light as it passed along the axis of a long solenoid. It is just about possible to demonstrate this.

Mathematical skills

- Resolving vectors (polarisation).
- Trigonometry (geometric optics). (A15, A20, A21)
- Most groups will appreciate a derivation of the equation in 6.1.

Syllabus A7: Superposition

Topic: superposing waves

Learning objectives

7.1 explain and use the concepts of 'coherence', 'path difference', 'superposition' and 'phase'

7.2 understand the origin of 'phase difference' and 'path difference', and calculate phase differences from path differences

7.3 understand how the phase of a wave varies with time and position

7.4 determine the resultant amplitude when two waves superpose, making use of diagrams

7.5 explain what is meant by a standing wave, how such a wave can be formed, and identify nodes and antinodes

Notes

- Stress that superposition applies for all waves, coherent or not. In the coherent cases, however, the resultant pattern can be understood much more easily. Superposition is not just another word for interference.
- Coherent sources maintain a constant phase difference but in most cases this will be zero.
- Students often confuse phase difference with path difference – it is worth emphasising the distinction right from the start. The equation:

  $$\Delta\phi = \frac{2\pi x}{\lambda}$$

  where x is path difference and $\Delta\phi$ is phase difference is useful at this stage.
- Simulations showing phasor rotation will reinforce the idea of phase and its link to angle.
- Compare the variations of phase and amplitude with time and position in a progressive wave with their variations in a standing wave.
- The phasor approach is helpful because it allows students to visualise the waves but some might also enjoy using algebra and trigonometry to derive standing waves and simple interference patterns.
- Point out that superposition conserves energy – e.g. the low (or zero) intensity delivered to minima in an interference pattern is balanced by the larger than expected intensity at maxima (4I in a two source pattern).

Mathematical skills

- Vector (addition) and resolution.
- Trigonometry (including the use of trigonometric relations if you derive equations for standing waves etc. with the more able students.)

Syllabus A7: Superposition

Topic: complex waves

Learning objectives	**Notes**
7.6 understand amplitude modulation as an example of superposition and use the terms *signal* and *carrier wave* 7.7 understand that a complex wave may be regarded as a superposition of sinusoidal waves of appropriate amplitudes, frequencies and phases	• This is an opportunity to link wave physics to communications. AM is mentioned specifically in the syllabus but it is also worth mentioning FM. • Make sure students are familiar with graphical representations of carrier and signal waves and their combined profile. • You could discuss signal spectrum and bandwidth. • Use sound capture and analysis software (such as *Audacity*) to display recorded sounds of various kinds. The use of a fast Fourier transform will give the frequency spectrum. Compare say a singing voice with a vibrating guitar string. • Many students will benefit from being introduced to vocabulary (‘overtones’, ‘harmonics’) enabling an explanation of the difference in sound between middle C on a violin and middle C on a piano. • Software such as *Focus on Waves*, *Modellus* or even Excel can be used to add sine waves of different frequencies to build up a complex wave. *Focus* provides a simple way to add sine waves visually (as in a simple synthesiser) and then play back the resultant.

Syllabus A7: Superposition

Topic: superposing waves

Learning objectives

7.8 recall that waves can be diffracted and that substantial diffraction occurs when the size of the gap or obstacle is comparable with the wavelength

7.9 recall qualitatively the diffraction patterns for a slit, a circular hole and a straight edge

7.10 recognise and use the equation

$$n\lambda = b \sin \theta$$

to locate the positions of destructive superposition for single slit diffraction, where b is the width of the slit

7.11 recognise and use the Rayleigh criterion

$$\theta \approx \frac{\lambda}{b}$$

for resolving power of a single aperture, where *b* is the width of the aperture

Notes

- While many students will already be familiar with the phenomenon of diffraction it is worth reinforcing this experimentally, perhaps with a circus of activities in which they can measure the resultant amplitude at different angles to the normal to an aperture e.g. using a ripple tank, 3 cm microwaves, 1 GHz radio waves and laser light.
- Students should understand that diffraction patterns result from superposition and a simple (cancelling by pairs) derivation of the single slit pattern is appropriate.
- Students should be able to draw a graphical representation of intensity versus angle for slits and circular apertures and show the effect of changing the aperture size or wavelength on the breadth of the pattern.
- Take care to distinguish the single slit diffraction equation from the diffraction for maxima in the N-source diffraction grating equation.
- An estimate of the resolving power of the eye can be made by getting students to look at two parallel fine lines drawn on white paper and to see the distance at which they can just resolve them.
- It is interesting to compare the diffraction limited resolving power of the unaided eye with a large radio telescope such as Jodrell Bank.

Mathematical skills

This is a good opportunity to introduce the use of radians and small angle approximations.

Syllabus A7: Superposition

Topic: superposing waves

Learning objectives

7.12 describe the superposition pattern for a diffraction grating and for a double slit and use the equation

$$d \sin \theta = n\lambda$$

to calculate the angles of the principal maxima for a diffraction grating and for a double slit

7.13 use the equation

$$\lambda = \frac{ax}{D}$$

for double-slit interference using light

Notes

- Young's double slit experiment is important historically and this should be pointed out, but the double slit is just the simplest (and least useful) example of an N-source diffraction grating. It is better to start from the general case and work back to the double slit.
- As more slits (sources) are added two things happen:

  (i) the maxima get brighter ($I \propto N^2$)
  (ii) the maxima become more sharply defined

  Both effects can be explained using the students' knowledge of superposition effects. Both make gratings ideal for precise analysis of light.
- Give students an opportunity to analyse the spectrum of light from various different kinds of source (discharge lamps, filament lamps, LEDs etc…).
- Spectroscopy has been one of the most useful techniques in the sciences e.g. allowing us to learn about atomic structure (energy levels in atoms); stellar atmospheres and the expanding universe (re-shifted spectra).
- The spectrum of harmonics on a vibrating string links to sections 7.5 and 7.6.

Mathematical skills

Geometry and trigonometry is needed to calculate path differences and to derive the

N-source formula. (A11, A17, A20)

Syllabus A8: Atomic and nuclear

Topic: the nucleus
nuclear processes
probability and radioactive decay
fission

Learning objectives

8.1 understand the importance of the alpha-particle scattering experiment in determining the nuclear model

8.2 describe atomic structure using the atomic model

8.3 show an awareness of the existence and main sources of background radiation

8.4 recognise nuclear radiations $(\alpha, \beta^-, \gamma)$ from their penetrating power and ionising ability, and recall the nature of these radiations

8.5 write and interpret balanced nuclear transformation equations using standard notation

8.6 understand and use the terms 'nucleon number' (mass number), 'proton number' (atomic number), 'nuclide' and 'isotope'

8.7 appreciate the spontaneous and random nature of nuclear decay

8.8 define and use the concept of activity as the number of decays occurring per unit time

8.9 understand qualitatively how a constant decay probability leads to the shape of a radioactive decay curve

8.10 determine the number of nuclei remaining or the activity of a source after a time which is an integer number of half-lives

8.11 understand the terms 'thermonuclear fusion', 'induced fission' and 'chain reaction'

8.12 recall that thermonuclear fusion and the fission of uranium-235 and plutonium-239 release large amounts of energy

Notes

This section will introduce students to many famous names in physics. It might be worthwhile giving some detailed background to the work of Rutherford, Curie, and Becquerel etc. in order to set the scene.

- Focus on the process whereby evidence leads to conclusions and eventually to the revolutionary idea of a nuclear model. Emphasise how this model helped illuminate the patterns of chemistry as well as explain the evidence presented by physics.
- Some idea of the relative size of the nuclear and atomic diameters is should be given in support of 8.2. Be prepared to answer questions on quarks.
- 8.6 should be a review of GCSE work, but should not be skipped.
- 8.4 can readily be demonstrated using a Geiger counter and ratemeter or datalogger. This activity often forms the basis of standard exam questions.
- Make it clear that the activity is not what is recorded on the counter, but is **proportional** to what is recorded on the counter. More able students might be able to estimate the pro+portionality constant by considering the area of a sphere and the area of the counter window.
- Using $^{4}_{2}\mathrm{He}$ and $^{0}_{-1}\mathrm{e}$ will better help students balance nuclear transformation equations for 8.5. Stress that new elements are formed by nuclear decay; this is the alchemy of medieval times.
- Stress that decay is a **nuclear** phenomenon; beta electrons come from the **nucleus**.
- Ask students to calculate the numbers of atoms present in your school source if you have one; in one gram of U-235 if you don't.
- For 8.8 mention $A = -\frac{\mathrm{d}N}{\mathrm{d}t}$, the becquerel, and the wide range of activity values.
- The classic 'Dice Throwing Experiment' effectively models nuclear decay, is fun and as such is worth class time. It leads to a graphical analogy of N vs t. 'Half–life' can be introduced.
- It is worth emphasising that with small values, random effects make an exact prediction impossible.

Syllabus A8: Atomic and nuclear (continued) **Topic: the nucleus** **nuclear processes** **probability and radioactive decay** **fission**	
	• Use an N vs t graph to show, qualitatively, how its negative gradient, $\frac{dN}{dt}$, decreases with each half life. The main points of 8.9 can then be covered. It also helps you justify the negative sign in the expression for activity. • 8.11 will provide more examples of balanced equations.
	Mathematical skills At this stage the rigours of differential calculus are not required. However, some teachers may judge that a more mathematical approach is more suitable for their students and may wish to extend their teaching to include some of the topics from 17 Nuclear physics. Part A24 requires students to determine slopes. It is not unreasonable to expect them to determine instantaneous activity values from an N vs t decay graph.

Syllabus A9: Quantum ideas

Topic: the photoelectric effect
the photon
wave-particle duality

Learning objectives

9.1 recall that, for monochromatic light, the number of photoelectrons emitted per second is proportional to the light intensity and that emission occurs instantaneously

9.2 recall that the kinetic energy of photoelectrons varies from zero to a maximum, and that the maximum kinetic energy depends on the frequency of the light but not on its intensity

9.3 recall that photoelectrons are not ejected when the light has a frequency lower than a certain threshold frequency which varies from metal to metal

9.4 understand how the wave description of light fails to account for the observed features of the photoelectric effect and that the photon description is needed

9.5 recall that the absorption of a photon of energy can result in the emission of a photoelectron

9.6 recognise and use the expression $E = hf$

9.7 understand and use the terms 'threshold frequency' and 'work function' and recall and use the expression $hf = \Phi + \frac{1}{2}mv_{max}{}^2$

9.8 understand the use of stopping potential to find the maximum kinetic energy of photoelectrons and convert energies between joules and electron-volts

Notes

Students find the concepts in this topic difficult but interesting because it takes them into new territory. Irrespective of the chosen teaching order, it is certain that students need time for ideas to sink in. The following notes suggest one approach.

- Historical background, referring to J.J Thomson, Bohr and Einstein will introduce the development of ideas.
- Introduce the terms 'photon' and 'quantum'; then the expression $E = hf$ follows naturally. Use the wave equation to derive $E = \frac{hc}{\lambda}$. Stress that energy must be in joules.
- Define the electron-volt, as in 9.8, practising energy unit conversions both ways. Less able students will find the eV difficult, so it is worth securing the conversion at this stage, before teaching the work function.Φ
- Build the expression $hf = \Phi + \frac{1}{2}mv_{max}{}^2$ in 9.7 by first describing the production of photoelectrons, then introducing the concept of the work function which can be underpinned by calculating the threshold frequencies for different metals. Emphasise the relevance of KE_{max}.
- The term 'work function' can cause confusion. Refer to it as '*the least work done by any escaping electron*' until the equation is understood.
- Worth exposing students to other possible variants of Einstein's equation in 9.7. Calculations can be complex and worth significant marks in an exam paper.
- Review intensity from 6.7. Learning objectives 9.1, 9.2 and 9.3 are best formalised once students have grasped the basics summarising their previous learning.
- As the gold leaf electroscope is no longer part of most standard syllabuses, referring to it will most likely confuse the students. Only demonstrate the classic 'zinc plate experiment' if your apparatus works! Use animation teaching aids to show the experiment otherwise.

Syllabus A9: Quantum ideas (continued) **Topic: the photoelectric effect** **the photon** **wave-particle duality**	
9.9 plot a graph of stopping potential against frequency to determine the Planck constant, work function and threshold frequency 9.10 understand the need for a wave model to explain electron diffraction 9.11 recognise and use the expression $\lambda = \frac{h}{p}$ for the de Broglie wavelength	• The wave/photon discussion, 9.4, could be covered at this stage. Students have difficulty writing coherent answers that link the relevant model to the particular observation, so practising the use of this explanation, developing coherent and lucid phrasing, is paramount. • There's an opportunity here to cover the history of wave/particle duality and to tell students of de Broglie. Calculate the wavelength of everyday objects and standard students. • 9.10 and 9.11 follow. Emphasise how the relationship $\lambda = \frac{h}{p}$ links aspects of duality. • The concept of 'stopping potential' will challenge some students. Want idea of reversing direction of electric field to just decelerate the fastest electrons. Experiments to measure stopping potentials secure learning – if your equipment works! Use animations in support. • Teachers are advised to look ahead to the more philosophical approach in section 19: 'Interpreting quantum theory', seeding those ideas here if the students take the bait.
	Mathematical skills There is much scope here for practising Part A26 – using the slope and intercept of a straight-line graph. vis. relationships in 9.7 and 9.9.

Syllabus B10: Rotational mechanics

Topic: kinematics of uniform circular motion/centripetal force

Learning objectives

10.1 define and use the radian

10.2 understand the concept of angular velocity, and recall and use the relationships $v = r\omega$ and $T = 2\pi / \omega$

10.3 recall and use the expression for centripetal force $F = \frac{mv^2}{r}$

10.4 derive, recall and use the expressions for centripetal acceleration $a = \frac{v^2}{r}$ and $a = r\omega^2$

Notes

- Many students will have misconceptions about force and motion and it is well worth beginning by reviewing the implications of Newton's Laws of motion, especially the 1st Law.
- Generalise the idea of acceleration by considering velocity as a vector so that a continually changing direction (with constant magnitude) is an acceleration.
- It is worth emphasising that *centripetal* is a **direction** word, just like *downward* or *sideways*. The gravitational force around the surface of Earth can be described as centripetal.
- The derivation of an expression for centripetal acceleration should be approached both as a mathematical exercise and as a discussion for the underlying concepts essential for an understanding of circular motion.
- Avoid giving the impression that centripetal forces are some additional force rather than a term used to describe the actual physical force (gravity, tension etc.) acting on an object in circular motion.
- Students will want to discuss 'centrifugal force'. Beware of simply dismissing this. It is better to explain why we introduce such 'inertial forces' when we try to explain dynamics from an accelerating (non-inertial) reference frame. In this sense it can be regarded as an imaginary force – it does not arise from a physical interaction.

Mathematical skills

- Radians
- Rate of change of a vector quantity (velocity)

Syllabus B10: Rotational mechanics

Topic: moment of inertia

Learning objectives

10.5 describe qualitatively the motion of a rigid solid object under the influence of a single force in terms of linear acceleration and rotational acceleration

10.6* use $I = \sum mr^2$ to calculate the moment of inertia of a body consisting of three or fewer point particles fixed together

10.7* use integration to calculate the moment of inertia of a ring, a disk and a rod

Notes

- A car wheel is a good simple example to start with – relative to its centre it simply rotates, but its centre of mass also moves with a linear velocity.
- Many students will be familiar with soccer free kicks where the ball is kicked off-centre and acquires a forward velocity of its centre of mass as well as an angular velocity relative to its centre of mass. During contact it has both linear acceleration (effect of the resultant force) and an angular acceleration (due to the resultant moment (torque).
- The expression for moment of inertia needs some justification. The dependence on mass is unlikely to be a surprise but the dependence on mass distribution is new. Tell them to take a biro between two fingers and try rotating it back and forth (a) along its long axis and (b) perpendicular to this axis about its centre. The latter case will give them a 'feel' for the 'resistance to angular acceleration'.
- The definition of the moment of inertia is the ratio torque/angular acceleration. It can be shown that this is equal to $\sum mr^2$ It is not a constant for an object, but depends on the axis of rotation chosen.

Mathematical skills

- The use of summation (e.g. for rotational kinetic energy) with appropriate nomenclature.
- Using small increments (e.g. δx, δm etc…) to set up integrals. (B10)
- Integration between limits. (B4)
- The algebraic expression for moment of inertia is easily extracted from the expression for rotational KE by summing the KE contribution from each point mass and using the analogy between rotational and linear motion:

$$KE = \frac{1}{2}mv^2 \qquad RKE = \frac{1}{2}\left(\sum_{i=1}^{i=N} m_i r_i^2\right)\omega^2$$

Syllabus B10: Rotational mechanics

Topic: kinematics of uniform circular motion

Learning objectives

10.8* deduce laws for rotational motion by analogy with Newton's laws for linear motion, including:

$$E = \frac{1}{2} I\omega^2$$

$$L = I\omega$$

$$\Gamma = I\frac{\mathrm{d}\omega}{\mathrm{d}t}$$

10.9* apply the laws of rotational motion to perform kinematic calculations regarding a rotating object when the moment of inertia is given

Notes

- The starting points for the analogy should be Newton's 2nd Law and the expressions for KE and rotational KE.
- Students should be encouraged to explore the analogy themselves, and should consider the rotational analogues of the '*suvat*' equations, conservation of angular momentum, conservation of energy and expressions for work done by a torque.
- While there are plenty of mathematical derivations and problems to solve in this section make sure you include plenty of relevant practical work – e.g. experiments to measure moments of inertia and compare them with theoretical predicted values.

Mathematical skills

- The following analogues are useful:

$s \rightarrow \theta$

$u \rightarrow \omega_i$

$v \rightarrow \omega_f$

$a \rightarrow \alpha = \frac{\mathrm{d}\omega}{\mathrm{d}t}$

$m \rightarrow I$

$p \rightarrow L$

$F \rightarrow \Gamma$

Syllabus B11: Oscillations

Topic: simple harmonic motion
energy in simple harmonic motion
forced oscillations, damping and resonance

Learning objectives

11.1 recall the condition for simple harmonic motion and hence identify situations in which simple harmonic motion will occur

11.2* show that the condition for simple harmonic motion leads to a differential equation of the form $\frac{d^2x}{dt^2} = \omega^2 x$ and that $x = A \cos \omega t$ is a solution to this equation

11.3* use differential calculus to derive the expressions $v = -A\omega \sin \omega t$ and $a = -A\omega^2 \cos \omega t$ for simple harmonic motion

11.4* recognise and use the expressions $x = A \cos \omega t$, $v = -A\omega \sin \omega t$, $a = -A\omega^2 \cos \omega t$ and $F = -m\omega^2 x$ to solve problems

11.5 recall and use the expression $T = \frac{2\pi}{\omega}$ as applied to a simple harmonic oscillator

11.6 understand the phase differences between displacement, velocity and acceleration in simple harmonic motion

11.7* show that the total energy of an undamped simple harmonic system is given by $E = \frac{1}{2}mA^2\omega^2$ and recognise that this is a constant

11.8 recognise and use the expression $E = \frac{1}{2}mA^2\omega^2$ to solve problems

11.9 distinguish between free, damped and forced oscillations

11.10 recall how the amplitude of a forced oscillation changes at and around the natural frequency of a system and describe, qualitatively, how damping affects resonance

Notes

This topic often proves challenging for many students because they are swamped by the quantity of mathematics. They lose sight of the principal properties of SHM and often fail to relate the mathematics to the behaviour of the oscillator. Needless to say it is vital that students solve lots of routine problems as they progress through the topics and it is worthwhile insisting they show their working on paper so that they automatically do so under exam conditions.

SHM simulations will help underpin and revise key ideas throughout the teaching.

- Project shadow of object on a turntable onto a screen to show oscillation along a straight line. This links to the simple idea of acceleration being directly proportional to (negative) displacement.
- Use motion sensor and data-logger to record how displacement, velocity and acceleration vary with time and how they are interlinked (11.6) before tackling 11.2* and 11.3*.
- Discuss how the direction of acceleration and the force producing it ($F = ma$) varies during a complete cycle in order to explain the minus sign in the differential equation (11.2*).
- Plot graph of acceleration v displacement to yield gradient and hence determine ω from gradient. Determine average value for period. Emphasise T rather than ω.
- Worth performing experiments to determine the average period of oscillators vis. simple pendulum and mass on a spiral spring; this provides good practice in basic techniques. (Formulae will have to be provided.)
- Demonstrate damping of SHM (sensor and logger to PC display) before discussing theory.
- Exam answers to questions on resonance/damping etc. are often poorly expressed although graphs of amplitude v frequency are readily recalled. Worth setting two or three past questions.
- It is a common error to increase the period of oscillation in graph of amplitude v time for lightly damped motion.
- Derivation in 11.7* is accessible but students often forget to square values in calculations.
- Total energy E graph as sum of PE and KE graphs.

Syllabus B11: Oscillations (continued) **Topic: simple harmonic motion** **energy in simple harmonic motion** **forced oscillations, damping and resonance**	
	Mathematical skills : This topic includes several starred items which will only appear in the 'mathematical' section: differential equations (B9*), differentiating trig. functions (B6) and relating differentiation to the slope of displacement and velocity graphs. (B4) SHM is a really good topic for tying together graphs and gradients, equations and differentiation and, of course, physical reality. It should not be rushed. It might be worth revising these skills in advance of teaching the topic so that they are readily applied and students do not lose sight of the physics. Plotting, for example, T^2 against l (length of a simple pendulum) yields value for g from gradient: harder example on straight line graph work. (A26) Data could also be used to plot log T v log l. (B3)

Syllabus B12: Electric fields

Topic: concept of an electric field
uniform electric fields
capacitance
electric potential
electric field of a point charge

Learning objectives

12.1 explain what is meant by an electric field and recall and use the expression electric field strength $E = \frac{F}{Q}$

12.2 recall that applying a potential difference to two parallel plates stores charge on the plates and produces a uniform electric field in the central region between them

12.3 derive the equations $Fd = QV$ and $E = \frac{V}{d}$ for a charge moving through a potential difference in a uniform electric field

12.4 recall that the charge stored on parallel plates is proportional to the potential difference between them

12.5 recall and use the expression for capacitance $C = \frac{Q}{V}$

12.6 recognise and use the expression $W = \frac{1}{2}QV$ for the energy stored by a capacitor, derive the expression from the area under a graph of charge stored against potential difference, and derive and use related expressions such as $W = \frac{1}{2}CV^2$

12.7 understand that the direction and electric field strength of an electric field may be represented by field lines (lines of force), and recall the patterns of field lines that represent uniform and radial electric fields

12.8 understand electric potential and equipotentials

Notes

- Draw attention to analogy to earlier definition of gravitational field strength.
- Units of N C^{-1} from $E = \frac{F}{Q}$ are one of several for E.
- Demonstrate the uniform electric field pattern: use sprinkling of semolina on olive oil between straight electrodes dipped sideways into the oil.
- Stress that a field description is not the definition of a uniform field: we want 'constant force per unit positive charge' idea.
- Can demonstrate radial field pattern at this stage in preparation for later work –12.7.
- Stress importance of this type of field – later work on capacitors, its role as a BASIC particle accelerator.
- Consider moving positive charge in addition to standard electron motion in the field and introduce idea of work being done to move charge against the field between the plates or, initially, to establish charge on the plates. (Part A 5.3: $V = \frac{W}{Q}$)
- Simple experiments with capacitors (charging a capacitor at constant current for different time intervals to different voltages) will yield the relationship for capacitance – gradient of Q/V graph – and helps secure the definition. Students have difficulty in understanding this definition.
- Stress that a capacitor with +Q on one plate and –Q on the other stores a charge of Q, not 2Q.
- Define the Farad. Revise prefixes, typically, 'nano' and 'pico'.
- Discuss the physics of charging a capacitor – charging process stops when terminal pd of capacitor equals that of supply. More able will appreciate why the rate of flow of the charge, i.e. current, decreases with time.
- Record energy stored in a capacitor by discharging through a lamp and measuring with a joulemeter.
- Show $W = \frac{1}{2}\frac{Q^2}{C}$, too. Lots of simple examples needed.
- Worth showing that the formulae covered so far are homogeneous with respect to base units.
- 12.7 Explain why radial field lines due to positive and negative charges have opposite directions. (Refer back to direction of gravitational field lines.) Vector nature of E.

Syllabus B12: Electric fields (continued) **Topic: concept of an electric field** **uniform electric fields** **capacitance** **electric potential** **electric field of a point charge**	
12.9 understand the relationship between electric field and potential gradient, and recall and use the equation $E=-\frac{\mathrm{d}V}{\mathrm{d}x}$ 12.10 recognise and use the $F=\frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$ for point charges 12.11 derive and use the expression $E=\frac{Q}{4\pi\varepsilon_0 r^2}$ for the electric field due to a point charge 12.12* use integration to derive $W=\frac{Q_1 Q_2}{4\pi\varepsilon_0 r}$ from $F=\frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$ for point charges 12.13* recognise and use the equation $W=\frac{Q_1 Q_2}{4\pi\varepsilon_0 r}$ for electric potential energy for point charges	• It is worth mentioning that capacitors *could* be used with charged of different sizes on the two plates, but that this would have to be done electrostatically, rather than with a circuit. • Zero of potential is taken to be at infinity. This is needed for later integrations. Avoid using the 'Earth' as the zero of potential. • 12.9 introduces second set of units for E. Explain significance of negative sign and that exam questions mostly focus on the magnitude of the potential gradient. • Students can plot a potential gradient using conducting paper, graph paper, voltmeter, probe and aluminium strip electrodes. • Include distribution of equipotentials in uniform and radial fields. • The mutual force between two point charges is an example of Newton's 3rd law. Determine the magnitude and direction of the resultant force on any given point charge which is one of three in a straight line. Higher attainers will enjoy problems on more complex arrangements. • Use software to show electric fields due to one or more point charges and, later, to show equipotentials. • Candidates sometimes forget to square their r value and some have trouble dealing with the simplification of the powers of ten when applying $F=\frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$. • Note characteristic shape of the inverse square law graph for F vs r and, consequently, E vs r. • E is a vector, W is a scalar. W is inversely proportional to r. Sketch typical graph shape. • Highlight the key steps taken in the integration to derive $W=\frac{Q_1 Q_2}{4\pi\varepsilon_0 r}$. Exam marking will credit distinct stages and expect some basic explanation to accompany the mathematics.

Syllabus B12: Electric fields (continued) **Topic: concept of an electric field** **uniform electric fields** **capacitance** **electric potential** **electric field of a point charge**	
	Mathematical skills Throughout this topic there are opportunities for students to apply high level mathematical skills and to handle both vector and scalar quantities. Plot F against $1/r^2$ to give straight line through origin. Significance of gradient worth mentioning. {To be compared later with analogous gravitation equations. (A28)} 12.12 applies the mathematical requirement in (B10*). There are examples of both $y = k/x$ and $y = 1/x^2$ relationships.

Syllabus B13: Gravitation

Topic: Kepler's laws
Newton's law of gravity
gravitational field of a point mass
gravitational potential energy (GPE)

Learning objectives

13.1 state Kepler's laws of planetary motion:

- Planets move in elliptical orbits with the Sun at one focus.
- The Sun-planet line sweeps out equal areas in equal times.
- The orbital period squared of a planet is proportional to its mean distance from the Sun cubed.

13.2 recognise and use the expression $F = \frac{-Gm_1 m_2}{r^2}$

13.3 use Newton's law of gravity and centripetal force to derive $r^3 \propto T^2$ for a circular orbit

13.4 understand energy transfer by analysis of the area under a gravitational force-distance graph

13.5 derive and use the expression $g = \frac{Gm}{r^2}$ for the magnitude of the gravitational field strength due to a point mass

13.6 recall similarities and differences between electric and gravitational fields

13.7 recognise and use the equation for gravitational potential energy for point masses $E = \frac{-Gm_1 m_2}{r}$

13.8 calculate escape velocity using the ideas of gravitational potential energy (or area under a force-distance graph) and energy transfer

13.9 calculate the distance from the centre of the Earth and the height above its surface required for a geostationary orbit

Notes

Students find gravitation interesting and much of what is included in the syllabus will stimulate questions from them. Needless to say, having completed the teaching of Electric Fields, teachers will be able to draw upon the same mathematical skills to facilitate learning of the Gravitation section. It is worthwhile having a bank of differentiated questions because some students will take longer than others to fully appreciate the concepts. Others will relish the new ideas and may ask challenging questions.

- Kepler's laws provide an opportunity for reading interesting historical background either from texts or the Internet. You may prefer to teach the laws after having covered sections 13.2 and 13.3.
- Problems involving ellipses will be challenging and it is important to emphasise that circular orbits are assumed in standard work.
- Section 13.2: inverse-square law again. Stress that F is proportional to the product, m_1m_2, of the masses. Idea of 'point masses' needed.
- Worth deriving the units of G and giving some historical background about its measurement.
- Determine magnitude of F for a wide range of masses. Students should appreciate that the gravitational force between common everyday objects is very small.
- Standard questions ignore the minus sign convention which indicates 'attraction'.
- Stress that Newton's law gives the expression for the centripetal force that causes orbital motion.
- Section 13.4 is preparatory to 13.8. Integration methods or a simpler 'counting' squares' method can be utilised. Draw attention to the magnitudes of the distances and forces involved.
- Section 13.5 Revise Part A work on uniform fields. Stress that the force per unit mass does rapidly change with distance and this will help in the understanding of GPE change with distance from a point mass.
- More able pupils might wish to learn that the inverse square law might well be due to gravitons spreading out through surface area.

Syllabus B13: Gravitation (continued)

Topic: Kepler's laws
Newton's law of gravity
gravitational field of a point mass
gravitational potential energy (GPE)

- Section 13.6 is probably best left till all the gravitational theory has been completed. It can be a useful formative assessment exercise.
- The derivation of $E = \frac{-Gm_1 m_2}{r}$ is not required but working through it can help clarify the concept of GPE. Perhaps first revise GPE in a uniform field vis. near the Earth's surface. Again, the relevance of the negative sign will need careful explanation at this stage.
- Note that *equipotentials* are not required but a reference to them would aid thorough coverage of section 13.6.
- Suggest that students work through some calculations for GPE at different distances from the Earth's centre, then changes in GPE can be determined. Possibly plot graph of GPE v r. This should help students understand that GPE becomes less negative as r increases.
- In order to determine the escape velocity it is helpful to introduce the idea that the total energy is positive and that it is the sum of the KE and GPE. Apply to other planets.
- Keep the equations simple, if possible, by first working with r, the satellite's orbital radius, rather than substituting ($R_{\text{earth}} + h$) to avoid algebraic errors.

Mathematical skills

Students can easily make mistakes with the powers of ten in Newton's law calculations. They need to make an estimate of the answer before entering data into their calculators. (A4)

(A24) and (B4) both refer to the skill of determining the area under a graph.

Errors are often made in the application of the calibration scales of the axes.

Syllabus B14: Electromagnetism

Topic: concept of a magnetic field
force on a current-carrying conductor
force on a moving charge
electromagnetic induction
the Hall effect

Learning objectives

14.1 understand and use the terms ‘magnetic flux density’, ‘flux’ and ‘flux linkage’

14.2 understand that magnetic fields are created by electric current

14.3 recognise and use the expression $F = BIL \sin \theta$

14.4 recognise and use the expression $F = BQv \sin \theta$

14.5 use Fleming’s left hand rule to solve problems

14.6 explain qualitatively the factors affecting the emf induced across a coil when there is relative motion between the coil and a permanent magnet or when there is a change of current in a primary coil linked with it

14.7 recognise and use the expression $E = \frac{-\mathrm{d}(N\Phi)}{\mathrm{d}t}$ and explain how it is an expression of Faraday’s and Lenz’s laws

14.8 derive, recall and use the equation $r = \frac{mv}{BQ}$ for the radius of curvature of a deflected charged particle

14.9 explain the Hall effect, and derive and use the equation $V = Bvd$

14.10 explain how electric and magnetic fields are used as a velocity selector in a mass spectrometer and derive, recall and use $v = \frac{E}{B}$

Notes

Throughout the teaching of this topic it is important to continuously remind students of the role played by magnetic flux. They readily use formulae to solve problems but all too often fail to visualise what is actually happening. This is a particular difficulty with electromagnetic induction.

- Worth revisiting early work on magnetic field patterns so that idea of flux will follow more readily. Emphasise the 3-dimensional aspect of flux so flux density can be visualised. The syllabus does not have $\Phi = BA$ in its formulae list but it could help when introducing and defining symbols Φ and B and stating the equivalence of magnetic flux density and field strength. Introduce the Weber.
- 14.2 will allow you to demonstrate fields associated with current-carrying conductors such as the straight wire, flat coil and solenoid. Useful discussions to be had about flux density and its dependence on current size etc. Useful simulations are available. Introduce the Tesla.
- 14.3 and 14.5 could be combined. FLHR is soon learnt when applied to different demonstration situations. However, it is worth showing how the force direction is related to the resultant magnetic field.
- $F = BIL \sin \theta$: Stress that L is the length of conductor *in the field*. Better they can work from first principles and understand the physics than worry about which angle is θ. The classic ‘top pan balance’ experiment provides a hidden example of Newton’s 3rd law.
- Worth showing the equivalence of expressions in 14.3 and 14.4. Both expressions provide a definition of the Tesla. Apply $F = BQv \sin \theta$ to both positively and negatively charged particles.
- Beware of students using the phrase ‘inducing forces’.
- Again, students often benefit from simple diagrams illustrating the flux linkage and its change due to motion or current variation. Worth spending time on these demonstrations, working up from the conductor/magnet scenario to two coaxial coils with a signal generator and CRO.

Syllabus B14: Electromagnetism (continued) **Topic: concept of a magnetic field** **force on a current-carrying conductor** **force on a moving charge** **electromagnetic induction** **the Hall effect**	
	• An equivalent word equation for $E = \frac{-\mathrm{d}(N\Phi)}{\mathrm{d}t}$ can help. Students can be fearful of this expression. A few worked examples, where they can recognise the reality of ‘$\mathrm{d}(N\Phi)$’ and ‘$\mathrm{d}t$’ help considerably as will discussion of Lenz’s law in the context of energy conservation. • Worth discussing comparative curvatures and directions in order to identify particles. This will link with later work on nuclear physics and provide a chance to revise circular motion. • The derivation is not too challenging but it is worth spending time on the concept of drift velocity and the explanation of how the electric and magnetic forces eventually balance. • Note that $v = \frac{E}{B}$ is to be known.
	Mathematical skills This section involves mainly substitution and rearrangement of formulae (A17) and the knowledge of unfamiliar units.

Syllabus B15: Special relativity

Topic: Maxwell's equations and the speed of light

Learning objectives

15.1* recall that Maxwell's equations describe the electromagnetic field and predict the existence of electromagnetic waves that travel at the speed of light (Maxwell's equations are not required)

Notes

- Begin by drawing on GCSE experience to reinforce the concept of a field in space – e.g. using simple electrostatic and magnetostatic demonstrations.
- The field concept is a radical one – it replaced 'instantaneous action-at-a-distance' with local action (charges are affected directly by fields where they are rather than distant charges).
- The field concept is linked to a causal chain – moving one charge affects the nearby field, which affects the field a little farther out and so on until eventually a change in field affects a distant charge.
- Maxwell unified EM phenomena such as Faraday's law, Ampere's theorem, Gauss' law etc… into a set of four equations.
- A disturbance in the field at one point (e.g. by accelerating a charge) affects the field at nearby points **with a delay**. Maxwell's equations can be used to derive the speed at which wave-like disturbances travel through the field –

  $$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$
- The speed of EM waves is the speed of light. Light is an EM wave.

Mathematical skills

- With a good group you might like to show them the equations and describe them qualitatively – but with a weaker group this would be counter-productive. (A7)

Syllabus B15: Special relativity

Topic: the ether hypothesis

Learning objectives

15.2* recall that analogies with mechanical wave motion led most physicists to assume that electromagnetic waves must be vibrations in an electromagnetic medium (the ether) filling absolute space

15.3* recall that experiments to measure variations in the speed of light caused by the Earth's motion through the ether gave null results

Notes

- Start by reviewing ideas of mechanical waves: e.g. sound, water waves, slinky – all require a medium, all require the vibration of mechanical particles… but light can travel through a vacuum, so **what vibrates?**
- Emphasise that a mechanical world view (e.g. a Newtonian view) leads to the idea that light needs a medium too – hence the Ether hypothesis.
- Explore the consequence of the ether hypothesis and link it to the Newtonian view of absolute space – if the ether fills (and is at rest in) absolute space then the speed of light is relative to this and a moving observer must see a variable speed of light.
- The Michelson-Morley experiment is worth describing and you may wish to discuss explanations for the null results – e.g. that the Earth drags ether with it or that the arms of the interferometer shrink as they move through the ether (Lorentz-Fitzgerald contraction).

Mathematical skills

- Relative velocity vectors can be used to calculate the effect of observer and apparatus motion through the ether on the measured speed of light (in 1D this is simply $c \pm v$).
- The Michelson-Morley experiment should be described and for good groups the delay can be calculated. (A16, A17)

Syllabus B15: Special relativity

Topic: the principle of relativity and time dilation

Learning objectives

15.4* understand that Einstein’s theory of special relativity dispensed with the ether and postulated that the speed of light is a universal constant

15.5* state Einstein’s special principle of relativity and recall that the constancy of the speed of light may be interpreted as a consequence of this

15.6* explain how Einstein’s postulate leads to the idea of time dilation expressed by the equation $t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$ and that this undermines the ideas of absolute space and time

Notes

- The most important idea to get across is that in the Newtonian world every observer operates in and measures the same absolute framework of space and time whereas in Einstein’s universe all observers have the same laws of physics but spatial and temporal measurements are relative.
- Einstein’s principle of relativity can be introduced via Galilean relativity: The laws of **mechanics** are the same in all inertial reference frames. Ask them about jumping up and down or dropping something in a plane. Einstein extended the principle to **all** the laws of physics (i.e. mechanics and EM).
- The speed of light follows from Maxwell’s equations so it must be the same value for all inertial observers.
- Compare light and sound. Sound travels through air and if the air is moving past an object the sound travels past the object at a speed greater / less than the speed of sound. This can never happen with light.
- When discussing time dilation between two moving inertial observers point out that it is arbitrary which one is taken to be ‘at rest’ and which one ‘moving’. Each sees the other’s clock slow down.
- N.B. The ‘paradox’ in the twin paradox is the apparent lack of symmetry – not the time difference.
- Point out that time dilation effects have been tested and verified repeatedly in particle accelerators and that time dilation makes time travel into the future science fact.

Mathematical skills

- The simplest derivation of the time dilation formula is probably by comparing two ‘light clocks’. All students ought to be able to cope with this.

Syllabus B16: Molecular kinetic theory

Topic: gas laws and temperature

Learning objectives

16.1 explain how empirical evidence leads to the gas laws and to the idea of an absolute scale of temperature

16.2 use the units Kelvin and degrees Celsius and convert from one to the other

16.3 recognise and use the Avogadro number $N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$

16.4 recall and use the expression

$$pV = nRT$$

as the equation of state for an ideal gas

Notes

- This is a good opportunity for a circus of experiments with different groups reporting back on results from testing each of the gas laws.
- Charles' law and the pressure law should give reasonable extrapolated predictions of absolute zero.
- This section could be used to review ideas of calibration using fixed points but don't get too side-tracked by subtleties of the triple point!
- The constant volume gas thermometer can be mentioned as an approximate practical realisation of the thermodynamic scale.
- Emphasise the need to convert temperatures in Celsius to the Kelvin scale before substituting into the gas law equations.
- The concept of the mole is simple but often seems to confuse students – it may be worth giving them some simple exercises calculating numbers of particles in known masses of gas, but to do this you will need to remind them of the idea of molar mass (and its close relation mass number).
- Describe the gas laws as macroscopic descriptions – at this stage the microscopic structure of a gas is irrelevant.

Mathematical skills

- Use the gas laws and ideal gas equation to practise rearranging equations. (A16, A17)
- Calculations involving the Avogadro number involve large numbers and manipulation in standard form. (A4, A5)

Syllabus B16: Molecular kinetic theory

Topic: the particle model

Learning objectives

16.5 describe Brownian motion and explain it in terms of the particle model of matter

16.6 understand that the kinetic theory model is based on the assumptions that the particles occupy no volume, that all collisions are elastic, and that there are no forces between particles until they collide

16.7 understand that a model will begin to break down when the assumptions on which it is based are no longer valid, and explain why this applies to kinetic theory at very high pressures or very high or very low temperatures

16.8 derive:

$$pV = \frac{1}{3}Nm\langle c^2\rangle$$

from first principles to illustrate how the microscopic particle model can account for macroscopic observations

16.9 recognise and use the expression:

$$\frac{1}{2}m\langle c^2\rangle = \frac{3}{2}kT$$

16.10 understand and calculate the root mean square speed for particles in a gas

Notes

- Take care to demonstrate Brownian motion clearly – a smoke cell and a microscope connected to a flexicam and TV can be used to demonstrate to the class in a darkened room.
- Einstein’s 1905 analysis of Brownian motion finally led to the widespread acceptance of atoms and molecules as aspects of physical reality rather than mathematical artefacts.
- Idealised models such as kinetic theory provide an opportunity to discuss the nature of physical theory and its relation to physical ‘reality’.
- Explaining macroscopic phenomena (LHS of equation) in microscopic terms (RHS of equation) is an example of reductionism in physics.
- Don’t get bogged down with the subtleties of deriving the kinetic theory equation – the important ideas are that pressure arises from summing and averaging the rate of molecular momentum change at the walls of the container.
- Boltzmann’s life, contribution to physics and tragic death provides a fascinating background story for this section.

Mathematical skills

- Some tricky ideas here: e.g. mean-squared velocity, root-mean-square speed. Start simply, with a few particles, and then generalise. (A27)
- Note that the average velocity of the molecules of a gas is 0. Squaring, averaging and then square rooting can be seen as one way of avoiding a problem caused by negative velocities.
- It might be helpful to think of the gas constant R as the molar equivalent of the Boltzmann constant k ($R = N_A k$).

Syllabus B16: Molecular kinetic theory

Topic: first law of thermodynamics and the Boltzmann factor

Learning objectives

16.11 understand the concept of internal energy as the sum of potential and kinetic energies of the molecules

16.12 recall and use the first law of thermodynamics expressed in terms of the change in internal energy, the heating of the system and the work done on the system

16.13 recognise and use the expression $W = p\Delta V$ for the work done on or by a gas.

16.14 understand qualitatively how the random distribution of energies leads to the Boltzmann factor

$$e^{-\frac{E}{kT}}$$

as a measure of the chance of a high energy

16.15 apply the Boltzmann factor to activation processes including rate of reaction, current in a semiconductor and creep in a polymer

Notes

- In an ideal gas the potential energy (ignoring gravity) is zero since the particles do not exert forces on one another except in collision. This is not the case for real gases.
- A suitable algebraic form for the first law is:
  $\Delta U = W + Q$
  or alternatively
  $\Delta U = Q - p\Delta V$
  where $p\Delta V$ is the work done by the gas.
- No need for detail of the Maxwell-Boltzmann distribution, but it is worth discussing graphs showing distributions of molecular energies and speeds.
- Beware of signs – the first law is expressed differently in different books – the key is to think of whether work is done on or by the system and whether energy is flowing into or out of the system.

Mathematical skills

The simplest way to ‘justify’ the Boltzmann factor as an exponential is to think of activation processes requiring particles to climb an ‘energy ladder’ as a result of ‘fortunate collisions’ (ones which add energy. If there is a constant probability for each such collision the chance of acquiring energy E falls off exponentially with E. (B1)

Syllabus B16: Molecular kinetic theory

Topic: the second law of thermodynamics and entropy

Learning objectives

16.16* describe entropy qualitatively in terms of the dispersal of energy or particles and realise that entropy is related to the number of ways in which a particular macroscopic state can be realised

16.17* recall that the second law of thermodynamics states that the entropy of an isolated system cannot decrease and appreciate that this is related to probability

16.18* understand that the second law provides a thermodynamic arrow of time that distinguishes the future (higher entropy) from the past (lower entropy)

16.19* understand that systems in which entropy decreases (e.g. humans) are not isolated and that when their interactions with the environment are taken into account their net effect is to increase the entropy of the Universe

16.20* understand that the second law implies that the Universe started in a state of low entropy and that some physicists think that this implies it was in a state of extremely low probability

Notes

- While the syllabus statements are qualitative a microscopic understanding of entropy needs some discussion of:

  (i) Probability (e.g. of distributing particles in a container or of energy distributed amongst particles

  (ii) Distributions (use analogies of tossing 100 coins or getting a favourable hand in poker)

  (iii) Number of ways of distributing energy amongst states (or atoms) e.g. energy shuffling exercises or simulations.
- Contrast the irreversibility of the second law with the reversibility of Newtonian mechanics and point out that kinetic theory is based on mechanics.
- Heat engines could be discussed and simple flow diagrams used to show how energy must be ‘dumped’ in the environment to ‘pay’ for the work extracted (and ensure entropy increases).

Mathematical skills

- Good groups can investigate number of ways and probabilities in more detail – the Einstein one-dimensional solid is an interesting (but challenging) model. (A27)
- Some teachers may wish to take this topic further by using some simple macroscopic equations linking entropy change to heat flow, e.g.

  $$\Delta S = \Delta Q/T$$

  allowing simple analysis of heat engines, limits to efficiency and the inevitability of heat flow from hot to cold.

Syllabus B17: Nuclear physics

Topic: equations of radioactive decay
mass excess and nuclear binding energy
antimatter
the standard model

Learning objectives

17.1 show that the random nature of radioactive decay leads to the differential equation $\frac{dN}{dt} = -\lambda N$ and that $N = N_0 e^{-\lambda t}$ is a solution to this equation

17.2 recall that activity $A = -\frac{dN}{dt}$ and show that $A = \lambda N$ and $A = A_0 e^{-\lambda t}$

17.3 show that the half-life $t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

17.4 use these equations to solve problems

17.5 recognise and use the expression $I = I_0 e^{-\mu x}$ as applied to attenuation losses

17.6 recognise that radiation emitted from a point source and travelling through a non-absorbing material obeys an inverse square law and use this to solve problems

17.7 estimate the size of a nucleus from the distance of closest approach of a charged particle

17.8 understand the concept of nuclear binding energy, and recognise and use the expression $\Delta E = c^2 \Delta m$ (binding energy will be taken to be positive)

17.9 understand and explain the curve of binding energy per nucleon against nucleon number

17.10 recall that antiparticles have the same mass but opposite charge and spin to their corresponding particles

17.11 relate the equation $\Delta E = c^2 \Delta m$ to the creation or annihilation of particle- antiparticle pairs

Notes

- In this area we tend to move seamlessly from number of atoms/nuclei to rate of decay/activity and so on to count rate. These are different quantities and it is worth emphasising to pupils that the readiness with which they are interchanged follows from their proportionality.
- 17.4 says it all. Candidates often stumble at the first hurdle because they do not know what the symbols in the 17.1–17.3 equations represent. Questions on radioactive decay are commonplace and so it is essential students have much practice in solving typical problems.
- The inverse square law also includes coverage of I vs x and I vs $1/x^2$ graphs in addition to calculations.
- Exponential decay curve questions are possible for attenuation loss situations.
- For 17.7 consider Rutherford's calculations for alpha particles and nuclei of gold. Students often fail to include the value of fundamental charge. Relate answers to earlier estimates in 8.2. The more able will enjoy extension work involving the density of nuclear matter.
- Probably easiest to mention the strong force at the outset. Students will then understand idea of work done to separate stationary nucleons.
- Note the reference to 'mass defect', Δm, in the contents list, too, and that the amu is quoted in the list of data.
- Binding energy is sometimes misunderstood as it is the energy required to split up a particle into its constituents. Hence, the larger the BE the more tightly bound is the nucleus.
- Extend student experience in their use of $\Delta E = c^2 \Delta m$ *and their units conversions*. Note that Δm is quoted in kg or amu, ΔE is quoted in J or eV, but stress that only J and kg are allowed when substituting in the formula.
- Draw attention to pairs other than electron/positron. Possibly cover content of 17.5 so that other leptons and quarks can be included.
- Explain that in annihilation momentum is conserved hence photon production. Students often make heavy weather of these calculations because the phenomena seem so bizarre.

<table>
<tr><th colspan="2">Syllabus B17: Nuclear physics (continued)

Topic: equations of radioactive decay
mass excess and nuclear binding energy
antimatter
the standard model</th></tr>
<tr><td rowspan="2">17.12 recall the quark model of the proton (uud) and the neutron (udd)
17.13 understand how the conservation laws for energy, momentum and charge in beta minus decay were used to predict the existence and properties of the antineutrino
17.14 balance nuclear transformation equations for alpha, beta minus and beta plus emissions
17.15 recall that the standard model classifies matter into three families: quarks (including up and down), leptons (including electrons and neutrinos), and force carriers (including photons and gluons)</td>
<td>• 17.2 Worth listing all the quarks just for interest. Gives completeness to a study of the standard model.
• Good idea to cover 17.14 before 17.15 so that students will have met the transformation equation they need to fully understand the prediction of the neutrino.
• The more able would appreciate a discussion of the quark transmutation associated with beta decays.
• 17.13 offers real challenge to many. Students often confuse the role played by each conservation law. A vector diagram approach to momentum conservation helps them understand the need for a ‘missing particle’. Suggest you move on to energy considerations and the E_k graph.
• The presence of the antineutrino also ensures that angular momentum (spin) is conserved during beta decay.
• There is no doubt that introducing this particle physics will stimulate much interest and many questions. Potential here for student research and team presentations.</td></tr>
<tr><td>Mathematical skills
17.1 and 17.2 encompass mathematical requirements in (B1, B5 and B8*).
8* involves differential equations of the form $\frac{dx}{dt} = -\lambda x$ which have solutions of the form $x = Ae^{-\lambda t}$. This will only be examined by optional questions in Paper 3.</td></tr>
</table>

Syllabus B18: The quantum atom

Topic: line spectra

energy levels in the hydrogen atom

Learning objectives	Notes
18.1 explain atomic line spectra in terms of photon emission and transition between discrete energy levels 18.2 apply the expression $E = hf$ to radiation emitted in a transition between energy levels 18.3 show an understanding of the hydrogen line spectrum, photons and energy levels as represented by the Lyman, Balmer and Paschen series 18.4 recognise and use the energy levels of the hydrogen atom as described by the empirical equation $E_n = \frac{-13.6eV}{n^2}$ 18.5* explain energy levels using the model of standing waves in a rectangular one-dimensional potential well 18.6* derive the hydrogen atom energy level equation $E_n = \frac{-13.6eV}{n^2}$ algebraically using the model of electron standing waves, the de Broglie relation and the quantisation of angular momentum	• 18.1, 18.2 and 18.3 can be treated as one subsection. Some historical background on models of the atom and discovery of emission spectra can be an effective introduction. • Revise appropriate terminology, the expression $E = hf$ and the conversion of units covered in section 9 and typical wavelengths and frequencies of the electromagnetic spectrum. Cover meaning of 'discrete'. • Stress that 'larger energy gaps' yield shorter wavelength photons. It is helpful to many students to progress through the series so that they can appreciate how different parts of the em. spectrum are emitted. Good software is helpful in illustrating this. • Worth clarifying the meaning of 'ground state' and 'excited states' as introduction to the 'potential well' idea. • Stress that 'energy transition arrows' on diagrams must begin and finish on energy level lines and 'downwards' indicates emission. • Possibly construct a diagram, to scale, of hydrogen energy levels in eV after calculating E_n for different principal quantum numbers, n. Relevance of negative sign. • 18.5 and 18.6 will only appear in section B of Paper 3 in Optional questions. • Students have met the concept of standing waves in section 6 and so should accept the usual diagrammatic representation of de Broglie wavelengths bound by the electron orbit. The algebra of the derivation is not onerous but the challenge is to link the ideas of the electron particle, its wave and further quantisation. • More able students enjoy deeper discussion of probability, the Bohr radius and the Schrodinger atom. • Some value here in discussing practical applications viz. lasers, fluorescent lamps, scintillation counters etc.
	Mathematical skills Manipulation of formulae (A15, A16 and A17).

Syllabus A19: Interpreting quantum theory

Topic: the double slit experiment

Learning objectives

19.1 interpret the double slit experiment using the Copenhagen interpretation (and collapse of the wave-function), Feynman's sum-over-histories and Everitt's many-worlds theory

19.2 describe and explain Schrödinger's cat paradox and appreciate the use of a thought experiment to illustrate and argue about fundamental principles

19.3 recognise and use $\Delta p \Delta x \geq \frac{h}{2\pi}$ and $\Delta E \Delta t \geq \frac{h}{2\pi}$ as forms of the Heisenberg uncertainty principle and interpret them

19.4 recognise that the Heisenberg uncertainty principle places limits on our ability to know the state of a system and hence to predict its future

19.5 recall that Newtonian Physics is deterministic but quantum theory is indeterministic

19.6 explain why Einstein thought that quantum theory undermined the nature of reality

Notes

- Historically Thomas Young's double-slit experiment measured the wavelength of light and showed that interference effects could be explained using a wave model.
- Students have already seen that the photoelectric effect cannot be explained using a simple wave model and that Einstein's photon theory has aspects of a particle model.
- It is important to emphasise that the incompatibility of the wave and particle models shows that neither captures the essence of light as a quantum object. This suggests that there is no classical analogue for quantum objects even though we can model their behaviour mathematically.
- Try to avoid spending too much time simply describing the interpretations – there is an opportunity to get students to research the interpretations and to debate their merits. They should also be encouraged to reflect on the relationship between models in physics and physical reality – in fact the very idea of an objective physical reality is challenged by quantum theory.
- The different interpretations and their philosophical implications are discussed in more detail in the notes that on pages 84–89.

Mathematical skills

This section can be approached in a qualitative and discursive way but there are good simple derivations and applications of the uncertainty principle (e.g. resonances in particle physics and a quantum explanation of diffraction.)

Syllabus B20: Astronomy and cosmology

Topic: standard candles and stellar radii

Learning objectives

20.1 Understand the terms 'luminosity' and 'flux'

20.2 Recall how flux reduces as an inverse square law $F = \frac{L}{4\pi d^2}$

20.3 Understand the need to use standard candles to help determine distances to galaxies

20.4 recognise and use Wien's law: $\lambda_{max} \propto \frac{1}{T}$ to estimate the peak surface temperature of a star either graphically or algebraically

20.5 recognise and use Stefan's law for a spherical body: $L = 4\pi\sigma r^2 T^4$

20.6 use Wien's displacement law and Stefan's law to estimate the radius of a star

Notes

- Luminosity of a star is its total power output (e.g. the Sun has a luminosity of about 3.8×10^{26} W). A good order of magnitude estimate of this can be made by estimating the Sun's intensity at the Earth's surface (e.g. by comparing it with a lamp of known power) and then using the inverse-square law.
- The luminosity of the Sun can be expressed as 380 yottowatts (YW), which can cheer students up.
- A standard candle is an object whose absolute luminosity is known. The inverse-square law is then used to calculate distances. Different types of objects are used at different distances on the cosmic distance scale.
- The two most important standard candles are:
  Cepheid variables.
  Type 1A supernovae
- The black-body radiation spectrum might have been mentioned in section A9 but if not it makes sense to introduce this by looking experimentally at the spectrum from a filament lap as the temperature is increased. Wien's law relates to the peak of the ideal black-body spectrum.
- Beware the tendency of students to refer to λ_{max} as the maximum wavelength.
- Dimensional analysis can be used to check the units for σ.
- Stefan's law can be used to estimate the temperature of a bulb filament by equating power input (IV) to power output and assuming the output is all radiated from the surface of the filament.
- To estimate stellar radii you will need the luminosity and peak wavelength for the star. This can be carried out experimentally for the Sun.

Mathematical skills

(A4, A5, A6, A17 and A25)

Syllabus B20: Astronomy and cosmology

Topics: Hubble’s law

Learning objectives

20.7 understand that the successful application of Newtonian mechanics and gravitation to the Solar System and beyond indicated that the laws of Physics apply universally and not just on Earth

20.8 recognise and use:

$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$ for a source of electromagnetic radiation moving relative to an observer.

20.9 state Hubble’s law and explain why galactic redshift leads to the idea that the Universe is expanding and to the Big Bang theory

Notes

- The historical and philosophical significance of 20.7 may well have been discussed previously but our knowledge of the distant universe depends on the assumption that the laws of physics are the same there as here.
- Students should be reminded that the speed of light is independent of the source or observer velocities.
- Even at this level students find it difficult to separate red-shifts from redness!
- There are some galactic blue-shifts, but only for nearby galaxies where their own local motion towards us exceeds the recession velocity due to cosmic expansion.
- Distinguish cosmic red-shifts due to expansion from Doppler shifts due to motion. This is important – expansion allows the relative recession velocity of distant galaxies to exceed c and hence create an horizon. If the galaxies were rushing away from us through an ether or absolute space then their maximum recession velocity would be c.
- As the Sun rotates, the Fraunhofer lines are (measurably, but very slightly) red-shifted on the receding side and blue shifted on the approaching side. The Sun, however, does not have a redder half and a bluer half.

Mathematical skills

- With mathematically able students it may be worth exploring the limitations of the simple Doppler formula by incorporating the effects of relativistic time dilation on the source frequency.

Syllabus B20: Astronomy and cosmology **Topics: Big Bang theory and the age of the universe**	
Learning objectives 20.10 explain how microwave background radiation provides empirical support for the Big Bang theory 20.11 understand that the theory of the expanding Universe involves the expansion of space-time and does not imply a pre-existing empty space into which this expansion takes place or a time prior to the Big Bang 20.12 recall and use the equation $v = H_0 d$ for objects at cosmological distances 20.13 derive an estimate for the age of the Universe by recalling and using the Hubble time $t \approx \frac{1}{H_0}$	**Notes** • Student research and presentations on competing theories of the structure of the universe (e.g. Steady State v Big Bang) will highlight the need for evidence. • The discovery of the microwave background radiation by Wilson and Penzias is an interesting historical story and well worth discussing. • More recent measurements and sky maps of the cosmic background radiation (by COBE and by WMAP) have provided crucial support for the Big Bang theory and have enabled cosmologists to refine their value for the Hubble constant and their estimates of the age of the universe. • Students should have some idea of the age and size of the visible universe. • The conceptual shift from a Big Bang in pre-existing empty space to the idea that it is the origin of space and time and that the expansion represents a changing scale is tricky and needs patient explanation and discussion. • The equation $v = H_0 d$ can be better understood when explained backwards. An object that has been travelling at twice the speed of another for the age of the universe is twice as far away. • The Hubble time is derived by assuming that the galaxies have had their current recession velocities ever since the Big Bang. This is likely to be an underestimate of age since galaxies have probably been slowing down.
	Mathematical skills The form of the Hubble law can be derived from a simple 1D model of equally spaced galaxies along a stretchy ruler – if the ruler's length is doubled then the distance between each galaxy doubles and the recession velocity of any pair of galaxies is directly proportional to their initial separation. (A9, A10)

Suggested experiments for Cambridge Pre-U Physics

Adapted from a document by Nick Fisher, Deputy Head Truro School (formerly Head of Science Rugby School).

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
1. Mechanics Scalars and vectors Moment of a force Kinematics Newton's laws of motion Conservation of linear momentum Pressure	Difficult concepts: • Rate of change (of momentum) • Projectile motion	• free fall under gravity using a digital camera • measuring impact forces using force sensors • video motion to plot motion graphs and estimate accelerations and forces • similarly, use pre-recorded events in Cambridge Multimedia Motion CD for analysing motion • force boards (analogy with rock climbing equilibrium of forces) • investigating projectiles using ball-bearings rolling down curtain track • 'monkey and hunter' demo • estimating the speed of an air rifle pellet using light gate and conservation of momentum in an inelastic collision with a cart • collision of frictionless pucks of different masses in 2-D to simulate particle collisions and momentum conservation
2. Gravitational fields Gravitational field strength Centre of gravity	Gravitational field is included to help prepare the concept for study of electromagnetic and gravitational fields from Part B The moment of a force from the Mechanics unit is needed before looking at centre of gravity idea	• stability of model fork lift trucks • centre of mass of an irregular laminar sheet using a plumb-line

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
3. Deformation of solids Elastic and plastic behaviour Stress and strain		• 3-point bend test • Young Modulus of a metal and a polymer
4. Energy concepts Work Power Potential and kinetic energy Energy conversion and conservation Specific latent heat Specific heat capacity		• hysteresis of rubber and work done in heating rubber from area within hysteresis loop • estimating the height of launch of a projectile from a catapult force-extension graph • bungee challenge (modelling using Lego and knitting elastic) • measuring the specific heat capacity of a metal and of water • measuring the latent heat of fusion of sodium acetate in a 'hand warmer' by using it to heat water
5. Electricity Electric current Potential difference and electromotive force Resistance and resistivity Conservation of charge and energy		• measuring internal resistance of a solar cell using a graph of terminal p.d. against current • measuring the maximum power of a cell by connecting load resistors • resistance of conducting putty and shape • resistivity of a metal wire by plotting resistance against length • modelling an archaeological resistance survey • potential dividers and a potentiometer balancing an emf • use of wheatstone bridge to detect small resistance changes

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
6. Waves Progressive waves Longitudinal and transverse waves Electromagnetic spectrum Polarisation Refraction	Waves must be studied before quantum ideas and before the unit on superposition	• polarisation of microwaves and strength of signal as receiver is rotated • GHz aerial transmitter/receiver kit to reduction in signal strength with distance • measuring Brewster angle with a polarising filter, glass block and ray box • measure refractive index of air to glass
7. Superposition Phase difference and path difference Diffraction N-source interference Standing waves	Superposition must be studied before quantum ideas. Phase angles in degrees.	• ripple tank practicals: diffraction and interference • diffraction of microwaves through a slit • laser light through an adjustable slit • signal generator, two loudspeakers and a microphone and oscilloscope (superposition of sound) • adjustable slits and coloured lamps to estimate resolving power • diffraction grating to measure the wavelength of monochromatic light • Melde’s method for investigating standing waves on a string • use of a sonometer or guitar string and audacity software to investigate how the length of string affects fundamental frequency • recording notes from a recorder using audacity to measure the speed of sound in air • confirming the speed of microwaves in a microwave oven using the idea of standing waves heating marshmallows, butter, etc. • model CD player using microwaves • GHz aerial transmitter/receiver kit to measure wavelength of standing waves

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
8. Atomic and nuclear The nucleus Nuclear processes Probability and radioactive decay Fission and fusion	Predicting activity after an integer number of half lives only The use of the exponential function is not introduced until unit 17 Nuclear Physics	• diffusion cloud chamber to investigate length of alpha tracks and estimate energy of alpha particles • absorption of alpha, beta and gamma with paper, aluminium and lead (no exponential needed) • half life idea using dice and coins • half life of protactinium
9. Quantum ideas The photoelectric effect The photon Wave-particle duality		• zinc plate, gold leaf electroscope, e.h.t. and u.v. lamp • colour of light and energy of photoelectrons using stopping voltage • graph of triggering voltage against frequency for different coloured LEDs to estimate Planck's constant • optical analogue of electron diffraction • electron diffraction by graphite
10. Rotational Mechanics (Part B)* Kinematics of uniform circular motion Centripetal force Moment of inertia Kinematics of rotational motion	Part B syllabus material Use of integration to calculate the moment of inertia of a ring, disk and rod. These more mathematical parts are only assessed in Section B of Paper 3 (approximately half of the unit) This unit introduces the radian. Rotational mechanics is included before Oscillations as it may help to study angular velocity and the radian before the mathematical analysis of simple harmonic motion	• measuring centripetal force at different speeds and radii • hollow and solid cylinders rolling down slopes • measuring the moment of inertia of a flywheel using energy transfer of GPE to translational and rotational KE

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
11. Oscillations* Simple harmonic motion Energy in simple harmonic motion Forced oscillations, damping and resonance	The more mathematical analysis is only assessed in Section B of Paper 3 (approximately one third of the unit) Studying rotational dynamics at the end of Year 1 introduces the radian and period before meeting oscillations Solutions to differential equations describing SHM need to be derived in this unit	• period of a simple pendulum • period of mass on a spring • oscillation of a tethered trolley • resonance of hacksaw blade with magnet, electromagnet and signal generator • Barton's pendulums • vibration generator K'Nex and simulation of resonance of buildings in seismic zones
12. Electric Fields* Concept of an electric field Uniform electric fields Capacitance electric potential electric field of a point charge	Inverse-square law – possible power law test from data using log-log graphical analysis Integration of inverse-square force to derive potential energy (only assessed in Section B of Paper 3) Exponential decay for capacitors is not in the syllabus as the concept of exponential change is dealt with in the Nuclear Physics unit	• electric fields using different shaped electrodes, e.h.t., castor oil and semolina (or grass seeds) • coulombmeters (or reed switches and galvanometers), capacitors and charge-voltage graphs • charging a 10 000 μF capacitor at different p.d. and discharging through an array of lightbulbs

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
13. Gravitation Kepler’s laws Newton’s law of gravity Gravitational field of a point mass Gravitational potential energy	Centripetal force (from the Rotational Mechanics unit) is needed Inverse square law for gravity Power law test using log-log graphical analysis for planetary data on radius and period of orbit	
14. Electromagnetism Concept of a magnetic field Force on a current-carrying conductor Force on a moving charge Electromagnetic induction The Hall effect	Electric fields needed before looking at the Hall effect	• motor force using digital balance, uniform magnetic filed and straight current carrying conductor • Hall effect • fine beam tube and Helmholtz coils to measure the specific charge for electrons • investigating strength of magnetic field varying with distance from magnets and electromagnets using search coil and CRO or digital flux meter • dropping neodymium magnet down copper pipe • eddy current braking with spinning disk in magnetic filed from electromagnet • back emf in a d.c. motor: investigating the efficiency of a motor working at constant speed • Hall effect in a semiconductor n type and p type

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
15. Special Relativity (Part B)* Einstein's special principle of relativity Time dilation	Part B Syllabus material Only assessed in Section B of Paper 3 This unit is included in the lower sixth to provide an opportunity to discuss philosophical ideas. It will stimulate some students to give talks and may encourage further background reading over the summer holidays. The electromagnetic spectrum needs to be studied before this topic The mathematics goes no further than Pythagoras' theorem	

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
16. Molecular kinetic theory* Absolute scale of temperature Equation of state Kinetic theory of gases Kinetic energy of a molecule First law of thermodynamics Entropy Thermodynamic arrow of time Second law of thermodynamics	The more descriptive aspects of entropy and are only assessed in Section B of Paper 3 (approximately one quarter of the unit) Use of the Boltzmann factor $e^{-E/kT}$	- 3-D Kinetic Theory Model - Boyle's law - Pressure law apparatus to help determine absolute zero - Boltzmann factor: plot ln I against $1/T$ to determine to what extent the number of free charges is related to $e^{-E/kT}$; measure the rate of a chemical reaction at different temperatures and plot ln(1/time of reaction) against $1/T$ - entropy and a concentration cell: produce an e.m.f. with two beakers of copper sulfate solution at different concentrations
17. Nuclear physics Equations of radioactive decay Mass excess and nuclear binding energy Antimatter The standard model	Use of exponential function Exponential changes with respect to time (activity) and distance (attenuation and losses) It would help to use a number of examples of the exponential function from other areas of physics	- testing exponential decay of the height of water leaking out of a burette with respect to time, ln(h) against t - modelling exponential decay with the head of a pint of beer; coins, dice, etc. - exponential decay of p.d. across a discharging capacitor as a further example of the concept exponential decay with respect to time (capacitor decay not in syllabus) - attenuation of count rate from Strontium-90 beta source absorbed by different thicknesses of aluminium - modelling attenuation of signal using infra-red jelly optical fibre - modelling attenuation using an LDR constant light source and sheets of tracing paper

Outline of content	Notes (sequencing, mathematical issues, etc.)	Suggested practical work
18. The Quantum Atom* Line spectra Energy levels in the hydrogen atom	Electric field for point charges needs to have been covered in Unit 12 Electron standing waves and derivation of the energy level equation for hydrogen will only be assessed in Part B of Paper 3	• spectrum of light from discharge tubes of hydrogen and helium using diffraction gratings • standing wave on a rubber cord of uniform width compared with standing wave on a rubber sheet of varying width • standing wave on a rubber sheet/drum
19. Interpreting Quantum Theory (Part B)* Interpretations of the double-slit experiment Schrödinger’s cat paradox The Heisenberg uncertainty principle	Part B syllabus material Only assessed in Section B of Paper 3 This unit is included in the lower sixth to provide an opportunity to discuss philosophical ideas. It may encourage further background reading over the summer holidays	• interference of single photons using a coarse diffraction grating, 1.25 V, 0.25 A m.e.s. lamp and filters (e.g. fogged photographic film)
20. Astronomy and Cosmology Standard candles Stellar radii Hubble’s law The Big Bang theory The age of the Universe		• inverse square law for light using a torch bulb and LDR • use of Bunsen’s method for estimating the luminosity of the Sun • datalogger spectrum analyser: blackbody spectrum and Wien’s law • use of sound software (e.g. *Audacity*) to measure Doppler shift for sound waves emitted by electronic buzzer

Investigation notes for teachers

The investigation

Each candidate will carry out an individual open-ended investigation occupying at most 20 hours of teaching time and homework (including planning and writing up). The entire 20 hours of the project should be completed within four weeks. The investigation employs and assesses experimental and investigative skills developed through practical work undertaken throughout the course.

The assessment of the Personal Investigation is in two parts.

1. a plan of the project handed in at the end of the first week
2. a written project report handed in at the end of the project

The project report will be marked by the teacher and moderated externally.

Choosing an investigation

This is a real challenge for some students but it is crucial!

A good investigation should:

- be safe
- be open-ended
- be possible – in general, and within the constraints of the school timetable and resources.
- allow for a variety of experiments using a range of apparatus
- yield quantitative data
- involve physics that is not trivial but is accessible to the student (albeit with thought)
- allow the student to be creative in his/her approach
- sustain the student’s interest
- be able to be completed (not necessarily exhaustively) in the allocated time.

Laboratory technicians

We all know how important technical support is to the day to day work of a Physics department, but students may not be aware of our dependence on the expertise (and patience) of our laboratory technicians. Investigative work provides an opportunity for students to interact directly with the technicians over an extended period of time. In many cases the technicians will act as demonstrators and advisers alongside the teacher. This will raise their profile in the minds of the students but do beware that investigative work can put extra pressure on busy technicians and present them with difficulties in what to prioritise. Having said that, technicians usually enjoy the chance to assist the students and students learn to be more appreciative of their support.

Safety

Student plans should be approved before they begin, so the initial experiments should be safe, but you will also need to monitor safety throughout the investigation as they develop their projects and request new apparatus or decide to use existing apparatus in a new way. These requests often pass through the technicians so it is important to establish a protocol that keeps the teacher responsible for safety in the loop.

Laboratory management

An ideal arrangement would be to allocate one laboratory to investigations for each set, and to give an individual space to each student. Approved plans should have provided details of initial apparatus requirements and these can be prepared in the student's area prior to their first lesson.

The start of an investigation is always busy. Students will have additional apparatus requirements and will need one to one discussions with teachers and technicians. If staffing allows it is very helpful to have a second teacher present at the start of an investigation (in schools where a set is shared it would be ideal if both teachers can be present).

Often the laboratory in which the investigations will take place is also needed for regular class teaching and practicals. In this case each student's apparatus can be stored at the end of each lesson on a trolley or in labelled trays which can be stored nearby or in the preparation room. However, some investigations are likely to involve large pieces of equipment that are difficult to move so these may have to remain in place or else these students may be found a separate work place elsewhere.

Monitoring progress

Students are expected to write up their experiments as they go along, keeping a day-by-day diary, processing data and evaluating results and conclusions. In practice this means that teachers need to check work and keep a record of progress during the investigation period. This is part of the assessment.

Writing up

The report of an investigation should include a diary showing what has been done in each laboratory session, but it is also important that the student draws the individual strands of practical work together to state a conclusion and to evaluate the research.

Timeline for an investigation

The flow chart on the next page gives a suggested timeline. The important points are:

- Practical work undertaken throughout the course is essential to ensure students have the necessary skills when they begin.
- Mini-investigations familiarise the students with extended practical work.
- Assessment of mini-investigations familiarise students with marking criteria.
- Classroom discussions clarify the nature of the task.
- Initial planning leads to safe and viable projects.
- Teacher monitoring ensures progress during the investigation.

Investigation plan

Following the flow-chart there is a two-page proforma that could be completed and submitted by students as an investigation plan.

Develop essential skills through practical skills tasks:
- Using different measuring instruments
- Dealing with experimental uncertainties
- Recording and processing data to look for relationships
- Writing up experimental work
- Evaluating experimental method and results

Mini-Investigation (e.g. start of U6 spring term):
- Semi-directed tasks
- Assessed using cut-down investigation criteria

Setting the scene and preparing the way:
- Class discussion of ‘appropriate projects’
- Initial topic selction and planning exercises
- Individual preparatory work – research/pilot tests

INVESTIGATION Week 1: The Plan
- Plan – submitted
- Starting point
- Apparatus requirements
- Risk assessment

Marking plan:
Plan is marked and approved/modified by teacher

INVESTIGATION Weeks 2 and 3:
- Individual experimental work
- Written record of work done
- Submission

INVESTIGATION Week 4:
Further experiments if required
Write-up and submission

Marking and internal moderation

INVESTIGATION PLAN

(Resize these text boxes to fit your proposal – the overall plan is expected to cover about two sides of A4)

Student name: **Teaching set:** **Teachers:**

Aim:

Working title:

Outline of initial experiments:

Diagram of initial experimental arrangement:

List of apparatus requirements:

Risk assessment:

Rough breakdown of sequence of work over 2 weeks:

Teacher's comments:

Signature of teacher:

Ideas

The list below is taken from Nick Fisher's (Rugby School) guide to Physics Personal Investigations and it is recommended that teachers download and consult this excellent resource from the Cambridge Pre-U Physics online discussion forum.

The following references are deliberately vague titles. They appear in no particular order, but a quick read through these outline ideas may provide some inspiration. Research questions will need to be developed. Relevant Physics will need to be researched. In consultation with the teacher, it will be helpful for students to explore some of the Physics and develop a focus for a project.

1. Forces acting on a power cable
2. Force time graphs and drop tests for ropes
3. The sagging of the rope in a Tyrolean traverse
4. Energy transfers in a model pole vault
5. Physics of a golf club
6. Bounce efficiency from a tennis racquet
7. Energy transfers and improving the efficiency of a bow and arrow
8. The spin of a ball
9. Impact forces and trainers
10. Shuttlecock design
11. How is the performance of a photovoltaic cell affected by the intensity and frequency of light, and temperature?
12. Resistance of a filament and temperature
13. Making and testing your own resistivity meter
14. Effectiveness of a car radiator
15. Heat pipes: On what does their rate of energy transfer depend and why? How efficient are they?
16. How fast do thermistors and other temperature sensing devices respond and why?
17. Micrometeoroid impact protection
18. Peltier heat pumps
19. Reflectivity of surfaces
20. Thermal insulation
21. Thermal archaeology. Can objects be detected beneath the soil due to their thermal properties?
22. The physics of sound production in a musical instrument
23. Investigation of end correction in wind instruments
24. The refractive index for different colours of light
25. An investigation into the dispersion effects of different materials
26. Pressure and the speed of sound
27. Ring of a bell
28. String telephones

29. What effect can a cylindrical lens have on the image of a point source, and why?
30. The absorption of alpha, beta and gamma radiation by different materials
31. Element detection in glazes with beta ray back-scattering
32. Investigation into thixotropy of custard and tomato ketchup
33. Design, make, calibrate and use your own rate of flow meter
34. The bendiness of wafers using a three-point bend test to measure the Young modulus etc.
35. How does the rotation of the plane of polarisation depend on the wavelength of visible light?
36. Photoelasticity
37. Greenhouse design and light input
38. Designing a hot-wire anemometer
39. Impact protection of packaging
40. Sound spectra from cracking brittle materials
41. Surface tension and temperature
42. Surface tension, inks and wrapping materials
43. Vortex shedding and flow
44. Strength of glass fibres
45. Accelerometers
46. Charge in flowing liquids
47. Methods for detecting cracks in rails
48. Eddy current braking efficiency
49. Eddy current braking of coins in slot machines
50. Hydrokinetic braking
51. Pressure and contact resistance
52. Spreader plates and magnetic fields
53. Capacitance of coaxial cable
54. Capacitance of non-parallel plate systems
55. Effect of claddings on optical fibres
56. Energy stored in capacitors
57. Polar liquids in electric fields
58. Response times of LEDs and LCDs
59. Speed of pulses down coaxial cables
60. Sound absorption
61. Reducing earthquake damage to model buildings
62. Vibration isolation of a hi-fi unit
63. Measurement of diameter of dust using diffraction
64. Torque-speed characteristics of electric motor

65. Measurement of a length of coaxial cable using capacitance, i.e. access to one end only
66. Spark gap and air pressure
67. Hysteresis losses in iron cores
68. Build a model suspension system and consider factors which affect amplitude of vibration in a wind
69. Factors affecting magnitude of a.c. current in an inductor/resistor circuit
70. Current/voltage/temperature characteristics of a filament lamp
71. Reflective/absorptive properties of different density materials using ultrasound
72. Does charging time affect the efficiency of recharging batteries?
73. Methods for measuring the viscosity of air
74. Efficiency of windmills
75. Efficiency of a d.c. electric motor
76. Rising bubbles
77. Rocket propulsion
78. Flames in fields
79. Car safety belts
80. A jumping aluminium ring near an alternating magnetic field
81. Gyroscopic effects
82. End corrections in open pipes
83. Bouncing balls
84. Creep in copper wires
85. Bicycle brake block performance
86. Pressure/volume of a balloon
87. Discharge of dry cells
88. Surface tension
89. Measuring speed using the Doppler effect with datalogging software
90. Parachutes
91. Water columns
92. Soap films

Examination advice

Doing the actual papers – some hints for students

The following bullet points list general advice for students sitting physics exam papers. The advice stems from the experience of setting and marking exam papers. While, no doubt, the advice is obvious to teachers, we thought it might be helpful to focus students' minds on guidance that will improve their access to readily available marks.

Structured question papers

Written answers

- Read the question carefully, especially the introductory text in the 'stem' of the question. It sets the scene.
- Make sure you answer the question asked.
- Note the key instruction words such as 'describe', 'explain', 'state', etc. [Worth reading through the definitions of these words at some stage in the course. See Appendix 7 of the syllabus]
- Look to the number of allocated marks. Each will correspond to a specific point.
- Think before you write. Longer answers may be improved by first jotting down key points i.e. outlining a short plan.
- Try to use scientific terminology in your answers.
- If you get stuck at the end of a long structured question remember that there is a logical sequence to the question. Look back over what you have been asked to do; it may help you tackle the last part.
- Finally, always write clearly and in good English. The examiner does have to be able to read and understand it in order to give you credit!

Basic calculations

- Make sure you know how to use the calculator you will be using in the examination (as well as any spares).
- Always show your working.
- First, state the relevant formula and make sure you know what the symbols represent.
- Write a substitution line either before or after you rearrange the formula.
- Take note prefixes with units e.g. mA, μC, nm.
- Make sure you have the correct units for substitution e.g. J, not eV.
- Think about your answer. Is it a sensible value?
- Quote answers to the same number of sig. figs. as given in the question.
- For problems involving several calculations use your calculator values, not rounded off answers – not a problem if you do, though.
- Units for answers are usually provided, but not always. Be alert.
- For vectors, state both its magnitude and its direction unless advised otherwise.

- Make sure you reset the mode on your calculator if you have used radian mode and then later need degree mode.
- Set work out as neatly as you can so that a quick check at the end of the exam (should time allow) is possible.
- Refer to the data sheet provided for values of constants. E.g. $g = 9.81\ \mathrm{N\ kg^{-1}}$, not $10\ \mathrm{N\ kg^{-1}}$. Don't rely on memory.

Graph questions

You are unlikely to have to plot many graphs but, in the event, remember to

- Use sensible scales (multiples of 2, 5, 10 etc.).
- Label axes and state units.
- Draw the best straight line or curve – no 'dot' to 'dot'–with one continuous line.
- Plot points accurately and mark with a cross or encircled dot.
- Draw lines with a sharpened pencil or drawing pen; do not use a ball-point or felt-tip pen.

You are very likely to have graphical exercises to answer as part of a structured question.

- Be prepared to determine the gradient of the graph and explain its physical significance. Note its units.
- Be prepared to read off the intercept and to explain its physical significance.
- Be able to draw direct comparisons between the terms in the equation for a graph and those in the general equation for a straight line.
  e.g. compare $R = W\frac{1}{I} - r$
  with $y = mx + c$
  where gradient $m \equiv E$ and intercept $c \equiv -r$
- Be able to recognise the effect of changing a physical quantity e.g. E on the gradient or e.g. r on the intercept.
- Know the typical shapes of graphs e.g. inverse square law, direct proportionality, exponential decay.
- Be able to use data from these graphs to verify that they obey the given relationship.

Multiple-choice papers

There are many different styles of question, too many to outline here, but students are often best going for their first choice and then moving on. Prevarication wastes valuable time.

Multiple-choice questions

- Better to first solve the problem and then to look for the option that matches your answer.
- If you are not sure how to solve it reduce your options by eliminating obvious wrong answers before selecting a possible right answer.
- If you can eliminate some answers but not eliminate all but one, make a note of those that have been eliminated so that if you have to guess later, you won't guess ones that you have eliminated earlier.
- Use the white space provided in the question paper to scribble working so that you can retrace the steps of your calculation if you need to, and as an aid when checking your answers.

Recommended texts

Author	Title	Publisher	Comment
GENERAL			
Adams S Allday J	*Advanced Physics*	Oxford University Press	An excellent comprehensive text which is detailed and stimulating to read. Very much the modern textbook which also includes a full mathematical exposition where further challenge is possible.
Duncan T	*Advanced Physics*	John Murray	The text is readily accessible to students, and provides full explanations that read well. Numerous examples of practical situations and problems are discussed.
Johnson K Hewett S Holt S Miller J	*Advanced Physics for You*	Stanley Thornes	This textbook has numerous worked examples, helpful chapter summaries and an easy-to-read style. It falls between the categories of standard textbook and a revision guide.
PHILOSOPHY OF PHYSICS			
Cushing J	*Philosophical Concepts in Physics*	Cambridge University Press	This places advances in physics against a historical and philosophical background. While it is a good resource for the teacher, relevant sections are also accessible to the well-motivated student.
Einstein A Infield L	*The Evolution of Physics*	Cambridge University Press	An old book but one that gives a careful conceptual explanation of the growth of physical ideas. It is well-written and will engage the intellectually curious student.
ADVANCED TEXTS FOR TEACHERS			
Einstein A and others	*The Principle of Relativity*	Dover	A collection of original papers on the special and general theory of relativity. Dover, 1952. Einstein's early papers are accessible to very good students.
Feynman R Leighton R Sands M	*The Feynman Lectures on Physics Volume 1*	Addison-Wesley	An inspired classic. The following chapters are recommended for teachers: Feynman Lectures I: 37 Quantum Behaviour: 37.1 to 37.8 Feynman Lectures I: 38 The Relation of Wave and Particle Viewpoints. 38.6
Galileo G	*Dialogue concerning the two chief world systems*	University of California Press	A surprisingly readable and intellectually exciting classic from the history of science.

Author	Title	Publisher	Comment
Longair M	*Theoretical Concepts in Physics*	Cambridge University Press	This is an inspiring book that deals with the development of key ideas in a series of illuminating case-studies. Great to dip into!
Wheeler J.A. Zurek W.H. (Editors)	*Quantum Theory and Measurement*	Princeton University Press	Original papers tracing the debates about the interpretation of quantum theory and the measurement problem.
COSMOLOGY			
Tayler Roger J	*The Hidden Universe*	Ellis Horwood	Very detailed specialist text suitable for reference but also well written and accessible.
Tayler R.J	*The Stars: their structure and evolution*	Cambridge University Press	A good reference book, recently revised, with full background information and explanations.
Scott Carole (editor)	*Images of the Universe*	Cambridge University Press	A series of articles written by specialist authors such as Martin Rees, Malcolm Longair and Heather Couper etc covering a wide range of topics. Suitable for all, including the devotee sixthformer.
Arny Thomas T	*Explorations. An introduction to Astronomy*	Mosby	Although only chapter 16 is dedicated to Cosmology there is much to enjoy dipping into. It is fully illustrated with many explanatory diagrams and pictures. A useful, comprehensive reference.
Background Reading			
Al-Kahlil J	*Quantum*		A modern foray into the world of quantum mechanics. Difficult concepts are tackled head-on.
Atkins P	*Four Laws That Drive the Universe.*	Oxford University Press	One of the most concise and clearest introductions to the laws of thermodynamics.
Baker J	*50 Physics Ideas You Should Know*		This book provides an interesting and immediate snapshot of prominent physics ideas resulting in familiarity but without too much depth.
Bishop C	*Advanced Physics Readers:* *Astrophysics*	John Murray	One of an excellent series, covering all and more of the specification. It goes well beyond but proves to be a reliable reference for all the immediate astrophysics and cosmology you are likely to need.
Close F	*The Cosmic Onion*	Heinemann	A classic text, possibly more appropriate for teachers than students. Detailed background information.

Author	Title	Publisher	Comment
Close F Marten M Sutton C	*The Particle Explosion*	Oxford University Press	Students will enjoy browsing through the vast array of beautiful photos. Visually stimulating, but supported by a detailed fascinating text.
Farmelo G	*The Strangest Man*	Faber & Faber	A recent detailed biography of Paul Dirac, one of Britain's greatest but least known physicists.
Feynman R	*QED – The strange theory of light and matter*	Princeton University Press	Feynman gives a brilliant explanation of the underlying quantum principles governing the interaction of light and electrons. Some parts require careful thought but it is a very rewarding book that gives a real insight into the mature of the quantum world.
Frayn M	*Copenhagen*	Methuen	Frayn's play about the enigmatic wartime encounter between Bohr and Heisenberg touches on many of the philosophical and ethical questions raised by nuclear and quantum physics.
Harrison E	*Cosmology*	Cambridge University Press	This well-written book shows how fundamental physical principles can be applied to the universe as a whole. It contains some excellent discussions on the philosophical implications of cosmological models and ideas.
McGuinness M Schwartz A	*Einstein for Beginners*		OK it's a cartoon book …. But it's fun and gives a good overview of Einstein the man and his ideas in the context of his times!
Polkinghorne J	*Quantum Theory. A very short introduction*	Oxford University Press	A convenient pocket-sized book that addresses the subatomic world in simple, non-mathematical language.
Snow C P	*The Physicists*	House of Stratus	A delightful book in which C P Snow relates wonderful anecdotes about the physics 'giants' of the twentieth century, their work and its contribution to a Golden Age in physics.
Weinberg S	*The First Three Minutes*	Flamingo	A pocket-sized paperback that explains, clearly and logically, the first three minutes in the evolution of the Universe. An excellent exposition that appeals to the specialist and layman alike.

Further notes on the interpretation of Quantum Theory

1. Using the Copenhagen interpretation to explain the double slit interference pattern (see *Advanced Physics,* Adams and Allday, OUP. pp. 334–335).

Assume a simple set-up in which monochromatic light from a point source approaches two narrow slits and is detected at a distant screen.

Light travelling from the source is described by a wavefunction, which interacts with both slits and creates a superposition pattern as in conventional wave theory. However, the wavefunction itself is not an observable physical quantity. Its amplitude-squared at each point on the screen is proportional to the probability of locating a photon at that point so the pattern itself is not a *direct* representation of the light intensity on the screen.

If the intensity of light from the sources is high then the actual light intensity pattern *is* the same as the pattern derived from wave theory (this is an example of the correspondence principle). However, if the intensity is low then the pattern can be seen to develop from a series of discrete events in which individual photons arrive at different locations on the screen. The 'intensity' derived from the wavefunction ψ represents the probability distribution for the arrival of photons but each discrete photon arrives in a particular place and is not 'smeared out' across the screen.

$$|\Psi|^2 \propto \text{probability of photon arrival}$$

If an individual photon is emitted and reaches the screen the wavefunction superposition pattern merely gives the distribution of probabilities for its arrival (large near the 'maxima' and small near the 'minima') but it cannot be used to predict where the photon will actually go.

This leads to the inevitable conclusion that two successive photons emitted from the source at the same time are unlikely to end up in the same place on the screen. In other words similar causes lead to *different* effects. This in sharp contrast to classical physics which is *deterministic* (the future is uniquely determined by the present plus the laws of physics). Quantum physics is *indeterministic* (the future is not completely determined by the present plus the laws of physics – it remains open). There is a brief discussion of determinism and indeterminism on page 13 of *Advanced Physics*.

The Copenhagen Interpretation gives two levels of description for the process. Firstly there is the interaction of the wavefunction with the apparatus which sets up a superposition pattern from which probabilities can be derived. Then there is the act of observation at which the wavefunction 'collapses' and a definite result is obtained. This problem of the '*collapse of the wavefunction*' (or the '*measurement problem*') is not explained by quantum physics and takes us from a continuous deterministic theory (the evolution of the wavefunction) to a discontinuous description of the world at odds with classical physics. It also introduces an aspect of non-locality to quantum theory. Prior to the observation the wavefunction extends across the entire screen. Once the observation locates the photon the wavefunction becomes zero everywhere except where the photon is, so an observation here has immediately affected the wavefunction in distant places (non-locally) where the probability of photon detection must fall from a finite value to zero.

2. What Einstein objected to

Einstein was particularly concerned about:

- indeterminacy (Heisenberg's uncertainty principle)
- the statistical interpretation (Born's interpretation)
- non-locality ('spooky action-at-a-distance')
- and the threat to realism (as illustrated in the EPR paradox)

While Einstein's own theory of relativity was radical, his approach was in many respects classical, dealing with continuous fields in space and time. The discontinuities of quantum theory (quantum jumps/collapse of the wavefunction) clashed with his own ideas about the nature of reality. He preferred to think that the indeterminacies and statistical predictions of quantum theory arose from a lack of detailed information about the world rather than a lack of information within it. This is quite subtle but can be illustrated by a parable about 'classical' and 'quantum' coins.

Imagine tossing a classical coin and covering it when it lands. What is the probability that it has landed showing heads up? Most people would say 50% assuming the coin is unbiased. However, on reflection, it is clear that the coin *has already landed* and so it is either heads (100%) or tails (100%). The 50% mentioned earlier refers to *our knowledge of the world*, not about the state of the world itself, which is determined from the moment the coin lands. The probabilities we use in kinetic theory are like this – we don't know the detailed positions and motions of the molecules so we assume that all microscopic configurations are equally likely. Einstein thought that a deeper theory than quantum mechanics would reveal underlying deterministic behaviour as a result of 'hidden variables'.

Now imagine a coin that behaves like a quantum particle with two final states, and apply something akin to the Copenhagen Interpretation to the process. The final state of the system is described by a superposition of wavefunctions representing the heads state and the tails state. When an observation is made the wavefunction collapses into one or other state. This means that the covered (not yet observed) coin is genuinely in a state where it has 50% chance of being heads and 50% chance of being tails. Even the coin does not 'know' what state it is in until we observe it. Prior to observation we cannot ascribe a definite heads or tails state to the coin. This is deeply disturbing to anyone who relies on common sense or classical physics. In classical physics we assume that objects in the unobserved world have definite properties (e.g. position and momentum). Einstein assumed that electrons (for example) had definite properties and that the uncertainly principle simply referred to our inability to measure these properties to infinite precision. In the quantum theory the properties themselves are not precisely defined and this is the root of indeterminism.

N.B. Einstein pursued this further in a famous paper of 1937 usually known as the 'EPR paper' (since the authors were Einstein, Podolsky and Rosen) in which he made a direct challenge on the Copenhagen interpretation by posing a thought experiment in which the uncertainty principle undermines (Einstein's view of) reality (particles possessing definite properties). It was not possible to carry out such an experiment at the time but eventually tests were performed (by Alain Aspect in Paris – testing a statistical correlation called the 'Bell inequality') and their results agreed with quantum theory.

The resources above contain many references to these ideas and experiments although the details are only really for very able students.

3. Schrödinger's cat

There is a brief discussion of Schrödinger's cat on p 335 of *Advanced Physics*.

It is worth pointing out that Schrödinger, like Einstein, was shocked by quantum theory and formulated the 'cat paradox' in order to show that there was something wrong in the conventional interpretation of the theory. The Copenhagen interpretation implies that a quantum system evolves continuously until an observation is carried out, at which time the wave function, which represents a superposition of all possible states of the system, 'collapses' to one definite state – the one registered by the observation. For radioactive decay this implies that the unstable nucleus is in a superposition of decayed and undecayed states. Schrödinger imagined an apparatus that could amplify the quantum effect up to macroscopic size without collapsing the wavefunction. In this case the macroscopic object was a cat. The cat is in a superposition of alive and dead states until an external observer opens the sealed box in which the experiment took place and the wavefunction collapses into one or other state.

There have been many interesting discussions of this experiment and many of these are covered in the resources recommended above. Some important questions can be used for discussion:

- Is there a limiting scale or level of complexity above which quantum effects are no longer relevant?
- What actually counts as an observation – must it be a human observer or does an automatic Geiger counter collapse the wavefunction?
- What causes wavefunction collapse?
- Does this imply we live in an observer-created reality?
- Does quantum decoherence* force a complex system into a classical state?

*Quantum decoherence is a process decribing the effect of a quantum system interacting irreversibly with its environment so that different parts of the system are no longer able to interfere with one another. This means that the system behaves in a classical way and quantum correlations are lost. The prevention of decoherence is a major challenge for designers of quantum computers (which rely on quantum superpositions in order to carry out parallel processing). If decoherence is mentioned an analogy can be made with optical interference. Car headlamps cannot form a two source interference pattern because they are incoherent sources (unlike the two slits in Young's experiment). With incoherent sources the intensities simply add. With coherent sources the amplitudes add (taking into account their relative phases) and the intensities derive from amplitudes-squared. Decoherence effectively destroys the phase relationships between quantum objects in a complex system.

It is worth pointing out that macroscopic quantum objects have now been created (Bose-Einstein condensates, superfluids, superconductors) and that large-scale versions of some classic experiments (double slits) have been carried out and found to agree with quantum predictions. In 1999 a diffraction pattern for C_{60} fullerenes was measured and they went on to demonstrate the interference of $C_{60}F_{48}$, a fluorinated buckyball of mass around 1600u composed of 108 atoms!

So far we have no evidence to suggest that quantum theory 'switches off' at any level of size or complexity although we do find that systems with large numbers of degrees of freedom and large energy tend to behave in a classical way.

One of the philosophical ideas that should be mentioned in this context is *reductionism* – the assumption that the behaviour of a complex system can be understood and explained in terms of the behaviour of its simpler constituents. Quantum theory purports to explain the behaviour of matter on the smallest scale so a simple reductionist view of physics implies that classical physics and all macroscopic observable phenomena should be derivable from quantum theory. An alternative to reductionism is strong emergence, the view that complex systems can exhibit properties and obey rules that are not derivable from the interactions between simpler parts at a lower level. The prevailing view in physics is strongly reductionist, hence the concerns over quantum weirdness and Schrödinger's motivation to publish the Cat 'Paradox'.

4. The uncertainty principle

Werner Heisenberg formulated his own version of quantum theory at about the same time that Erwin Schrödinger proposed the wavefunction. Heisenberg's mathematics looked quite different to Schrödinger's. Whereas the wavefunction itself seemed to describe a continuous process taking place in a quantum interaction (and at first glance looked pretty much like the waves of classical physics), Heisenberg invented a matrix of possibilities linking initial and final states – in other words the observable (measurable) states. There was no attempt to model the hidden process of (for example) photon emission or atomic excitation. Heisenberg's mathematics was new and unfamiliar and many physicists found this difficult to understand. Einstein referred to it as a 'witch's calculus'. However, it was later shown to be mathematically equivalent to the Schrödinger approach and in some areas of physics it became the preferred method for problem solving (e.g. scattering problems in particle physics).

A central idea in Heisenberg's quantum theory is the uncertainty (or indeterminacy) principle. Certain pairs of variables in classical mechanics are mathematically linked to one another – e.g. x-position and x-momentum or energy and time (the technical term is 'canonically conjugate' variables). The uncertainty principle puts a limit on the precision of our measurements. One way to illustrate this is to imagine trying to pin down the x-position of an electron. For example, we could direct a beam of electrons at a screen with a narrow slit in it (the width of the slit lying in the x-direction). Electrons emerging on the far side of the slit must have an x-position (near the slit) which lies within the limits of the slit itself, so the narrower the slit, the smaller the uncertainty in x-position. However, electrons behave as quantum objects so they diffract as they pass through the slit. This leads to an uncertainty in their momentum parallel to the slit (we cannot predict which way each electron will go after passing through the slit although we can describe a probability distribution of electron trajectories – a diffraction pattern). In the Copenhagen Interpretation we can simply say that the narrower the slit the broader the diffraction pattern and so the wider the range of directions in which the electron is 'deflected' on emerging from the slit (i.e. the larger the uncertainty in the x-component of the electron's momentum). However, the diffraction pattern is just the pattern of $|\Psi|$ and determines the probability of finding the electron in that region or on that path. When we put a detector in place discrete electrons turn up, but we cannot predict exactly where, only where is more or less likely. The narrower the slit, the broader the pattern and vice versa, illustrating the inseparable connection between these variables.

This uncertainty can be quantified: $\Delta p \Delta x \geq \frac{h}{2\pi} \Delta p \Delta x$ and $\Delta E \Delta t \geq \frac{h}{2\pi}$

The constant on the right hand side of the equations is linked to h (the Planck constant) and the fact that h is so small means that we do not usually notice quantum indeterminacy in everyday life (although it is interesting to speculate on what our experiences would be like if h was large). In fact students can read an excellent fantasy about this in the updated version of George Gamow's famous Mr Tompkins books: *The New World of Mr Tompkins* – George Gamow/Russell Stannard (Cambridge University Press 1999). The first half of this deals with relativistic ideas (e.g. what if the speed of light was very low) and the second half with quantum ideas (*what if h was large*?). It is fun, thought-provoking and informative.

The energy-time version of the uncertainty principle can be illustrated by considering the lifetimes of short-lived subatomic particles. Those that exist for a very short time have a large uncertainty in their mass (related to rest energy by Einstein's equation).

The implications of indeterminacy were the subject of many of the Einstein-Bohr discussions (mentioned previously). Heisenberg's indeterminacy is not just about our ability to measure things, it seems to apply to the properties themselves. This is what upset Einstein. He felt that even if we are unable to make a precise measurement of position and momentum for an electron, nonetheless the electron must possess precise values for those properties. Quantum theory, and the experiments that have been carried out to test it suggest that the properties themselves are indeterminate, in a sense the electron 'does not know' where it is (in much the same way as the alive/dead cat does not know its final state).

5 Richard Feynman and the 'sum-over-histories' approach

Feynman developed a new approach to quantum theory that helped to elucidate how quantum ideas could be used to explain the interaction of light with matter. This resulted in QED (quantum electrodynamics) for which he shared the Nobel Prize with Tomonoga and Schwinger (who proposed different ways of approaching the same problems). Feynman's approach forms the starting point for the treatment of quantum effects in the OCR Advancing Physics course (Physics B) and the chapter on quantum behaviour in the student AS text book is well worth reading.

The catch phrase is that quantum objects (e.g. photons or electrons) 'explore all paths'. Each path is then associated with a phasor which rotates at a particular frequency ($f = E/h$ for the photon or $f = \mathrm{KE}/h$ for an electron in free space). If there is more than one path from source to detector (e.g. 2 paths in the double slit experiment) then each path contributes a phasor. If the paths are of different lengths then there is a phase difference between phasors at the detector. They add like vectors and the square of the resultant phasor amplitude is proportional to the probability of arrival for the quantum object.

Feynman gave a simple description of quantum rules in QED:

> *"Grand Principle: The probability of an event is equal to the square of the length of an arrow called the 'probability amplitude'…..*
>
> *General Rule for drawing arrows if an event can happen in alternative ways: Draw an arrow for each way, and then combine the arrows ("add them") by hooking the head of one to the tail of the next. A "final arrow" is then drawn from the tail of the first arrow to the head of the last one. The final arrow is the one whose square gives the probability of the entire event."*
>
> Richard P. Feynman: QED

It is important to realise that the 'sum of all histories' or 'many paths' approach does not imply that individual photons or electrons actually travel along all paths – the exploration itself is not observable (like the wavefunction in the process of interacting with the apparatus).

6 The Many-Worlds interpretation

Hugh Everitt III proposed this interpretation of quantum theory in 1957 as a way to reconcile the idea of a continuous evolution of the wavefunction with the discontinuous collapse of the wavefunction when an observation is made. In simple terms it takes all the superposed possibilities *as actualities in parallel worlds*. In Schrödinger's cat experiment, for example, there is a world in which the cat is dead and one in which the cat lives. There is no need for wavefunction collapse because all possible worlds exist. A strong criticism of this formulation is that it is rather profligate! If it is correct, then we exist in one universe embedded in a multiverse of non-communicating parallel universes. Other versions of ourselves live out diverging lives in other strands of the multiverse. These ideas have been explored in an accessible way by David Deutsch in *The Fabric of Reality*. In fact Deutsch proposes that the many-worlds interpretation might actually be tested experimentally.

The idea of a multiverse raises interesting questions about the nature of science and scientific theories. If parallel universes cannot (even in principle) be observed then what right do we have to say they exist? Is it sufficient that they help smooth out the logic of our prevailing theories? Of course some physicists think that there may be ways to observe their effects because they interact with our own strand of the multiverse (Deutsch is one of them). Another modern topic that raises similar questions is string theory. The boundary between physics and metaphysics can be a little hazy!

N.B. There is another kind of ‘multiverse’ postulated by cosmologists and particle physicists. This multiverse assumes that there is a multiplicity of different universes in each of which the laws of physics are different (e.g. different values of the fundamental constants). The many-worlds theory described above assumes an infinite number of parallel universes in which the laws of physics are the same.

7 Determinism and indeterminism

These are important terms and students need to be both familiar with them and able to discuss their significance in terms of classical and quantum theory.

Determinism means that every event is causally determined – there is an unbroken chain of prior events which led up to that event. This also implies that the future is unique and inevitable. Of course it does not imply that we can be in a position to make precise predictions about the future. If Newtonian mechanics is true AND it is a complete description of the physical world (including the inner workings of our brains) then everything is determined and free will appears to be an impossibility.

Pierre Laplace described a thought experiment that illustrates this:

> *“….we must consider the present state of the universe as the effect of its previous state and as the cause of its following one. An intelligence which could know, at a given instant, the forces by which nature is animated and the respective situation of the beings whom compose it – and also was sufficiently vast to submit these data to analysis – would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, like the past, would be present before its eyes.”*
>
> (Pierre Laplace, *Essai Philosophiae sur les Probabilités*, Paris 1814)

The fact that similar causes can lead to different effects in quantum theory (the theory only provides us with probabilities) means that quantum theory is indeterministic – the same present is consistent with an infinite number of different possible futures). The fact that quantum theory leaves the future ‘open’ might be good news for those who believe in free will, but it is not clear whether quantum theory does or does not solve this problem. In fact it is hard to find a clear-cut definition of what is meant by ‘free-will’ so while discussions of the significance of quantum theory for free-will, consciousness etc… are fascinating it probably wise not to spend too much time on them! On the other hand the difference between a deterministic and an indeterministic universe is certainly worth discussing.

Recommended resources

History of physics

- *The World Treasury of Physics, Astronomy and Mathematics* – Little, Brown and Co., Editor Timothy Ferris 1991

Short popular articles by world-leading physicists such as Planck, Einstein, Wheeler.

- *The Book of the Cosmos* – Perseus Publishing, Editor Dennis Danielson, 2001

Short historical articles from Heraclitus to Hawking dealing with the evolving view of the cosmos.

Physics modelling software

- *Yenka* software is available from Crocodile Clips at:

www.crocodile-clips.com/

A powerful but more expensive alternative is *Interactive Physics*.

www.design-simulation.com/ip/index.php

Mathematical modelling software

This excellent and versatile mathematical modelling package is available for download here (it is also used with the OCR Advancing Physics course).

- Modellus 4

http://modellus.fct.unl.pt/

Physics animations

There is a good selection here:

http://phys23p.sl.psu.edu/phys_anim/Phys_anim.htm

Focus simulation software

www.focuseducational.com/html/product_overview.php/pid/43

The following packages are good value and useful for presentations:

- *Focus on Waves* CDROM
- *Focus on Fields* CDROM

Analysis of motion

- *PhysVis*

PhysVis available free on the Advancing Physics (IOP/OCR) CDROM.

- High-speed photography

If you have access to a high-speed camera (such as the Casio Exxlim) this can allow startling investigations of 'invisible' phenomena (e.g. the mechanics of a small water drop bouncing on a hydrophobic surface – such as sooted glass, or the shockwaves generated by a ball-bearing falling into sand).

Spectroscopy

- Nicol digital spectrometer

A digital spectrometer can be used to display spectra from various sources. The Nicol spectrometer uses an optical fibre to direct light onto a grating and then onto an electronic light sensor. Position corresponds to wavelength.

Resources for particular sections of the syllabus

15. Special Relativity

- DVD Beyond the Mechanical Universe: Vol 4 - Maxwell's Equations, Optics, Michelson-Morley Experiment, Lorentz Transformation

This is part of a series of DVDs entitled 'Beyond the Mechanical Universe' which consists of 52 30-minute DVDs, many of which could be used at various points in the course. The DVD on the Michelson-Morley experiment provides excellent historical detail and context.

www.learner.org/catalog/series42.html

- Michelson-Morley animation:

http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/mmexpt6.htm

Some excellent notes and animations about special relativity can be found here:

www.upscale.utoronto.ca/GeneralInterest/Harrison/SpecRel/SpecRel.html#Constancy

- Lecture 20 from the sterling Berkeley series 'Physics for Future Presidents' Source: Berkeley.Edu provides a stimulating introduction to basic concepts including relativity.

http://video.google.com/videoplay?docid=2799918968211631427&hl=en#

- This applet is a simple animation demonstrating time dilation. It is one of a series from the Contemporary College Physics Simulation Library. The author is Walter Fendt

www.walter-fendt.de/ph11e/timedilation.htm

- Six short videos dramatise major events and discoveries by Einstein. They are entitled BBC Horizon - Einstein's Unfinished Symphony and they can be accessed on YouTube.
- The Elegant Universe-Part1 is a very good video introducing string theory and presenting it as a possible 'theory of everything'. It makes reference to gravitation and Einstein's theories.

http://video.google.com/videoplay?docid=-1322493346942339345&hl=en#

16. Thermodynamics:

The OCR Advancing Physics course synoptic paper (June 2009) was based on an excellent article about thermodynamics and the arrow of time. This could be used to teach many of the ideas in sections 16.16 to 16.20.

Article, 'Thermodynamics and the Arrow of Time' is here:

www.ocr.org.uk/download/pp_07_jun/ocr_18069_pp_07_jun_l_gce_jun.pdf

- Questions are here:

www.ocr.org.uk/download/pp_07_jun/ocr_18074_pp_07_jun_l_gce_jun.pdf

The Advanced Physics Placement B series from the Monterey Institute provides explanations of kinetic theory, that of ideal gases and the laws of thermodynamics through accessible animations and practical everyday examples. Very watchable.

- The Laws of Thermodynamics

www.archive.org/details/AP_Physics_B_Lesson_29

- Ideal gases

www.archive.org/details/AP_Physics_B_Lesson_28

Atomscope is an unsophisticated but very useful software package that enables you as a teacher to add explanation to the depth you think appropriate and, in that respect, it is a strong contender as a teaching tool. There are simulations of diffusion and other phenomena, too. Popular with students.

www.visualsimulations.co.uk

17. Nuclear Physics

An interactive table of nuclides is useful – e.g.

http://atom.kaeri.re.kr/ton/nuc1.html

or

www.nndc.bnl.gov/chart/

18. The Quantum Atom

Applets and animations can be valuable tools for this section.
Here is an applet using a simple idea of waves constrained by circular orbits around the hydrogen nucleus:

www.walter-fendt.de/ph11e/bohrh.htm

Here is an applet which allows you to construct the hydrogen line spectrum from its energy levels:

www.bpreid.com/applets/hel.html

Here is a simulation of the hydrogen orbitals:

www.falstad.com/qmatom/

19. Interpreting Quantum Theory

Try these You-tube clips

- Dr Quantum Double Slit Experiment:

www.youtube.com/watch?v=DfPeprQ7oGc

- Big Bang Theory humorous clip (Schrödinger's Cat):

www.youtube.com/watch?v=HCOE__N6v4o

- The Bohr-Einstein debate:

In 1949 Niels Bohr was invited to reflect on his arguments and discussions with Einstein regarding quantum theory. The resulting essay was published in the 'Library of Living Philosophers' and has been reproduced elsewhere since. Einstein wrote a reply in the same year. The two documents are still relevant and exciting to read. They also show how two brilliant physicists used simple understandable models to try to get to grips with new and disorienting ideas. The articles are available online at:

www.marxists.org/reference/subject/philosophy/works/bohr/htm

www.marxists.org/reference/subject/philosophy/works/ge/einstein/htm

Joseph Emerson delivers a extended series of lectures on the Interpretation of Quantum Theory which can be accessed from the Perimeter Institute for Theoretical Physics. Lecture 1 covers the 'Structure of Quantum Theory' while Lectures 2 & 3 deal with the 'Basics of Interpretation', 'Orthodox and Copenhagen Interpretations' and 'the Measurement Problem(Schrodinger's Cat)'.

http://streamer.perimeterinstitute.ca/mediasite/viewer/FrontEnd/Front.aspx?&shouldResize=False

- *Copenhagen*, Michael Frayn, Methuen 1998
- *Quantum Mechanics and Experience*, David Z Albert Harvard University Press 1994
- *QED: The Strange Theory of Light and Matter*, R.P.Feynman, Princeton, 1985
- *Quantum Reality: Beyond the New Physics*, Nick Herbert, Rider, 1985.
- *In search of Schrodinger's Cat*, John Gribbin, Corgi 1985
- *Quantum Theory and Measurement*, J.A.Wheeler (Editor) and W.H.Zurek (Editor), Princeton 1992

This is an advanced resource containing many of the key papers (e.g. The Cat paradox, the Uncertainty Principle, EPR etc…) on the conceptual foundations of quantum theory and is a recommended resource for the interested teacher.

- *Advancing Physics AS*, Jon Ogborn (Editor) and Mary Whitehouse (Editor), Institute of Physics Publishing 2001.

This gives a good qualitative description and applications of the sum-over-histories approach to quantum theory.

- *The Fabric of Reality*, David Deutsch, Penguin 1997.

Deutsch explores the implications of the many-worlds interpretation (or theory) of quantum mechanics. His own research has helped prepare the way for quantum computation.

- *The New World of Mr Tompkins,* George Gamow (Author) and Russell Stannard (Editor), Cambridge University Press 2001.

This is an updated version of the classic scientific fantasy in which Mr Tompkins dozes off in physics lectures and imagines himself in a world in which the speed of light and Planck's constants have very different values. Well worth a read.

20. Astronomy and Cosmology

- PROJECT CLEA software – available for free download from the university of Gettysburg:

www3.gettysburg.edu/~marschal/clea/CLEAhome.html

There are some outstanding interactive simulations that can provide valuable practical work for students.

- Cosmos DVD – Carl Sagan – has excellent 10 minute clips that can be used to illustrate the ideas in this section.

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