Singapore Examinations and Assessment Board

CAMBRIDGE International Education

Singapore–Cambridge General Certificate of Education Advanced Level Higher 2 (2027)

Physics (Syllabus 9478)

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INTRODUCTION

The syllabus has been designed to build on and extend the content coverage at O-Level. Candidates will be assumed to have knowledge and understanding of Physics at O-Level, either as a single subject or as part of a balanced science course.

AIMS

The aims of a course based on this syllabus should be to:

1 provide students with an experience that develops their interest in physics and builds the knowledge, skills and attitudes necessary for further studies in related fields

2 enable students to become scientifically literate citizens who are well-prepared for the challenges of the 21st century

3 develop in students the understanding, skills, ethics and attitudes relevant to the *Practices of Science,* including the following:

3.1 understanding the nature of scientific knowledge
3.2 demonstrating the ways of thinking and doing
3.3 relating science, technology, society and environment

4 develop in students an understanding that a small number of basic principles and core ideas can be applied to explain, analyse and solve problems in a variety of systems in the physical world.

PRACTICES OF SCIENCE

Science as a discipline is more than the acquisition of a body of knowledge (e.g. scientific facts, concepts, laws and theories), it is a way of knowing and doing. It includes an understanding of the nature of scientific knowledge and how this knowledge is generated, established and communicated. Scientists rely on a set of established procedures and practices associated with scientific inquiry to gather evidence and test their ideas on how the natural world works. However, there is no single method, and the real process of science is often complex and iterative, following many different paths. While science is powerful, generating knowledge that forms the basis for many technological feats and innovations, it has limitations.

The *Practices of Science* are explicitly articulated in this syllabus to allow teachers to embed them as learning objectives in their lessons. Students' understanding of the nature and the limitations of science and scientific inquiry are developed effectively when the practices are taught in the context of relevant science content. Attitudes relevant to science such as *inquisitiveness*, *concern for accuracy and precision*, *objectivity*, *integrity* and *perseverance* should be emphasised in the teaching of these practices where appropriate. For example, students learning science should be introduced to the use of technology as an aid in practical work or as a tool for the interpretation of experimental and theoretical results.

The *Practices of Science* comprise three components:

1 Demonstrating Ways of Thinking and Doing (WOTD)

The Ways of Thinking and Doing in Science illustrate a set of established procedures and practices associated with scientific inquiry to gather evidence and test ideas on how the natural world works. There are three broad, iterative domains of scientific activity: investigating, evaluating and reasoning, and developing explanations and solutions.

1.1 Posing questions and defining problems
1.2 Designing investigations
1.3 Conducting experiments and testing solutions
1.4 Analysing and interpreting data
1.5 Communicating, evaluating and defending ideas with evidence
1.6 Making informed decisions and taking responsible actions
1.7 Using and developing models[1]
1.8 Constructing explanations and designing solutions

2 Understanding the Nature of Scientific Knowledge (NOS)

Science is an epistemic endeavour to build a better understanding of reality.

2.1 Science is an evidence-based, model-building enterprise to understand the real world.
2.2 Science assumes natural causes, order and consistency in natural systems.
2.3 Scientific knowledge is generated through established procedures and critical debate.
2.4 Scientific knowledge is reliable, durable and open to change in light of new evidence.

3 Relating Science-Technology-Society-Environment (STSE)

Science is not done completely independently of the other spheres of human activity. The relationships and connections to these areas are important as students learn science in context.

3.1 There are risks and benefits associated with the applications of science in society.
3.2 Applications of science often have ethical, social, economic, and environmental implications.
3.3 Applications of new scientific discoveries often drive technological advancements while advances in technology enable scientists to make new or deeper inquiry.

[1] *A model is a representation of an idea, an object, a process or a system that is used to describe and explain phenomena that cannot be experienced directly. Models exist in different forms from the concrete, such as physical, scale models to abstract representations, such as diagrams or mathematical expressions. The use of models involves the understanding that all models contain approximations and assumptions limiting their validity and predictive power.*

CURRICULUM FRAMEWORK

The *Values, Ethics, Attitudes*, the *Practices of Science,* the *Disciplinary Content* and *Learning Experiences* are put together in a framework (**Figure 1**) to guide the development of the A-Level Physics curriculum.

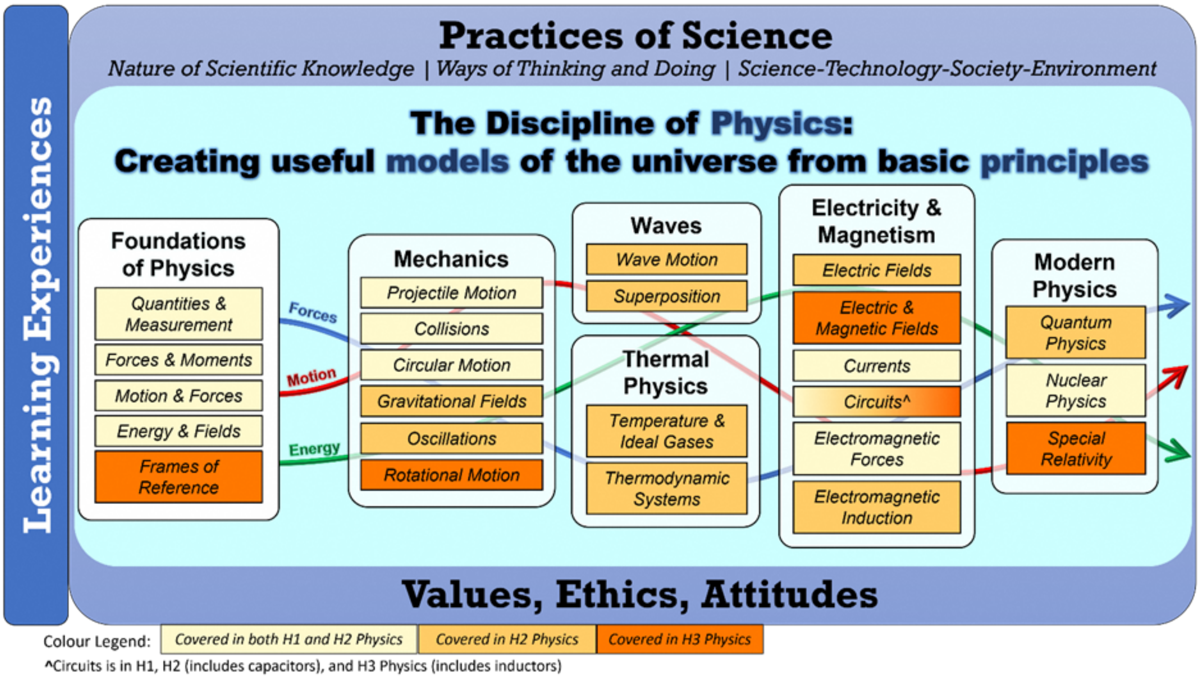

Figure 1: A-Level Physics Curriculum Framework

The *Practices of Science* highlight the ways of thinking and doing that are inherent in the scientific approach, with the aim of equipping students with the understanding, skills, and attitudes shared by the scientific disciplines, including an appropriate approach to ethical issues.

The *Disciplinary Content* is organised around conceptual strands that are explored in different contexts. This content is coherently developed with a consideration of conceptual progression and framed by *Core Ideas in Physics* to help students integrate knowledge and link concepts across different topics.

The *Values, Ethics, Attitudes* undergird the study of science and the use of related knowledge and skills to make a positive contribution to humanity.

The *Learning Experiences*[2] refer to a range of learning opportunities that enhance students' learning of physics. Real-world contexts can help illustrate the application of physics concepts and bring the subject to life. These *Learning Experiences* would include experimental (practical work) activities and ICT tools that can be used to build students' understanding and model-making. The *Learning Experience*s are not meant to be prescriptive or exhaustive but serve as examples of the range of learning experiences that can enhance students' learning of physics.

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[2] The Learning Experiences can be found in the Teaching and Learning Syllabus.

ASSESSMENT OBJECTIVES

The assessment objectives listed below reflect those parts of the aims and *Practices of Science* that will be assessed.

A Knowledge with understanding

Candidates should be able to demonstrate knowledge and understanding in relation to:

1 scientific phenomena, facts, laws, definitions, concepts, theories;

2 scientific vocabulary, terminology, conventions (including symbols, quantities and units);

3 scientific instruments and apparatus, including techniques of operation and aspects of safety;

4 scientific quantities and their determination;

5 scientific and technological applications with their social, economic and environmental implications.

The syllabus content defines the factual knowledge that candidates may be required to recall and explain. Questions testing these objectives will often begin with one of the following words: *define*, *state*, *describe* or *explain* (see the glossary of terms).

B Handling, applying and evaluating information

Candidates should be able (in words or by using symbolic, graphical and numerical forms of presentation) to:

1 locate, select, organise and present information from a variety of sources;

2 handle information, distinguishing the relevant from the extraneous;

3 manipulate numerical and other data and translate information from one form to another;

4 use information to identify patterns, report trends, draw inferences and report conclusions;

5 present reasoned explanations for phenomena, patterns and relationships;

6 make predictions and put forward hypotheses;

7 apply knowledge, including principles, to novel situations;

8 bring together knowledge, principles and concepts from different areas of physics, and apply them in a particular context;

9 evaluate information and hypotheses;

10 demonstrate an awareness of the limitations of physical theories and models.

These assessment objectives cannot be precisely specified in the syllabus content because questions testing such skills may be based on information that is unfamiliar to the candidate. In answering such questions, candidates are required to use principles and concepts that are within the syllabus and apply them in a logical, reasoned or deductive manner to a novel situation. Questions testing these objectives will often begin with one of the following words: *predict*, *suggest*, *deduce*, *calculate* or *determine* (see the glossary of terms).

C Experimental skills and investigations

Candidates should be able to:

1 follow a detailed set or sequence of instructions and use techniques, apparatus and materials safely and effectively;

2 make, record and present observations and measurements with due regard for precision and accuracy;

3 interpret and evaluate observations and experimental data;

4 identify a problem and design and plan investigations;

5 evaluate methods and techniques and suggest possible improvements.

SCHEME OF ASSESSMENT

All candidates are required to enter for Papers 1, 2, 3 and 4.

Paper	Type of Paper	Duration	Weighting (%)	Marks
1	**Multiple Choice**	1 h	15	30
2	**Structured Questions**	2 h	30	75
3	**Longer Structured Questions**	2 h	35	75
4	**Practical**	2 h 30 min	20	50

Paper 1 (1 h, 30 marks).

30 multiple-choice questions. All questions will be of the direct choice type with four options.

Paper 2 (2 h, 75 marks)

This paper will consist of a variable number of structured questions plus one or two data-based questions and will include questions which require candidates to integrate knowledge and understanding from different areas of the syllabus. All questions are compulsory and answers will be written in spaces provided on the Question Paper. The data-based question(s) will constitute 20–25 marks.

Paper 3 (2 h, 75 marks)

This paper will consist of two sections and will include questions which require candidates to integrate knowledge and understanding from different areas of the syllabus. All answers will be written in spaces provided on the Question Paper.

- Section A worth 55 marks will consist of a variable number of structured questions, all compulsory.
- Section B worth 20 marks will consist of a choice of one from two 20-mark questions.

Paper 4 (2 h 30 min, 50 marks)

This paper will consist of two sections and assess appropriate aspects of objectives C1 to C5 in the following skill areas:

- Planning (P)
- Manipulation, measurement and observation (MMO)
- Presentation of data and observations (PDO)
- Analysis, conclusions and evaluation (ACE)

The assessment of Planning (P) will have a weighting of 4%. The assessment of skill areas MMO, PDO and ACE will have a weighting of 16%.

The assessment of PDO and ACE may also include questions on data analysis which do not require practical equipment and apparatus. Candidates will be required to process and analyse data using spreadsheet software. All answers will be written in spaces provided on the Question Paper. Candidates will be allocated 1 h 15 min for access to apparatus and materials of each section (see page 31). Candidates will not be permitted to refer to books and laboratory notebooks during the assessment.

Weighting of Assessment Objectives

Assessment Objectives		Weighting (%)	Assessment Components
A	**Knowledge with understanding**	36	Papers 1, 2, 3
B	**Handling, applying and evaluating information**	44	Papers 1, 2, 3
C	**Experimental skills and investigations**	20	Paper 4

ADDITIONAL INFORMATION

Mathematical Requirements

The mathematical requirements are given on pages 34 and 35.

Data and Formulae

Data and Formulae, as printed on pages 41 and 42, will appear as pages 2 and 3 in Papers 1, 2 and 3.

Conventions, Symbols, Signs and Abbreviations

Conventions, symbols, signs and abbreviations used in examination papers will follow the recommendations made in the Association for Science Education publication *Signs, Symbols and Systematics (The ASE Companion to 16-19 Science, 2000)*. The units kilowatt hour (kWh), atmosphere (atm), electron volt (eV) and unified atomic mass unit (u) may be used in examination papers without further explanation.

Disallowed Subject Combinations

Candidates may not simultaneously offer Physics at H1 and H2 levels.

CONTENT OVERVIEW

Light escapes from a giant ball of hydrogen gas and radiates through free space. The sky is blue, we think, as our neurons process the signals generated from photons activating retinal cells. The Sun is white, yet may appear yellow while the sky appears blue…

'Nobody ever figures out what life is all about, and it doesn't matter. Explore the world. Nearly everything is really interesting if you go into it deeply enough.' – Richard P. Feynman

In physics, we create useful **models** of the universe and attempt to make sense of nature. Starting from a small number of basic principles, we work out their implications and compare them against observations. As a natural science, physics ultimately relies on empirical evidence obtained through careful observations and experimentation.

Several revolutionary paradigms have emerged in the historical development of the discipline of physics. While each paradigm considers a different set of principles as fundamental, the older paradigms like *Newtonian Mechanics* remain relevant – coherent[3] application of its principles produces excellent agreement between theory and experiment in many cases.

Still, the universe is a tremendously complex place. Science and physics are not 'finished' as no paradigm has yet proven fully satisfactory as a 'theory of everything'. There is much we know, and much more to find out. So stay curious!

The core content selected for the Singapore Advanced-Level H2 Physics Curriculum is organised into six sections[4], which provide rich contexts and applications to spark the joy of learning:

- Foundations of Physics. This introductory section is designed to strengthen the framework and approach to physics that learners bring along from secondary school. An appreciation for measurement and uncertainty anchors the *Ways of Thinking and Doing* articulated in the *Practices of Science*. Physical quantities are modelled as mathematical objects like scalars and vectors, and simple examples are used to illustrate the key conceptual strands of **motion**, **forces**, and **energy** that thread through the syllabus.

- Mechanics. Each topic in mechanics is built around real-world contexts to deepen learners' understanding of **motion**, **forces**, and **energy**. Learners will sharpen their quantitative and analytical skills as they bridge real-world observations and theory by conducting investigations and experiments to study the mechanics of **systems**. Think about how gravity affects the vertical motion but not the horizontal motion of a thrown ball. In collisions, careful consideration of *before* and *after* allows us to **model** and extract information about the dramatic and short-lived impact event. Why does the Earth maintain a circular orbit around the Sun? Is there acceleration when moving with constant speed? Oscillatory perturbations from stable equilibrium also recalls the regularity and **pattern** of circular motion.

- Waves. The collective behaviour of synchronised oscillators is modelled as **waves**. These ripples in space and time can transfer **energy** without transferring **matter**. To describe and represent wave motion, learners first need to pick up the necessary mathematical language and terminology, focusing initially on visualising waves in one spatial and one temporal dimension. Using the principle of linear superposition, a wide range of phenomena involving wave interference can be explained, predicting complex **patterns** with the aid of geometric reasoning.

- Thermal Physics. The everyday concepts of heat and temperature are re-examined. Single-particle mechanics is applied to **model** an ideal gas, which is one of the simplest many-body **systems**. A crucial purpose of this section is to connect the **microscopic** behaviour of individual constituents with the **macroscopic** properties of the collective **system**, for learners to *simultaneously* see the forest *and* the trees. The strand of **energy** provides insight into physical processes like melting and boiling for material substances generalised beyond ideal gases. The overlap with what learners might have encountered in chemistry provides opportunities for teachers to discuss cross-curricular connections.

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[3] This coherence owes a large part to the use of logical reasoning and mathematics. For an extended discussion, see Wigner, E.P. (1960), The unreasonable effectiveness of mathematics in the natural sciences. Richard courant lecture in mathematical sciences delivered at New York University, May 11, 1959. *Comm. Pure Appl. Math.*, 13: 1-14. https://doi.org/10.1002/cpa.3160130102

[4] For H1 Physics, the sections on Waves and Thermal Physics are omitted in view of the reduced syllabus scope.

- Electricity & Magnetism. In this section, learners explore the **diversity** of phenomena related to the fundamental physical property of (electric) charge, which experiences **forces** when interacting with electric and magnetic **fields**. There is a close analogy between mass in a gravitational field and charge in an electric field. Electromagnetic forces can cause the kinds of **motion** studied in the earlier mechanics topics, and the **microscopic** behaviour of individual charges is connected to the **macroscopic** property of current in circuit **systems**. The principle of **conservation** of **energy** guides the analysis of circuits containing resistors and e.m.f. sources. The consideration of charge storage in capacitors deepens learners' appreciation of applications in electronics. The mathematics of oscillations and **waves** prove useful here for describing alternating currents in the electrical grid.

- Modern Physics. This final section interrogates the **structure** of atoms – peering past their vast electronic shells into their central cores, the incredibly dense nuclear regions. In that secret heart of atoms, the electrical repulsion of like charges is overwhelmed by mysterious nuclear **forces**, which act as an invisible hand causing random and spontaneous disintegration for radioactive substances. **Conservation** laws also guide the analysis of nuclear reactions such as fusion and fission, which humanity has exploited in times of peace but also in times of war. Learners catch glimpses into a paradigm shift that famously rocked the foundations of physics – the quantum revolution. **Waves** are particle-like, particles are wave-like; nature at its smallest scales does not behave in accordance with a deterministic classical clockwork conception, requiring a new framework to harmonise both particle-like and wave-like properties into a coherent theory expressed in terms of probability, complex numbers, and linear algebra.

'Everything should be made as simple as possible, but no simpler.' – Albert Einstein[5]

To truly appreciate physical reality, we need the courage and tenacity to experiment, the humility and skepticism to question even our most basic assumptions, and the creativity and imagination to build alternative theories…

[5] The actual line from a 1933 lecture by Einstein is "It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience." [Source: Nature 557, 30 (2018). doi: https://doi.org/10.1038/d41586-018-05004-4]

SECTION I FOUNDATIONS OF PHYSICS

1 Quantities and Measurement

Content

- Physical quantities and SI units
- Errors and uncertainties
- Scalars and vectors

Learning Outcomes

Candidates should be able to:

(a) recall and use the following SI base quantities and their units: mass (kg), length (m), time (s), current (A), temperature (K), amount of substance (mol)

(b) recall and use the following prefixes and their symbols to indicate decimal sub-multiples or multiples of both base and derived units: pico (p), nano (n), micro (μ), milli (m), centi (c), deci (d), kilo (k), mega (M), giga (G), tera (T)

(c) express derived units as products or quotients of the SI base units and use the named units listed in 'Summary of Key Quantities, Symbols and Units' as appropriate

(d) use SI base units to check the homogeneity of physical equations

(e) make reasonable estimates of physical quantities included within the syllabus

(f) show an understanding of the distinction between random errors and systematic errors (including zero error) which limit precision and accuracy

(g) assess the uncertainty in derived quantities by adding absolute or relative (i.e. fractional or percentage) uncertainties or by numerical substitution (rigorous statistical treatment is not required)

(h) distinguish between scalar and vector quantities, and give examples of each

(i) add and subtract coplanar vectors

(j) represent a vector as two perpendicular components.

2 Forces and Moments

Content

- Types of force
- Moment and torque
- Translational and rotational equilibrium

Learning Outcomes

Candidates should be able to:

(a) describe the forces on a mass, charge and current-carrying conductor in gravitational, electric and magnetic fields, as appropriate

(b) show a qualitative understanding of forces including normal force, buoyant force (upthrust), frictional force and viscous force, e.g. air resistance. (knowledge of the concepts of coefficients of friction and viscosity is not required)

(c) recall and apply Hooke's law ($F = kx$, where k is the force constant) to new situations or to solve related problems

(d) define and apply the moment of a force and the torque of a couple

(e) show an understanding that a couple is a pair of forces which tends to produce rotation only

(f) show an understanding that the weight of a body may be taken as acting at a single point known as its centre of gravity

(g) apply the principle of moments to new situations or to solve related problems

(h) show an understanding that, when there is no resultant force and no resultant torque, a system is in equilibrium

(i) use free-body diagrams and vector triangles to represent forces on bodies that are in rotational and translational equilibrium.

3 Motion and Forces

Content

- Kinematics
- Uniformly accelerated linear motion
- Mass and linear momentum
- Laws of motion

Learning Outcomes

Candidates should be able to:

(a) show an understanding of and use the terms position, distance, displacement, speed, velocity and acceleration

(b) use graphical methods to represent distance, displacement, speed, velocity and acceleration

(c) identify and use the physical quantities from the gradients of position–time or displacement–time graphs and areas under and gradients of velocity–time graphs, including cases of non-uniform acceleration

(d) derive, from the definitions of velocity and acceleration, equations which represent uniformly accelerated motion in a straight line

(e) solve problems using equations which represent uniformly accelerated motion in a straight line, e.g. for bodies falling vertically without air resistance in a uniform gravitational field

(f) show an understanding that mass is the property of a body which resists change in motion (inertia)

(g) define and use linear momentum as the product of mass and velocity

(h) state and apply each of Newton's laws of motion:

1st law: a body at rest will stay at rest, and a body in motion will continue to move at constant velocity, unless acted on by a resultant external force;

2nd law: the rate of change of momentum of a body is (directly) proportional to the resultant force acting on the body and is in the same direction as the resultant force;

3rd law: the force exerted by one body on a second body is equal in magnitude and opposite in direction to the force simultaneously exerted by the second body on the first body.

(i) recall the relationship resultant force $F = ma$, for a body of constant mass, and use this to solve problems.

4 Energy and Fields

Content

- Energy stores and transfers
- Work done by a force
- Kinetic energy
- Concept of a field
- Potential energy
- Power and efficiency

Learning Outcomes

Candidates should be able to:

(a) show an understanding that physical systems can store energy, and that energy can be transferred from one store to another

(b) give examples of different energy stores and energy transfers, and apply the principle of conservation of energy to solve problems

(c) show an understanding that work is a mechanical transfer of energy, and define and use work done by a force as the product of the force and displacement in the direction of the force

(d) derive, from the definition of work done by a force and the equations for uniformly accelerated motion in a straight line, the equation $E_k = ½mv^2$

(e) recall and use the equation $E_k = ½mv^2$ to solve problems

(f) show an understanding of the concept of a field as a region of space in which bodies may experience a force associated with the field

(g) define gravitational field strength at a point as the gravitational force per unit mass on a mass placed at that point, and define electric field strength at a point as the electric force per unit charge on a positive charge placed at that point

(h) represent gravitational fields and electric fields by means of field lines (e.g. for uniform and radial field patterns), and show an understanding of the relationship between equipotential surfaces and field lines

(i) show an understanding that the force on a mass in a gravitational field (or the force on a charge in an electric field) acts along the field lines, and the work done by the field in moving the mass (or charge) is equal to the negative of the change in potential energy

(j) distinguish between gravitational potential energy, electric potential energy and elastic potential energy

(k) recall that the elastic potential energy stored in a deformed material is given by the area under its force–extension graph and use this to solve problems

(l) define power as the rate of energy transfer

(m) show an understanding that mechanical power is the product of a force and velocity in the direction of the force

(n) show an appreciation for the implications of energy losses in practical devices and solve problems using the concept of efficiency of an energy transfer as the ratio of useful energy output to total energy input.

SECTION II MECHANICS

5 Projectile Motion

Content

- Free fall
- Gravitational potential energy in a uniform field
- Effects of air resistance

Learning Outcomes

Candidates should be able to:

(a) describe and use the concept of weight as the force experienced by a mass in a gravitational field

(b) describe and explain motion due to a uniform velocity in one direction and a uniform acceleration in a perpendicular direction

(c) derive, from the definition of work done by a force, the equation $\Delta E_p = mg\Delta h$ for gravitational potential energy changes in a uniform gravitational field (e.g. near the Earth's surface)

(d) recall and use the equation $\Delta E_p = mg\Delta h$ to solve problems

(e) describe qualitatively, with reference to forces and energy, the motion of bodies falling in a uniform gravitational field with air resistance, including the phenomenon of terminal velocity.

6 Collisions

Content

- Impulse
- Conservation of momentum and energy

Learning Outcomes

Candidates should be able to:

(a) recall that impulse is given by the area under the force–time graph for a body and use this to solve problems

(b) state the principle of conservation of momentum

(c) apply the principle of conservation of momentum to solve simple problems including inelastic and (perfectly) elastic interactions between two bodies in one dimension (knowledge of the concept of coefficient of restitution is not required)

(d) show an understanding that, for a (perfectly) elastic collision between two bodies, the relative speed of approach is equal to the relative speed of separation

(e) show an understanding that, whilst the momentum of a closed system is always conserved in interactions between bodies, some change in kinetic energy usually takes place.

7 Circular Motion

Content

- Kinematics of uniform circular motion
- Centripetal acceleration

Learning Outcomes

Candidates should be able to:

(a) express angular displacement in radians

(b) show an understanding of and use the concept of angular velocity

(c) recall and use $v = r\omega$ to solve problems

(d) show an understanding of centripetal acceleration in the case of uniform motion in a circle, and qualitatively describe motion in a curved path (arc) as due to a resultant force that is both perpendicular to the motion and centripetal in direction

(e) recall and use centripetal acceleration $a = r\omega^2$, and $a = \frac{v^2}{r}$ to solve problems

(f) recall and use $F = mr\omega^2$, and $F = \frac{mv^2}{r}$ to solve problems.

8 Gravitational Fields

Content

- Newton's laws of gravitation
- Gravitational field strength
- Gravitational potential and energy
- Escape velocity and circular orbits

Learning Outcomes

Candidates should be able to:

(a) recall and use Newton's law of gravitation in the form $F = G\frac{m_1 m_2}{r^2}$

(b) derive, from Newton's law of gravitation and the definition of gravitational field strength, the field strength due to a point mass, $g = G\frac{M}{r^2}$

(c) recall and use $g = G\frac{M}{r^2}$ for the gravitational field strength due to a point mass to solve problems

(d) show an understanding that near the surface of the Earth, gravitational field strength is approximately constant and equal to the acceleration of free fall

(e) define gravitational potential at a point as the work done per unit mass by an external force in bringing a small test mass from infinity to that point

(f) solve problems using the equation $\phi = -G\frac{M}{r}$ for the gravitational potential in the field due to a point mass

(g) show an understanding that that the gravitational potential energy of a system of two point masses is $U_G = -G\frac{Mm}{r}$

(h) recall that gravitational field strength at a point is equal to the negative potential gradient at that point and use this to solve problems

(i) analyse problems related to escape velocity by considering energy stores and transfers

(j) analyse circular orbits in inverse square law fields by relating the gravitational force to the centripetal acceleration it causes

(k) show an understanding of satellites in geostationary orbit and their applications.

9 Oscillations

Content

- Simple harmonic motion
- Energy in oscillations

Learning Outcomes

Candidates should be able to:

(a) describe simple examples of free oscillations, where particles periodically return to an equilibrium position without gaining energy from or losing energy to the environment

(b) investigate the motion of an oscillator using experimental and graphical methods

(c) show an understanding of and use the terms amplitude, period, frequency, angular frequency, phase and phase difference and express the period in terms of both frequency and angular frequency

(d) show an understanding that $a = -\omega^2 x$ is the defining equation of simple harmonic motion, where acceleration is (directly) proportional to displacement from an equilibrium position and acceleration is always directed towards the equilibrium position

(e) recognise and use $x = x_0 \sin \omega t$ as a solution to the equation $a = -\omega^2 x$

(f) recognise and use the equations $v = v_0 \cos \omega t$ and $v = \pm\omega\sqrt{\left(x_0^2 - x^2\right)}$

(g) describe, with graphical illustrations, the relationships between displacement, velocity and acceleration during simple harmonic motion

(h) describe the interchange between kinetic and potential energy during simple harmonic motion

(i) describe practical examples of damped oscillations, with particular reference to the effects of the degree of damping (light/under, critical, heavy/over), and to the importance of critical damping in applications such as a car suspension system

(j) describe graphically how the amplitude of a forced oscillation changes with driving frequency, resulting in maximum amplitude at resonance when the driving frequency is close to or at the natural frequency[6] of the system

(k) show a qualitative understanding of the effects of damping on the frequency response and sharpness of the resonance

(l) describe practical examples of forced oscillations and resonance, and show an appreciation that there are some circumstances in which resonance is useful, and other circumstances in which resonance should be avoided.

[6] Natural frequency refers to the frequency when the system is in free oscillation.

SECTION III WAVES

10 Wave Motion

Content

- Properties of waves
- Energy transfer by progressive waves
- Polarisation

Learning Outcomes

Candidates should be able to:

(a) show an understanding that mechanical waves involve the oscillations of particles within a material medium, such as a string or a fluid, and electromagnetic waves involve the oscillations of electromagnetic fields in space and time

(b) show an understanding of and use the terms displacement, amplitude, period, frequency, phase, phase difference, wavelength and speed

(c) deduce, from the definitions of speed, frequency and wavelength, the equation $v = f\lambda$

(d) recall and use the equation $v = f\lambda$

(e) analyse and interpret graphical representations of transverse and longitudinal waves with respect to variations in time and position (space)

(f) show an understanding that energy is transferred due to a progressive wave without matter being transferred

(g) recall and use the term intensity as the power transferred (radiated) by a wave per unit area, and the relationship $intensity \propto (amplitude)^2$ for a progressive wave

(h) show an understanding of and apply the concept, that the intensity of a wave from a point source and travelling without loss of energy obeys an inverse square law to solve problems

(i) show an understanding that polarisation is a phenomenon associated with transverse waves

(j) recall and use Malus' law ($intensity \propto \cos^2\theta$) to calculate the amplitude and intensity of a plane-polarised electromagnetic wave after transmission through a polarising filter.

11 Superposition

Content

- Principle of superposition
- Standing waves
- Interference of two or more point sources
- Diffraction through a finite-size gap

Learning Outcomes

Candidates should be able to:

(a) explain and use the principle of superposition in simple applications

(b) show an understanding of experiments which demonstrate standing (stationary) waves using microwaves, stretched strings and air columns

(c) explain the formation of a standing (stationary) wave using a graphical method, and identify nodes and antinodes, differentiating between pressure and displacement nodes and antinodes for sound waves

(d) determine the wavelength of sound using standing (stationary) waves

(e) show an understanding of the terms diffraction, interference, coherence, phase difference and path difference

(f) show an understanding of phenomena which demonstrate two-source interference using water waves, sound waves, light and microwaves

(g) show an understanding of the conditions required for two-source interference fringes to be observed

(h) recall and use the equation $\frac{ax}{D} = \lambda$ to solve problems for double-slit interference, where a is the slit separation and x is the fringe separation

(i) recall and use the equation $a \sin\theta = n\lambda$ to solve problems involving the principal maxima of a diffraction grating, where a is the slit separation

(j) describe the use of a diffraction grating to determine the wavelength of light (knowledge of the structure and use of a spectrometer is not required)

(k) show an understanding of phenomena which demonstrate diffraction through a single slit or aperture, or across an edge, such as the diffraction of water waves in a ripple tank with both a wide gap and a narrow gap, or the diffraction of sound waves from loudspeakers or around corners

(l) recall and use the equation $b \sin\theta = \lambda$ to solve problems involving the positions of the first minima for diffraction through a single slit of width b

(m) recall and use the Rayleigh criterion $\theta \approx \frac{\lambda}{b}$ for the resolving power of a single aperture, where b is the width of the aperture.

SECTION IV THERMAL PHYSICS

12 Temperature and Ideal Gases

Content

- Empirical gas laws
- Kinetic theory of gases

Learning Outcomes

Candidates should be able to:

(a) show an understanding that a thermodynamic scale of temperature has an absolute zero and is independent of the property of any particular substance

(b) convert temperatures measured in degrees Celsius to kelvin: $T / \text{K} = T / {}^\circ\text{C} + 273.15$

(c) recall and use the equation of state for an ideal gas expressed as $pV = NkT$, where N is the number of particles

(d) state that one mole of any substance contains 6.02×10^{23} particles, and use the Avogadro constant $N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$ as well as the relationship $Nk = nR$ between the Boltzmann constant and the molar gas constant, where n is the number of moles and $N = nN_A$

(e) state the basic assumptions of the kinetic theory of gases

(f) explain how the random motion of gas particles exerts mechanical pressure and hence derive, using the definition of pressure as force per unit area, the relationship $pV = \frac{1}{3}Nm\langle c^2 \rangle$ (a simple model considering one-dimensional collisions and then extending to three dimensions using $\langle {c_x}^2 \rangle = \frac{1}{3}\langle c^2 \rangle$ is sufficient)

(g) recall and use the relationship that the mean translational kinetic energy of a particle of an ideal gas is (directly) proportional to the thermodynamic temperature (i.e. $\frac{1}{2}m\langle c^2 \rangle = \frac{3}{2}kT$) to solve problems.

13 Thermodynamic Systems

Content

- Internal energy
- Heating and work done
- Laws of thermodynamics
- Specific heat capacity and specific latent heat

Learning Outcomes

Candidates should be able to:

(a) show an understanding that the macroscopic state of a system determines the internal energy of the system, and that internal energy can be expressed as the sum of a random distribution of microscopic kinetic and potential energies associated with the particles of the system

(b) show an understanding that the thermodynamic temperature of a system is (directly) proportional to the mean microscopic kinetic energy of particles

(c) show an understanding that when two systems are placed in thermal contact, energy is transferred (by heating) from the system at higher temperature to the system at lower temperature, until they reach the same temperature and achieve thermal equilibrium (i.e. no net energy transfer)

(d) show an understanding of the difference between the work done by a gas and the work done on a gas, and calculate the work done by a gas in expanding against a constant external pressure: $W = p\Delta V$

(e) recall and apply the zeroth law of thermodynamics that if two systems are both in thermal equilibrium with a third system, then they are also in thermal equilibrium with each other

(f) recall and apply the first law of thermodynamics, $\Delta U = Q + W$, that the increase in internal energy of a system is equal to the sum of the energy transferred to the system by heating and the work done on the system

(g) define and use the concepts of specific heat capacity and specific latent heat.

SECTION V ELECTRICITY AND MAGNETISM

14 Electric Fields

Content

- Coulomb's law
- Electric field strength
- Electric potential and energy
- Uniform electric fields
- Capacitance

Learning Outcomes

Candidates should be able to:

(a) recall and use Coulomb's law in the form $F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$ for the electric force between two point charges in free space or air

(b) recall and use $E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$ for the electric field strength due to a point charge, in free space or air, to solve problems

(c) define electric potential at a point as the work done per unit charge by an external force in bringing a small positive test charge from infinity to that point

(d) use the equation $V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$ for the electric potential in the field due to a point charge, in free space or air

(e) show an understanding that the electric potential energy of a system of two point charges is $U_E = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r}$

(f) recall that electric field strength at a point is equal to the negative potential gradient at that point and use this to solve problems

(g) calculate the field strength of the uniform electric field between charged parallel plates in terms of the potential difference and plate separation

(h) calculate the force on a charge in a uniform electric field

(i) describe the effect of a uniform electric field on the motion of a charged particle

(j) define capacitance as the ratio of the charge stored to the potential difference and use $C = \frac{Q}{V}$ to solve problems

(k) recall that the electric potential energy stored in a capacitor is given by the area under the graph of potential difference against charge stored, and use this and the equations $U = \frac{1}{2}QV$, $U = \frac{1}{2}\frac{Q^2}{C}$ and $U = \frac{1}{2}CV^2$ to solve problems.

15 Currents

Content

- Current and drift velocity
- Potential difference and power
- Power supplies: d.c. and a.c.

Learning Outcomes

Candidates should be able to:

(a) show an understanding that electric current is the rate of flow of charge and solve problems using $I = \frac{Q}{t}$

(b) derive and use the equation $I = nAvq$ for a current-carrying conductor, where n is the number density of charge carriers and v is the drift velocity

(c) recall and solve problems using the equation for potential difference in terms of electrical work done per unit charge, $V = \frac{W}{Q}$

(d) recall and solve problems using the equations for electrical power $P = VI$, $P = I^2R$ and $P = \frac{V^2}{R}$

(e) distinguish between electromotive force (e.m.f.) and potential difference (p.d.) using energy considerations

(f) show an understanding of and use the terms period, frequency, peak value and root-mean-square (r.m.s.) value as applied to an alternating current or voltage

(g) represent a sinusoidal alternating current or voltage by an equation of the form $x = x_0 \sin \omega t$

(h) deduce that the mean power in a resistive load is half the maximum (peak) power for a sinusoidal alternating current

(i) distinguish between r.m.s. and peak values, and recall and use $I_{rms} = \frac{I_0}{\sqrt{2}}$ and $V_{rms} = \frac{V_0}{\sqrt{2}}$ for the sinusoidal case

(j) explain the use of a single diode for the half-wave rectification of an alternating current.

16 Circuits

Content

- Circuit symbols and diagrams
- Resistance, resistivity and internal resistance
- Resistors in series and parallel
- RC circuits with d.c. source

Learning Outcomes

Candidates should be able to:

(a) recall and use appropriate circuit symbols

(b) draw and interpret circuit diagrams containing sources, switches, resistors (fixed and variable), ammeters, voltmeters, lamps, thermistors, light-dependent resistors, diodes, capacitors and any other type of component referred to in the syllabus

(c) define the resistance of a circuit component as the ratio of the potential difference across the component to the current in it, and solve problems using the equation $V = IR$

(d) recall and solve problems using the equation relating resistance to resistivity, length and cross-sectional area, $R = \frac{\rho l}{A}$

(e) sketch and interpret the I–V characteristics of various electrical components in a d.c. circuit, such as an ohmic resistor, a semiconductor diode, a filament lamp and a negative temperature coefficient (NTC) thermistor

(f) explain the temperature dependence of the resistivity of typical metals (e.g. in a filament lamp) and semiconductors (e.g. in an NTC thermistor) in terms of the drift velocity and number density of charge carriers respectively

(g) show an understanding of the effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power

(h) solve problems using the formula for the combined resistance of two or more resistors in series

(i) solve problems using the formula for the combined resistance of two or more resistors in parallel

(j) solve problems involving series and parallel arrangements of resistors for one source of e.m.f., including potential divider circuits which may involve NTC thermistors and light-dependent resistors

(k) solve problems using the formulae for the combined capacitance of two or more capacitors in series and in parallel

(l) describe and represent the variation with time, of quantities like current, charge and potential difference, for a capacitor that is charging or discharging through a resistor, using equations of the form $x = x_0\, e^{-\frac{t}{\tau}}$ or $x = x_0\,[1 - e^{-\frac{t}{\tau}}]$, where $\tau = RC$ is the time constant.

17 Electromagnetic Forces

Content

- Magnetic fields and magnetic flux density due to currents
- Force on a current-carrying conductor
- Force on a moving charge

Learning Outcomes

Candidates should be able to:

(a) show an understanding that a magnetic field is an example of a field of force produced either by current-carrying conductors or by permanent magnets

(b) sketch magnetic field lines due to currents in a long straight wire, a flat circular coil and a long solenoid

(c) use $B = \frac{\mu_0 I}{2\pi d}$, $B = \frac{\mu_0 NI}{2r}$ and $B = \mu_0 nI$ for the magnetic flux densities of the fields due to currents in a long straight wire, a flat circular coil and a long solenoid respectively

(d) show an understanding that the magnetic field due to a solenoid may be influenced by the presence of a ferrous core

(e) show an understanding that a current-carrying conductor placed in a magnetic field might experience a force

(f) recall and solve problems using the equation $F = BIl \sin \theta$, with directions as interpreted by Fleming's left-hand rule

(g) define magnetic flux density as the force acting per unit current per unit length on a conductor placed perpendicular to the magnetic field

(h) show an understanding of how the force on a current-carrying conductor can be used to measure the magnetic flux density of a magnetic field using a current balance

(i) explain the forces between current-carrying conductors and predict the direction of the forces

(j) predict the direction of the force on a charge moving in a uniform magnetic field

(k) recall and solve problems using the equation $F = BQv \sin \theta$

(l) describe and analyse deflections of beams of charged particles by uniform electric fields and uniform magnetic fields

(m) explain how perpendicular electric and magnetic fields can be used in velocity selection for charged particles.

18 Electromagnetic Induction

Content

- Magnetic flux
- Faraday's and Lenz's laws of electromagnetic induction
- Power transformers

Learning Outcomes

Candidates should be able to:

(a) define magnetic flux as the product of magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density

(b) show an understanding of and use the concept of magnetic flux linkage

(c) recall and use $\Phi = BA$ and $N\Phi = NBA$ to solve problems, where N is the number of turns

(d) infer from appropriate experiments on electromagnetic induction:

(i) that a changing magnetic flux can induce an e.m.f.

(ii) that the direction of the induced e.m.f. opposes the change producing it

(iii) the factors affecting the magnitude of the induced e.m.f.

(e) recall and solve problems using Faraday's law of electromagnetic induction and Lenz's law

(f) explain simple applications of electromagnetic induction

(g) show an understanding of the principle of operation of a simple iron-core transformer and recall and solve problems using $\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$ for an ideal transformer.

SECTION VI MODERN PHYSICS

19 Quantum Physics

Content

- The particulate nature of light
- The wave nature of particles
- Quantisation of energy in matter

Learning Outcomes

Candidates should be able to:

(a) show an understanding that the existence of a threshold frequency in the photoelectric effect provides evidence that supports the particulate nature of electromagnetic radiation while phenomena such as interference and diffraction provide evidence that supports its wave nature

(b) state that a photon is a quantum of electromagnetic radiation, and recall and use the equation $E = hf$ for the energy of a photon to solve problems, where h is the Planck constant

(c) show an understanding that while a photon is massless, it has a momentum given by $p = \frac{E}{c}$ and $p = \frac{h}{\lambda}$, where c is the speed of light in free space

(d) show an understanding that electron diffraction and double-slit interference of single particles provide evidence that supports the wave nature of particles

(e) recall and use the equation $\lambda = \frac{h}{p}$ for the de Broglie wavelength to solve problems

(f) show an understanding that the state of a particle can be represented as a wavefunction ψ , e.g. for an electron cloud in an atom, and that the square of the wavefunction amplitude $|\psi|^2$ is the probability density function (including calculation of normalisation factors for square and sinusoidal wavefunctions)

(g) show an understanding that the principle of superposition applies to the wavefunctions describing a particle's position, leading to standing wave solutions for a particle in a box and phenomena such as single-particle interference in double-slit experiments

(h) show an understanding that the Heisenberg position-momentum uncertainty principle $\Delta x \Delta p \gtrsim h$ relates to the necessity of a spread of momenta for localised particles, and apply this to solve problems

(i) show an understanding of standing wave solutions ψ_n for the wavefunction of a particle in a one-dimensional infinite square well potential

(j) solve problems using $E_n = \frac{h^2}{8mL^2}n^2$ for the allowed energy levels of a particle of mass m in a one-dimensional infinite square well of width L

(k) show an understanding of the existence of discrete electronic energy levels for the electron's wavefunction in isolated atoms (e.g. atomic hydrogen) and deduce how this leads to the observation of spectral lines

(l) distinguish between emission and absorption line spectra

(m) solve problems involving photon absorption or emission during atomic energy level transitions.

20 Nuclear Physics

Content

- The nuclear atom
- Radioactive decay
- Nuclear processes and conservation laws
- Mass defect and nuclear binding energy

Learning Outcomes

Candidates should be able to:

(a) infer from the results of the Rutherford α-particle scattering experiment the existence and small size of the atomic nucleus

(b) distinguish between nucleon number (mass number) and proton number (atomic number)

(c) show an understanding that an element can exist in various isotopic forms, each with a different number of neutrons in the nucleus, and use the notation ${}^{A}_{Z}X$ for the representation of nuclides

(d) show an understanding of the spontaneous and random nature of nuclear decay

(e) infer the random nature of radioactive decay from the fluctuations in count rate

(f) show an understanding of the origin and significance of background radiation

(g) show an understanding of the nature and properties of α, β and γ radiations (knowledge of positron emission is not required)

(h) define the terms activity and decay constant and recall and solve problems using the equation $A = \lambda N$

(i) infer and sketch the exponential nature of radioactive decay and solve problems using the relationship $x = x_0 e^{-\lambda t}$ where x could represent activity, number of undecayed particles or received count rate

(j) define and use half-life as the time taken for a quantity x to reduce to half its initial value

(k) solve problems using the relation $\lambda = \dfrac{\ln 2}{t_{\frac{1}{2}}}$

(l) discuss qualitatively the applications (e.g. medical and industrial uses) and hazards of radioactivity based on:

(i) half-life of radioactive materials

(ii) penetrating abilities and ionising effects of radioactive emissions

(m) represent simple nuclear reactions by nuclear equations of the form ${}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H$

(n) state and apply to problem solving the concept that nucleon number, charge and mass-energy are all conserved in nuclear processes

(o) show an understanding of how the conservation laws for energy and momentum in β decay were used to predict the existence of the (anti)neutrino (knowledge of the antineutrino and the zoo of particles is not required)

(p) show an understanding of the concept of mass defect

(q) recall and apply the equivalence between energy and mass as represented by $E = mc^2$ to solve problems

(r) show an understanding of the concept of nuclear binding energy and its relation to mass defect

(s) sketch the variation of binding energy per nucleon with nucleon number

(t) explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.

PRACTICAL ASSESSMENT

Scientific subjects are, by their nature, experimental. It is therefore important that, wherever possible, the candidates carry out appropriate practical work to complement the learning of theoretical principles and develop the practical skills, experimental attitudes and mindset required to conduct scientific investigations.

Paper 4 Practical

This paper is designed to assess a candidate's competence in those practical skills which can realistically be assessed within the context of a formal practical assessment.
Candidates will be assessed in the following skill areas:

(a) Planning (P)

Candidates should be able to:
- define a question/problem using appropriate knowledge and understanding
- give a clear logical account of the experimental procedure to be followed
- describe how the data should be used in order to reach a conclusion
- assess the risks of the experiment and describe precautions that should be taken to keep risks to a minimum.

(b) Manipulation, measurement and observation (MMO)

Candidates should be able to:
- demonstrate a high level of manipulative skills in all aspects of practical activity
- make and record accurate observations with good details and measurements to an appropriate degree of precision
- make appropriate decisions about measurements or observations
- recognise anomalous observations and/or measurements (where appropriate) with reasons indicated.

(c) Presentation of data and observations (PDO)

Candidates should be able to:
- present all information in an appropriate form
- manipulate measurements effectively in order to identify trends/patterns
- present all quantitative data to an appropriate number of decimal places / significant figures.

(d) Analysis, conclusions and evaluation (ACE)

Candidates should be able to:
- analyse and interpret data or observations appropriately in relation to the task
- draw conclusions from the interpretation of experimental data or observations and underlying principles
- make predictions based on their data and conclusions
- identify significant sources of errors, limitations of measurements and/or experimental procedures used, explaining how they affect the final result(s)
- state and explain how significant errors/limitations may be overcome or reduced, as appropriate, including how experimental procedures may be improved.

The assessment of skill area P will be set in the context of the syllabus content, requiring candidates to apply and integrate knowledge and understanding from different sections of the syllabus. It may also require treatment of given experimental data to draw a relevant conclusion and in the analysis of a proposed plan.

The assessment of skill areas MMO, PDO and ACE will be set in the context of the syllabus. The assessment of PDO and ACE may also include questions on data analysis, which do not require practical equipment and apparatus. Candidates will be required to process and analyse data using spreadsheet software.

Within the Scheme of Assessment, the practical paper constitutes 20% of the Higher 2 examination. It is therefore recommended that the schemes of work include learning opportunities that apportion a commensurate amount of time for the development and acquisition of practical skills. The guidance material for practical work, which is published separately, will provide examples of appropriate practical activities.

Candidates are **not** allowed to refer to notebooks, textbooks or any other information in the Practical examination.

Apparatus List

This list below gives guidance to centres concerning the apparatus and items that are expected to be generally available for examination purposes. The list is not intended to be exhaustive. To instil some variation in the questions set, some novel items are usually required.

Unless otherwise stated, the rate of allocation is ‘per candidate’. The number of sets of apparatus assembled for each experiment should be sufficient for half the candidates to undertake that particular experiment at the same time: some spare sets should be provided. Each candidate will have access to a computer installed with spreadsheet software for the duration of the examination and a quick reference guide for the duration of the examination.

Candidates will have access to the apparatus and materials of each section of the paper for 1 h 15 min. Candidates will be told which section to attempt first.

<table>
<tr><th>Electrical</th><th>Mechanics and General Items</th></tr>
<tr><td>ammeter (analogue): f.s.d. 500 mA and 1 A</td><td>pendulum bob</td></tr>
<tr><td rowspan="5">digital ammeter – minimum ranges:
0–10 A reading to 0.01 A or better,
0–200 mA reading to 0.1 mA or better,
0–20 mA reading to 0.01 mA or better,
0–200 μA reading to 0.1 μA or better
(digital multimeters are suitable)</td><td>stand, boss and clamp: × 3 (rod length: 2 × 60 cm, 1 × 90 cm)</td></tr>
<tr><td>G-clamp × 2</td></tr>
<tr><td>pivot</td></tr>
<tr><td>pulley</td></tr>
<tr><td rowspan="2">tuning forks (set of 8 pc): (1 set per 4–6 candidates)</td></tr>
<tr><td>voltmeter (analogue): f.s.d. 3 V</td></tr>
<tr><td rowspan="3">digital voltmeter – minimum ranges:
0–2 V reading to 0.001 V or better,
0–20 V reading to 0.01 V or better
(digital multimeters are suitable)</td><td>newton-meter: 1 N, 10 N</td></tr>
<tr><td>rule with millimeter scale (2 × 1 m, 1 × 0.5 m, 1 × 300 mm)</td></tr>
<tr><td rowspan="2">digital micrometer screw gauge (1 per 4–6 candidates)</td></tr>
<tr><td rowspan="2">galvanometer (analogue): centre-zero, f.s.d. ±35 mA, reading to 1 mA or better</td></tr>
<tr><td>digital vernier calipers (1 per 4–6 candidates)</td></tr>
<tr><td>power supply: 12 V d.c. (low resistance)</td><td>stopwatch (reading to 0.1 s or better)</td></tr>
<tr><td>cells: 2 × 1.5 V with holder, 2 V</td><td>protractor</td></tr>
<tr><td>lamp and holder: 6 V, 300 mA; 2.5 V, 0.3 A</td><td>balance to 0.01 g (1 per 8–12 candidates)</td></tr>
<tr><td>rheostat: max resistance: 22 Ω, rating: at least 3.3 A</td><td>beaker: 100 cm^3, 2 × 250 cm^3</td></tr>
<tr><td>switch</td><td>Plasticine</td></tr>
<tr><td>jockey</td><td>Blu-Tack</td></tr>
<tr><td>leads and crocodile clips</td><td>wire cutters</td></tr>
<tr><td rowspan="2">wire: constantan 26, 28, 30, 32, 34, 36, 38 s.w.g. or metric equivalents</td><td>bare copper wire: 18, 26 s.w.g.</td></tr>
<tr><td>springs</td></tr>
</table>

magnets and mounting: 2 × magnadur magnets plus small iron yoke for mounting, 2 × bar magnets	spirit level (1 per 4–6 candidates)
	stout pin or round nail
compasses: 2 × small	optical pin
	slotted masses: 1 each 5 and 10 g; 2 × 20 g; 4 × 50 g; 1 × 50 g hanger
Thermal	
long stem thermometer: –10 ˚C to 110 ˚C at 1 ˚C intervals	slotted masses: 4 × 100 g; 1 × 100 g hanger
metal calorimeter	cork
measuring cylinder: 50 cm^3, 100 cm^3	string / thread / twine
plastic or polystyrene cup 200 cm^3	scissors
means to heat water safely to boiling	adhesive tape
heating mat	card (assorted sizes)
stirrer	sand and tray
	wood (assorted sizes, for various uses, e.g. support)
	bricks: 2 × (approx. 22 cm × 10 cm × 7 cm)

The apparatus and material requirements for Paper 4 will vary year on year. Centres will be notified in advance of the details of the apparatus and materials required for each practical examination.

MATHEMATICAL REQUIREMENTS

Arithmetic

Candidates should be able to:

(a) recognise and use expressions in decimal and standard form (scientific) notation.

(b) use appropriate calculating aids (electronic calculator or tables) for addition, subtraction, multiplication and division. Find arithmetic means, powers (including reciprocals and square roots), sines, cosines, tangents (and the inverse functions), exponentials and logarithms (lg and ln).

(c) take account of accuracy in numerical work and handle calculations so that significant figures are neither lost unnecessarily nor carried beyond what is justified.

(d) make approximate evaluations of numerical expressions (e.g. $\pi^2 \approx 10$) and use such approximations to check the magnitude of machine calculations.

Algebra

Candidates should be able to:

(a) change the subject of an equation. Most relevant equations involve only the simpler operations but may include positive and negative indices and square roots.

(b) solve simple algebraic equations. Most relevant equations are linear but some may involve inverse and inverse square relationships. Linear simultaneous equations and the use of the formula to obtain the solutions of quadratic equations are included.

(c) substitute physical quantities into physical equations using consistent units and check the dimensional consistency of such equations.

(d) formulate simple algebraic equations as mathematical models of physical situations, and identify inadequacies of such models.

(e) recognise and use the logarithmic forms of expressions like ab, a / b, x^n, e^{kx}; understand the use of logarithms in relation to quantities with values that range over several orders of magnitude.

(f) manipulate and solve equations involving logarithmic and exponential functions.

(g) express small changes or errors as percentages and *vice versa.*

(h) comprehend and use the symbols $<$, $>$, «, », $\approx$, /, $\propto$, $\langle x \rangle$ (= $\bar{x}$), Σ, Δx, δx, $\sqrt{}$.

Geometry and trigonometry

Candidates should be able to:

(a) calculate areas of right-angled and isosceles triangles, circumference and area of circles, areas and volumes of rectangular blocks, cylinders and spheres.

(b) use Pythagoras' theorem, similarity of triangles, the angle sum of a triangle.

(c) use sines, cosines and tangents (especially for 0°, 30°, 45°, 60°, 90°). Use the trigonometric relationships for triangles:

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}; \qquad a^2 = b^2 + c^2 - 2bc\cos A$$

(d) use $\sin\theta \approx \tan\theta \approx \theta$ and $\cos\theta \approx 1$ for small θ; $\sin^2\theta + \cos^2\theta = 1$.

(e) understand the relationship between degrees and radians (defined as arc/radius), translate from one to the other and use the appropriate system in context.

Vectors

Candidates should be able to:

(a) find the resultant of two coplanar vectors, recognising situations where vector addition is appropriate.

(b) obtain expressions for components of a vector in perpendicular directions, recognising situations where vector resolution is appropriate.

Graphs

Candidates should be able to:

(a) translate information between graphical, numerical, algebraic and verbal forms.

(b) select appropriate variables and scales for graph plotting.

(c) for linear graphs, determine the slope, intercept and intersection.

(d) choose, by inspection, a straight line which will serve as the best straight line through a set of data points presented graphically.

(e) recall standard linear form $y = mx + c$ and rearrange relationships into linear form where appropriate.

(f) sketch and recognise the forms of plots of common simple expressions like $1 / x$, x^2, $1 / x^2$, $\sin x$, $\cos x$, e^{-x}.

(g) use logarithmic plots to test exponential and power law variations.

(h) understand, draw and use the slope of a tangent to a curve as a means to obtain the gradient, and use notation in the form dy / dx for a rate of change.

(i) understand and use the area below a curve where the area has physical significance.

Any calculator used must be on the Singapore Examinations and Assessment Board list of approved calculators.

REQUIREMENTS ON USE OF SPREADSHEET FOR PRACTICAL ASSESSMENT

Candidates should be able to:

(a) import data files (in xlsx format) into the spreadsheet for subsequent processing

(b) input data obtained from an experiment for subsequent processing.

Functions within the spreadsheet

Candidates should be able to:

(a) perform mathematical operations as stipulated in the Mathematical Requirements including sines, cosines, tangents (and the inverse functions) on angles in radians (converting from degrees as necessary), exponentials and logarithms (lg and ln), and use of scientific notation (e.g. 3.00 E + 14 for 3.00×10^{14}).

(b) use features for numerical data manipulation
- (i) use and input formulae and duplicate formulae across cells
- (ii) adjust formatting (e.g. data type) and duplicate formatting across cells

(c) plot a labelled line graph using selected data from a table
- (i) adjust the scale of both axes
- (ii) use selected data points to give a line of best fit (using built-in functions to add a linear trendline)
- (iii) display the equation of a trendline
- (iv) determine the area under a curve (e.g. summation of rectangular or trapezoidal areas)
- (v) determine the gradient at a point on a curve (e.g. calculating $\frac{\Delta y}{\Delta x}$ in a small interval near the point)

GLOSSARY OF TERMS USED IN PHYSICS PAPERS

It is hoped that the glossary will prove helpful to candidates as a guide, although it is not exhaustive. The glossary has been deliberately kept brief not only with respect to the number of terms included but also to the descriptions of their meanings. Candidates should appreciate that the meaning of a term must depend in part on its context. They should also note that the number of marks allocated for any part of a question is a guide to the depth of treatment required for the answer.

1 *Define* (*the term(s)* ...) is intended literally. Only a formal statement or equivalent paraphrase, such as the defining equation with symbols identified, being required.

2 *What is meant by ...* normally implies that a definition should be given, together with some relevant comment on the significance or context of the term(s) concerned, especially where two or more terms are included in the question. The amount of supplementary comment intended should be interpreted in the light of the indicated mark value.

3 *Explain* may imply reasoning or some reference to theory, depending on the context.

4 *State* implies a concise answer with little or no supporting argument, e.g. a numerical answer that can be obtained 'by inspection'.

5 *List* requires a number of points with no elaboration. Where a given number of points is specified, this should not be exceeded.

6 *Describe* requires candidates to state in words (using diagrams where appropriate) the main points of the topic. It is often used with reference either to particular phenomena or to particular experiments. In the former instance, the term usually implies that the answer should include reference to (visual) observations associated with the phenomena. The amount of description intended should be interpreted in the light of the indicated mark value.

7 *Discuss* requires candidates to give a critical account of the points involved in the topic.

8 *Deduce/Predict* implies that candidates are not expected to produce the required answer by recall but by making a logical connection between other pieces of information. Such information may be wholly given in the question or may depend on answers extracted in an earlier part of the question.

9 *Suggest* is used in two main contexts. It may either imply that there is no unique answer or that candidates are expected to apply their general knowledge to a 'novel' situation, one that formally may not be 'in the syllabus'.

10 *Calculate* is used when a numerical answer is required. In general, working should be shown.

11 *Measure* implies that the quantity concerned can be directly obtained from a suitable measuring instrument, e.g. length, using a rule, or angle, using a protractor.

12 *Determine* often implies that the quantity concerned cannot be measured directly but is obtained by calculation, substituting measured or known values of other quantities into a standard formula.

13 *Show* is used when an algebraic deduction has to be made to prove a given equation. It is important that the terms being used by candidates are stated explicitly.

14 *Estimate* implies a reasoned order of magnitude statement or calculation of the quantity concerned. Candidates should make such simplifying assumptions as may be necessary about points of principle and about the values of quantities not otherwise included in the question.

15 *Sketch,* when applied to graph work, implies that the shape and/or position of the curve need only be qualitatively correct. However, candidates should be aware that, depending on the context, some quantitative aspects may be looked for, e.g. passing through the origin, having an intercept, asymptote or discontinuity at a particular value. On a sketch graph it is essential that candidates clearly indicate what is being plotted on each axis.

16 *Sketch,* when applied to diagrams, implies that a simple, freehand drawing is acceptable: nevertheless, care should be taken over proportions and the clear exposition of important details.

17 *Compare* requires candidates to provide both similarities and differences between things or concepts.

TEXTBOOKS

Teachers and students may find reference to the following books helpful.

Adams, S., & Allday, J. (2000). *Advanced physics*. Oxford, United Kingdom: Oxford University Press. (ISBN: 9780199146802)

Akrill, T. B., Millar, C., & Bennet, G. A. G. (2011). *Practice in physics* (4th ed.). London: Hodder Education. (ISBN: 1444121251)

Breithaupt, J. (2000). *New understanding physics for advanced level* (4th ed.). Cheltenham: Nelson Thornes. (ISBN: 0748743146)

Boohan, R (2016). *The Language of Mathematics in Science: A Guide for Teachers of 11–16 Science. Association for Science Education*. (ISBN: 9780863574559) [https://www.ase.org.uk/mathsinscience]

Duncan, T. (2000). *Advanced physics* (5th ed.). London: Hodder Education. (ISBN: 0719576695)

Giancoli, D. C. (2013). *Physics: Principles with applications* (7th ed.). Boston, MA: Addison-Wesley. (ISBN: 0321625927)

Mike, C. (2001). *AS/A-Level physics essential word dictionary*. Philip Allan Publishers. (ISBN: 0860033775)

Sang, D., Jones, G., Chadha, G., Woodside, R., Stark, W., & Gill, A. (2014). *Cambridge international AS and A level physics coursebook* (2nd ed.). Cambridge, United Kingdom: Cambridge University Press. (ISBN: 9781107697690)

Serway, R. A., Jewett, J. W., & Peroomian, V. (2014). *Physics for scientists and engineers with modern physics* (9th ed.). Boston, MA: Brooks/Cole. (ISBN: 1133953999)

Urone, P. P. (2001). *College physics* (2nd ed.). Pacific Grove, CA: Brooks/Cole. (ISBN: 0534376886)

Walker, J., Resnick, R., & Halliday, D. (2014). *Fundamentals of physics* (10th ed.). Hoboken, NJ: Wiley. (ISBN: 111823071X)

Teachers are encouraged to choose texts for class use that they feel will be of interest to their students and will support their own teaching style.

SUMMARY OF KEY QUANTITIES, SYMBOLS AND UNITS

The following list illustrates the symbols and units that will be used in question papers.

Quantity	***Usual symbols***	***Usual unit***
Base Quantities		
mass	m	kg
length	l	m
time	t	s
electric current	I	A
thermodynamic temperature	T	K
amount of substance	n	mol
Other Quantities		
distance	d	m
displacement	s, x	m
area	A	m^2
volume	V, v	m^3
density	ρ	kg m^{-3}
speed	u, v, w, c	m s^{-1}
velocity	u, v, w, c	m s^{-1}
acceleration	a	m s^{-2}
acceleration of free fall	g	m s^{-2}
force	F	N
weight	W	N
momentum	p	N s
work	w, W	J
energy	E, U, W	J
potential energy	E_p	J
kinetic energy	E_k	J
heating	Q	J
change of internal energy	ΔU	J
power	P	W
pressure	p	Pa
torque	T, τ	N m
gravitational constant	G	N kg^{-2} m^2
gravitational field strength	g	N kg^{-1}
gravitational potential	ϕ	J kg^{-1}
angle	θ	°, rad
angular displacement	θ	°, rad
angular speed	ω	rad s^{-1}
angular velocity	ω	rad s^{-1}

Quantity	***Usual symbols***	***Usual unit***
period	T	s
frequency	f	Hz
angular frequency	ω	rad s^{-1}
wavelength	λ	m
speed of electromagnetic waves	c	m s^{-1}
electric charge	Q	C
elementary charge	e	C
electric potential	V	V
electric potential difference	V	V
electromotive force	E	V
resistance	R	Ω
resistivity	ρ	Ω m
capacitance	C	F
electric field strength	E	N C^{-1}, V m^{-1}
permittivity of free space	ε_0	F m^{-1}
magnetic flux	Φ	Wb
magnetic flux density	B	T
permeability of free space	μ_0	H m^{-1}
force constant	k	N m^{-1}
Celsius temperature	θ, T	°C
specific heat capacity	c	J K^{-1} kg^{-1}
molar gas constant	R	J K^{-1} mol^{-1}
Boltzmann constant	k	J K^{-1}
Avogadro constant	N_A	mol^{-1}
number	N, n, m	
number density (number per unit volume)	n	m^{-3}
Planck constant	h	J s
work function energy	Φ	J
activity of radioactive source	A	Bq
decay constant	λ	s^{-1}
half-life	$t_{\frac{1}{2}}$	s
relative atomic mass	A_r	
relative molecular mass	M_r	
atomic mass	m_a	kg, u
electron mass	m_e	kg, u
neutron mass	m_n	kg, u
proton mass	m_p	kg, u
molar mass	M	kg mol^{-1}
proton number	Z	
nucleon number	A	
neutron number	N	

DATA AND FORMULAE

Data

speed of light in free space	$c = 3.00 \times 10^{8}\ \text{m s}^{-1}$
permeability of free space	$\mu_0 = 4\pi \times 10^{-7}\ \text{H m}^{-1}$
permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-12}\ \text{F m}^{-1}$
	$(\frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^{9}\ \text{m F}^{-1})$
elementary charge	$e = 1.60 \times 10^{-19}\ \text{C}$
Planck constant	$h = 6.63 \times 10^{-34}\ \text{J s}$
unified atomic mass constant	$u = 1.66 \times 10^{-27}\ \text{kg}$
rest mass of electron	$m_e = 9.11 \times 10^{-31}\ \text{kg}$
rest mass of proton	$m_p = 1.67 \times 10^{-27}\ \text{kg}$
molar gas constant	$R = 8.31\ \text{J K}^{-1}\ \text{mol}^{-1}$
Avogadro constant	$N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$
Boltzmann constant	$k = 1.38 \times 10^{-23}\ \text{J K}^{-1}$
gravitational constant	$G = 6.67 \times 10^{-11}\ \text{N m}^{2}\ \text{kg}^{-2}$
acceleration of free fall	$g = 9.81\ \text{m s}^{-2}$

Formulae

uniformly accelerated motion	$s = ut + \frac{1}{2}at^2$
	$v^2 = u^2 + 2as$
work done on / by a gas	$W = p\,\Delta V$
pressure	$p = \frac{F}{A}$
gravitational potential	$\phi = -\frac{GM}{r}$
temperature	$T / \text{K} = T / {}^\circ\text{C} + 273.15$
pressure of an ideal gas	$p = \frac{1}{3}\frac{Nm}{V}\langle c^2\rangle$
mean translational kinetic energy of an ideal gas particle	$E = \frac{3}{2}kT$

displacement of particle in s.h.m.	$x = x_0 \sin \omega t$
velocity of particle in s.h.m.	$v = v_0 \cos \omega t = \pm \omega \sqrt{(x_0^2 - x^2)}$
electric current	$I = nAvq$
resistors in series	$R = R_1 + R_2 + \ldots$
resistors in parallel	$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$
capacitors in series	$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots$
capacitors in parallel	$C = C_1 + C_2 + \ldots$
energy in a capacitor	$U = \frac{1}{2}QV = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2$
charging a capacitor	$Q = Q_0\left[1 - e^{-\frac{t}{\tau}}\right]$
discharging a capacitor	$Q = Q_0 e^{-\frac{t}{\tau}}$
RC time constant	$\tau = RC$
electric potential	$V = \frac{Q}{4\pi\varepsilon_0 r}$
alternating current / voltage	$x = x_0 \sin \omega t$
magnetic flux density due to a long straight wire	$B = \frac{\mu_0 I}{2\pi d}$
magnetic flux density due to a flat circular coil	$B = \frac{\mu_0 N I}{2r}$
magnetic flux density due to a long solenoid	$B = \mu_0 n I$
energy states for quantum particle in a box	$E_n = \frac{h^2}{8mL^2} n^2$
radioactive decay	$x = x_0 e^{-\lambda t}$
radioactive decay constant	$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$