PHYSICS
SYLLABUS
Pre-University
Higher 2
Syllabus 9749

Implementation starting with
2019 Pre-University One Cohort

Ministry of Education
SINGAPORE

CONTENTS

1. INTRODUCTION

1.1 BACKGROUND

Design of the A-Level science curriculum

The Higher 2 (H2) science subjects are the central pieces of the science curriculum at the A-Level, and were reviewed with the intention to shape how science is taught and learnt at the pre-university level. The curriculum aims to lay a strong foundation of knowledge, skills and attitudes in order to prepare our students well for university, work and life in the future.

The curriculum design took into consideration MOE's key initiatives of Student-Centric, Values-Driven Education (SVE), the development of 21st Century Competencies (21CC) in our students, changes to other equivalent qualifications, feedback and observations from local universities, findings from science education research and feedback from schools and teachers.

Purpose of H2 science curriculum

A strong background in science prepares students to take on careers in science and engineering-related sectors as well as opens up in-roads to many opportunities even in fields not traditionally associated with the hard sciences. Beyond career considerations, science education should also contribute to the development of a scientifically literate citizenry. Therefore, the purpose of the H2 science curriculum should encompass the following aims:

- <u>For all students</u>: As future citizens in an increasingly technologically-driven world and as future leaders of the country, they should be equipped to make informed decisions based on sound scientific knowledge and principles about current and emerging issues which are important to one's self, society and the world at large (for example, in appreciating the energy constraints faced by Singapore, or understanding the mechanisms involved in epidemics);

- <u>For students who intend to pursue science further</u>: As practitioners and innovators, the learner of science should possess a deeper grasp of scientific knowledge and be well-versed in scientific practices, at the level of rigour befitting the A-Level certification.

Key features of H2 science curriculum

- **<u>Use of core ideas to frame the teaching and learning of science</u>**
  Core ideas represent the enduring understanding that emerges from learning each science subject. These ideas cut across traditional content boundaries, providing a broader way of thinking about phenomena in the natural world. This is to shift the students' learning mentality from a compartmentalised view of scientific knowledge to a more coherent and integrated understanding of science. The use of core ideas in science to frame the curriculum can help to build deep conceptual understanding in students so

that they can better apply these concepts to solve problems in novel situations and contexts.

- **Understand that science as a discipline is more than the acquisition of a body of knowledge**
  The Practices of Science emphasises that science as a discipline is more than the acquisition of a body of knowledge (e.g. scientific facts, concepts, laws, and theories); it is also a way of knowing and doing. The Practices of Science includes an understanding of the nature of scientific knowledge and how such knowledge is generated, established and communicated. Please refer to Section 1.4 for more details.

- **Use of a range of appropriate real-world contexts in the teaching and learning of H2 science**
  Research shows that students find the teaching and learning of science more meaningful and interesting when set in appropriate contexts. The use of real-world contexts also provides authentic platforms to bring out classroom discourse and deliberations on the social, economic, moral and ethical dimensions of science based on sound scientific explanations.

- **Strengthen the teaching of science through the use of a wider range of pedagogies**
  The use of inquiry-based pedagogical approaches, which include the skilful use of Information and Communication Technology (ICT), will engage students in critical thinking, reasoning and argument. In addition, through practical and hands-on activities, students will learn and assimilate key concepts and skills better. Students enjoy practical work and regard it as a constructive learning activity. Science education should also aim to develop students as independent and self-directed learners with the habit of inquiry and constant pursuit of knowledge.

1.2 PURPOSE AND VALUE OF PHYSICS

Physics is a fundamental science which is concerned with understanding the natural world. A small number of basic principles and laws can be applied to explain and predict a wide range of physical events and phenomena. The fundamental theories of physics form the bedrock of many modern technologies and are responsible for practical applications in and the advancement of several different fields of science and technology. H2 Physics exposes students to the science process skills of investigation, reasoning, analysis and evaluation, which are transferrable and useful to everyday life. It also develops attitudes and dispositions such as critical thinking and logical analysis, a curious and inquiring mind, and the ability to solve problems and grasp complex concepts.

A unique feature in the study and practice of physics is the extensive use of models, especially those expressed in mathematical language, to explain observations and make predictions. A model serves as a bridge between abstract scientific theories and the observations and experiences of the real world. Models should be tested through experiments and must be consistent with available evidence. Hence, they can change and evolve with new evidence. The learner should be cognisant of the assumptions and limitations that are inherent in the use of models as they simplify complex real world phenomena. Knowledge and understanding of the use of models in the learning of physics is highly transferable to other disciplines, such as modelling of biological processes, weather patterns, earthquakes, and even the movement of people or financial markets.

1.3 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 science inquiry skills
   - 3.3. relating science and society

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.

1.4 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.

Teaching students the nature of science helps them to develop an accurate understanding of what science is and how it is practised and applied in society. Students should be encouraged to consider relevant ethical issues, how scientific knowledge is developed, and the strengths and limitations of science. Teaching the nature of science also enhances the students' understanding of science content, increases their interest in science and helps show its human side. Science teaching should emphasise *how* we know as well as *what* we know.

Understanding the nature of scientific knowledge, demonstrating science inquiry skills and relating science and society are the three components that form our Practices of Science. Students' understanding of the nature and 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 are emphasised.

The curriculum provides opportunities for students to reflect how the Practices of Science contribute to the accumulation of scientific knowledge. Students are encouraged to think about the 'whys' when planning and conducting investigations, developing models or engaging in scientific arguments. Through such reflection, they can come to understand the importance of each practice and develop a nuanced appreciation of the nature of science.

The Practices of Science comprise three components:

A. Understanding the nature of scientific knowledge
B. Demonstrating science inquiry skills
C. Relating science and society

A. Understanding the Nature of Scientific Knowledge

- A1. Understand that science is an evidence-based, model-building enterprise concerned with the natural world
- A2. Understand that the use of both logic and creativity is required in the generation of scientific knowledge
- A3. Recognise that scientific knowledge is generated from consensus within the community of scientists through a process of critical debate and peer review
- A4. Understand that scientific knowledge is reliable and durable, yet subject to revision in the light of new evidence

B. Demonstrating Science Inquiry Skills

- B1. Identify scientific problems, observe phenomena and pose scientific questions/hypotheses
- B2. Plan and conduct investigations by selecting the appropriate experimental procedures, apparatus and materials with due regard for accuracy, precision and safety
- B3. Obtain, organise and represent data in an appropriate manner
- B4. Analyse and interpret data
- B5. Construct explanations based on evidence and justify these explanations through sound reasoning and logical argument
- B6. Use appropriate models to explain concepts, solve problems and make predictions
- B7. Make decisions based on evaluation of evidence, processes, claims and conclusions
- B8. Communicate scientific findings and information using appropriate language and terminology

C. Relating Science and Society

- C1. Recognise that the application of scientific knowledge to problem solving could be influenced by other considerations such as economic, social, environmental and ethical factors
- C2. Demonstrate an understanding of the benefits and risks associated with the application of science to society

C3. Use scientific principles and reasoning to understand, analyse and evaluate real-world systems, as well as to generate solutions for problem solving

Developing 21st Century Competencies Through the Learning of Science

To prepare our students for the future, a Framework for 21st Century Competencies (21CC) and Student Outcomes was developed by MOE (see Figure 1.1). This 21CC framework is meant to equip students with the key competencies and mindsets to be successful in the 21st century.

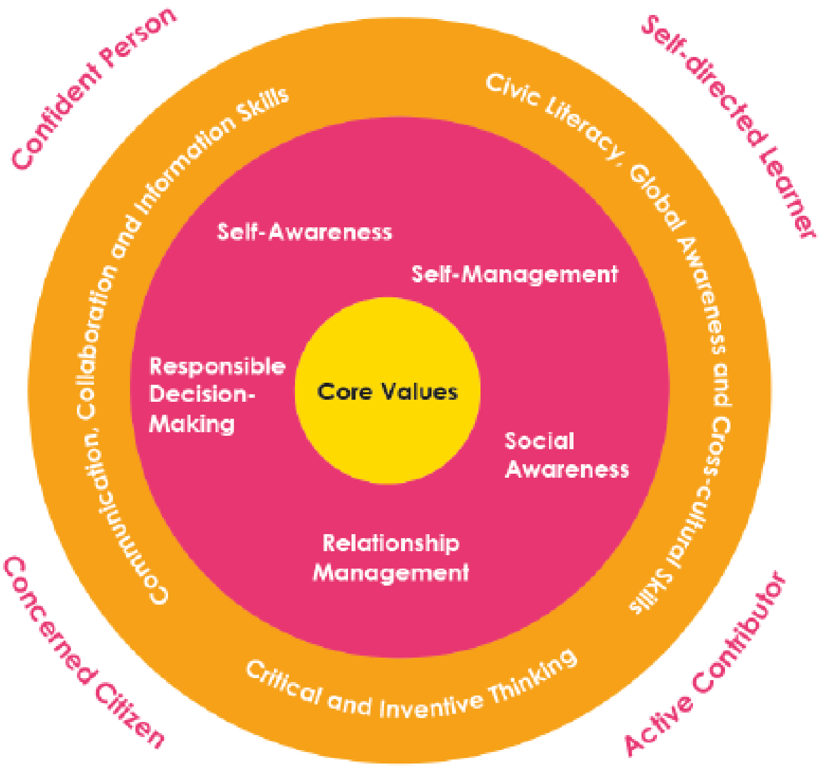

Figure 1.1. Framework for 21st Century Competencies and Student Outcomes

The features and intent of the Practices of Science are consistent with the emphasis on developing 21CC in our students.

The development of 21CC is not separate from the learning of science. The features of scientific inquiry, such as the processes of scientific investigation, reasoning, modelling and problem solving support a student's development of 21CC. The nature and limitations of science and scientific inquiry are developed effectively when scientific practices are learnt in the context of relevant science content. Deep disciplinary learning in science develops 21CC and promotes the process of learning for transfer to other areas of life.

1.5 H2 Physics Curriculum Framework

The Practices of Science, Core Ideas in physics and Learning Experiences are put together in a framework (see Figure 1.2) to guide the development of the H2 Physics curriculum.

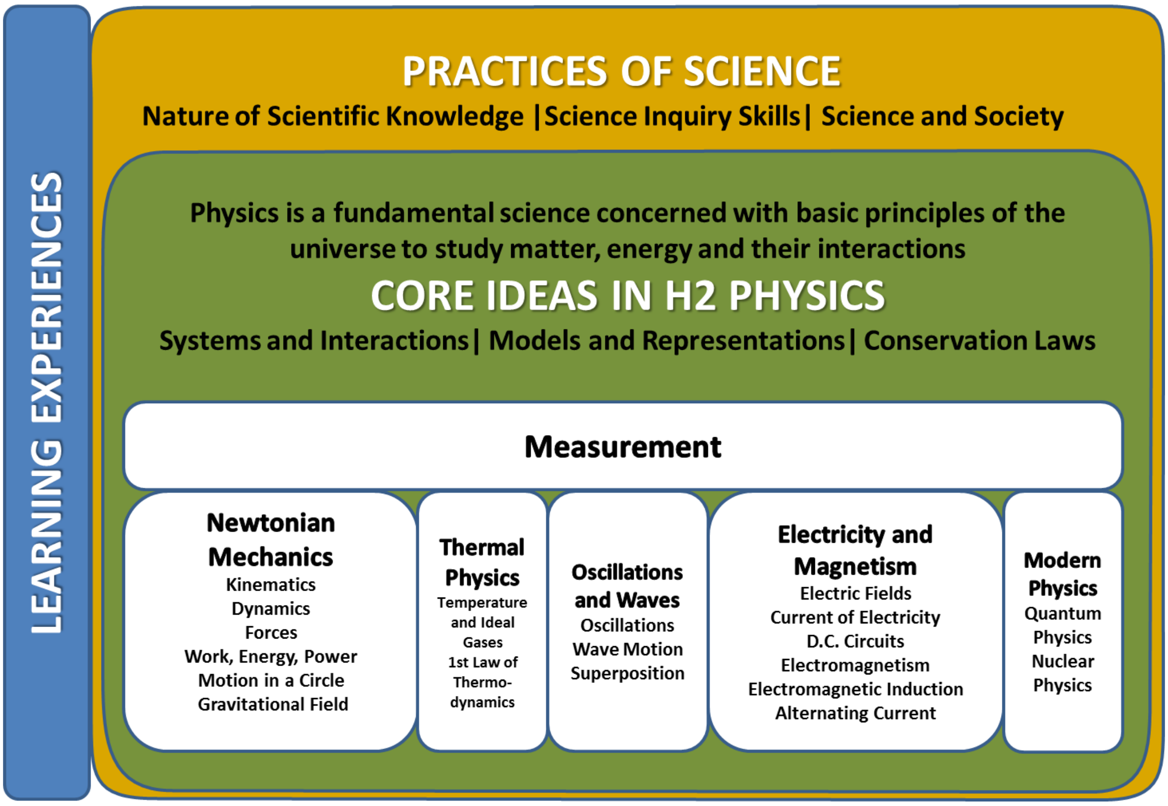

Figure 1.2. Overview of the H2 Physics Curriculum Framework

The Practices of Science are common to the natural sciences of Physics, Chemistry and Biology. These practices 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 Core Ideas help students to integrate knowledge and link concepts across different topics, and highlight important themes that recur throughout the curriculum. The syllabus content is organised into sections according to the main branches and knowledge areas of physics, i.e. Newtonian Mechanics, Thermal Physics, Oscillations and Waves, Electricity and Magnetism, and Modern Physics. This allows for a focused, systematic and in-depth treatment of the topics within each section.

The Learning Experiences refer to a range of learning opportunities selected by teachers to link the physics content of the Core Ideas with the Practices of Science, to enhance students' learning of the concepts. Real-world contexts can help illustrate the physics concepts and their applications. Experimental activities and ICT tools can also be used to build students' understanding.

2. CONTENT

2.1 CORE IDEAS IN PHYSICS

Physics encompasses the study of systems spanning a wide range of distances and times: from 10^{-15} m (e.g. sub-atomic particles) to larger than 10^{30} m (e.g. galaxies), from near-instantaneous events, such as the current flow with a flick of a switch, to slow-evolving phenomena, such as the birth and death of a star.

A small number of basic principles and laws can be applied to study and make sense of this wide variety of simple and complex systems. Similarly, a few core ideas that cut across traditional content boundaries can be introduced in the curriculum to provide students with a broader way of thinking about the physical world.

These Core Ideas are fundamental in the study of physics and help students integrate knowledge and link concepts across different topics. They provide powerful analytical tools which can explain phenomena and solve problems.

1 SYSTEMS AND INTERACTIONS

1.1 Defining the **systems** under study (by specifying their **boundaries** and making explicit **models** of the systems) provides tools for understanding and testing ideas that are applicable throughout physics.

1.2 **Objects** can be treated as having no **internal structure** or an internal structure that can be ignored. A **system**, on the other hand, is a collection of objects with an internal structure which may need to be taken into account.

1.3 Physical events and phenomena can be understood by studying the **interactions** between objects in a system and with the environment.

1.4 Students should be able to identify **causal relationships** when analysing interactions and **changes** in a system.

1.5 Interactions between objects in a system can be modelled using **forces** (e.g. a system of forces applied to move a mass; a system of two masses colliding; a system of the moon orbiting around the Earth; a system of electrical charges; a system of current in a straight wire placed in a magnetic field).

1.6 Fields existing in space are used to explain interactions between objects that are not in contact. Forces at a distance are explained by fields that can transfer **energy** and can be described in terms of the arrangement and properties of the interacting objects. These forces can be used to describe the relationship between electrical and magnetic fields.

1.7 **Equilibrium** is a unique state where the relevant physical properties of a system are balanced (e.g. the attainment of constant temperature at thermal equilibrium when objects of different temperatures interact, or an object returning to its equilibrium position after undergoing damped oscillatory motion).

1.8 Simplified **microscopic** models can be used to explain **macroscopic** properties observed in systems with complex and random interactions between a large number of objects:

1.8.1 Microscopic models are applied in the study of electricity, thermodynamics and waves. Macroscopic properties (e.g. current, temperature and wave speed) are used to investigate interactions and changes in these systems.

1.8.2 These macroscopic properties can be linked to complex interactions at the microscopic level, for example: the motion of electrons giving rise to current in a circuit, the random motion of atoms and molecules of an object giving rise to its thermal energy and the oscillatory motion of many particles giving rise to a wave motion.

1.8.3 Such complex systems may also be better characterised by **statistical averages** (e.g. drift velocity, temperature) as these quantities may be more meaningful than the properties and behaviours of individual components (e.g. electron movement in a wire resulting in the current).

2 MODELS AND REPRESENTATIONS

2.1 **Models** use reasonable **approximations** to simplify real-world phenomena in order to arrive at useful ways to explain or analyse systems.

2.2 The awareness of the approximations used in a proposed model allows one to estimate the **validity** and **reliability** of that model.

2.3 Models are tested through observations and experiments and should be **consistent with available evidence**. Models can evolve and be refined in the light of new evidence.

2.4 The assumptions made in defining a system will determine how interactions are described and analysed. Understanding the limits of these assumptions is a fundamental aspect of modelling.

2.5 The use of **representations** is inherent in the process of constructing a model. Examples of representations are pictures, motion diagrams, graphs, energy bar charts and mathematical equations.

2.6 Mathematics is an important tool in physics. It is used as a **language** to describe the relationships between different physical quantities and to solve numerical problems.

2.7 Representations and models help in analysing phenomena, solving problems, making predictions and communicating ideas.

3 CONSERVATION LAWS

3.1 **Conservation laws** are fundamental among the principles in physics used to understand the physical world.

3.2 When analysing physical events or phenomena, the choice of system and associated conservation laws provides a powerful set of tools to use to predict the possible outcome of an interaction.

3.3 Conservation laws **constrain** the possible behaviours of objects in a system, or the outcome of an interaction or process.

3.4 Associated with every conservation law in classical physics is a physical quantity, a scalar or a vector, which characterises a system.

3.5 In a **closed** system, the associated physical quantity has a constant value independent of interactions between objects in the system. In an **open** system, the changes of the associated physical quantity are always equal to the transfer of that quantity to or from the system by interactions with other systems.

3.6 In physics, charge, momentum, mass-energy and angular momentum are conserved.

3.7 Examples of how conservation laws are used in our syllabus:

3.7.1 Conservation of momentum in collisions and explosions allowing the prediction of subsequent motion of the objects or particles.

3.7.2 Conservation of energy to calculate the change in total energy in systems that are open to energy transfer due to external forces (work is done), thermal contact processes (heating occurs), or the emission or absorption of photons (radiative processes).

3.7.3 Conservation of mass-energy, charge and nucleon number in nuclear reactions to enable the calculation of relevant binding energies and identification of the resulting nuclides.

2.2 SECTIONS AND TOPICS IN H2 PHYSICS

The 20 topics in H2 Physics are organised into six main sections, as listed in Table 2.1. A broad narrative is provided for each of the main sections, followed by a list of guiding questions and learning outcomes for each of the topics.

Table 2.1: Main sections and topics for H2 Physics

Sections	Topics
I. Measurement	1. Measurement
II. Newtonian Mechanics	2. Kinematics 3. Dynamics 4. Forces 5. Work, Energy, Power 6. Motion in a Circle 7. Gravitational Field
III. Thermal Physics	8. Temperature and Ideal Gases 9. First Law of Thermodynamics
IV. Oscillations and Waves	10. Oscillations 11. Wave Motion 12. Superposition
V. Electricity and Magnetism	13. Electric Fields 14. Current of Electricity 15. D.C. Circuits 16. Electromagnetism 17. Electromagnetic Induction 18. Alternating Current
VI. Modern Physics	19. Quantum Physics 20. Nuclear Physics

2.3 Section I: Measurement

Links between sections and topics

Physics is an experimental science. Precise measurements enable the collection of useful experimental data that can be tested against theoretical predictions to refine the development of physical theories. Experimental evidence is the ultimate authority in discriminating between competing physical theories. Scientific knowledge continues to evolve as data from new or improved measurements helps us to understand and quantify the natural world.

Measurements are subject to uncertainty (also known as error), and it is important to estimate these to understand the reliability of the measurements. Error analysis involves estimating uncertainties and figuring out how to reduce them if necessary. In an experiment, the record of measurements made should include the estimated uncertainties, and document an analysis of the possible sources of errors with a discussion of steps taken to reduce the uncertainties. Doing this enables better conclusions to be drawn from the experimental data.

The act of measurement sometimes affects the system being measured due to the interaction between the measuring device and the measured system. Common examples of this include measurements made using a thermometer, voltmeter or ammeter. Thus, improving the accuracy of measurements often requires the invention of better instruments or processes. At the quantum scale, however, there is an inherent limit to the precision of observations because any measurement inevitably alters the quantum state of the system being measured. This peculiar aspect of nature is associated with Heisenberg's uncertainty principle.

Applications and relevance to daily life

Physicists are very serious about measurement, and the other sciences and society as a whole have benefited from the spill-over effects of the invention of many amazing measuring devices and techniques. Modern engineering also depends heavily on accurate measurements in areas like design, construction, optimisation and communication. Precise measurements have made many advanced technological applications possible; examples include the study and manipulation of materials, and breakthroughs in fields as diverse as geophysics and biology. Measurements using sophisticated devices like magnetic resonance imaging (MRI) scanners are also important for the medical industry, to provide a wealth of data that aids in clinical diagnosis and informs treatment decisions.

Topic 1: Measurement

Guiding Questions

- How are the standards for measurements established?
- Why is uncertainty inherent in all measurements?
- How can uncertainties be estimated? How can they be reduced if necessary?
- Why does the uncertainty of a measurement matter?
- How is the skill of making estimates of physical quantities useful and how can this skill be developed?

Measurement	**Learning Outcomes** Students should be able to:
Physical quantities and SI units	(a) recall the following base quantities and their SI units: mass (kg), length (m), time (s), current (A), temperature (K), amount of substance (mol). (b) express derived units as products or quotients of the base units and use the named units listed in 'Summary of Key Quantities, Symbols and Units' as appropriate. (c) use SI base units to check the homogeneity of physical equations. (d) show an understanding of and use the conventions for labelling graph axes and table columns as set out in the ASE publication *Signs, Symbols and Systematics (The ASE Companion to 16–19 Science, 2000)*. (e) 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). (f) make reasonable estimates of physical quantities included within the syllabus.
Scalars and vectors	(g) distinguish between scalar and vector quantities, and give examples of each. (h) add and subtract coplanar vectors. (i) represent a vector as two perpendicular components.
Errors and uncertainties	(j) show an understanding of the distinction between systematic errors (including zero error) and random errors. (k) show an understanding of the distinction between precision and accuracy. (l) assess the uncertainty in a derived quantity by addition of actual, fractional, percentage uncertainties or by numerical substitution (a rigorous statistical treatment is not required).

2.4 Section II: Newtonian Mechanics

Links between sections and topics

Newtonian mechanics is a successful physical theory that explains the relationship between force and motion. Conceptually, mechanics consists of the study of how objects move (kinematics) and of the reason why objects move in the way they do (dynamics). It is usually assumed that all students of physics have at least an understanding of Newtonian mechanics.

The study of kinematics begins with the introduction of precise terminology and language for describing motion, to reduce ambiguity in expression and confusion in thought. One-dimensional motion is introduced and discussed with the (verbal, mathematical, graphical) language of kinematics before more complex two-dimensional motions such as projectile motion and circular motion are studied. To scope the syllabus, we restrict ourselves to modelling the motion of bodies where effects such as the rotation or even the change in shape of the body are insignificant, and hence such bodies are assumed to be well-described as point objects.

The study of dynamics is grounded on Newton's three laws of motion, which accurately model systems as diverse as the planets of the solar system and helium atoms in a container. However, experiments and observations have proven that the validity of Newtonian mechanics breaks down for objects moving close to the speed of light, or objects at the subatomic scale. In these situations, special relativity and quantum mechanics respectively are the more appropriate physical theories that apply.

Forces play a central role in Newton's laws of motion, and forces common in everyday life such as tension, friction, air resistance, etc. are discussed. Many of these everyday forces are actually electromagnetic interactions, one of the four fundamental forces in nature (other than gravitation, the weak interaction, and the strong interaction). We pay particular attention also to situations in which various forces act on a rigid object yet the object is maintained in static equilibrium.

The concept of energy is one of the most fundamental concepts in science, and is discussed in the context of Newtonian mechanics. Energy is present in various forms, endlessly transformed from one form to another. The conservation of energy is an essential principle in physics. The concept of work links energy and force, as work is a means of transferring energy through the application of a force. In certain situations, the concepts of work and energy can be applied to solve the dynamics of a mechanical system without directly resorting to Newton's laws. Beyond mechanics, this problem-solving approach focusing on energy can be applied to a wide range of phenomena in electromagnetism, and thermal and nuclear physics. The work-energy approach often provides a much simpler analysis than that obtained from the direct application of Newton's laws, since the former deals with scalar rather than vector quantities.

APPLICATIONS AND RELEVANCE TO DAILY LIFE

Newtonian mechanics is the foundation of contemporary science and is also the basis for much engineering and applied science. It is of paramount importance to a civil engineer to know the effects of forces acting on a structure such as a bridge. Someone designing a vehicle to break the world speed record had better be conversant in the concepts of force and energy to stand a chance in the competition. While relativistic corrections are sometimes important for space science, the principles of Newtonian mechanics are largely sufficient for satellite technologies that give us global communication and navigation systems such as GPS.

Links to Core Ideas		
Systems and Interactions	**Models and Representations**	**Conservation Laws**
• The interactions of an object with other objects can be described by forces • A force acting on an object can cause a change in its momentum (or velocity) or its kinetic energy or produce a torque on it • Potential energy and kinetic energy are two basic types of energy • Work is the transfer of mechanical energy • F_G as interaction between a mass placed in an external g-field	• Newton's laws of motion • Newton's law of gravitation • Uniform circular motion • Common representations: e.g. motion diagrams, free-body diagrams, energy bar charts, field lines and equipotential lines, force-position graph of g-field (inverse square law), etc. • Simplifying assumptions: e.g. point masses, frictionless planes, massless strings, isolated systems, incompressible fluids, taking g on surface of Earth as approximately constant, etc.	• Conservation of mass • Conservation of energy (e.g. work-energy theorem) • Conservation of momentum

TOPIC 2: KINEMATICS

Guiding Questions

- How can the motion of objects be described, represented, quantified and predicted?
- How would an object falling freely in a gravitational field move?

Kinematics	**Learning Outcomes** Students should be able to:
Rectilinear motion	(a) show an understanding of and use the terms 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 displacement-time graphs and areas under and gradients of velocity-time graphs, including cases of non-uniform acceleration.

Kinematics	Learning Outcomes Students should be able to:
	(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, including the motion of bodies falling in a uniform gravitational field without air resistance. (f) describe qualitatively the motion of bodies falling in a uniform gravitational field with air resistance.
Non-linear motion	(g) describe and explain motion due to a uniform velocity in one direction and a uniform acceleration in a perpendicular direction.

TOPIC 3: DYNAMICS

Guiding Questions

- How do forces affect the motion of an object?
- When is momentum conserved during interactions between objects?
- How can we analyse interactions using the principle of momentum conservation?

Dynamics	Learning Outcomes Students should be able to:
Newton's laws of motion	(a) state and apply each of Newton's laws of motion. (b) show an understanding that mass is the property of a body which resists change in motion (inertia). (c) describe and use the concept of weight as the force experienced by a mass in a gravitational field.
Linear momentum and its conservation	(d) define and use linear momentum as the product of mass and velocity. (e) define and use impulse as the product of force and time of impact. (f) relate resultant force to the rate of change of momentum. (g) recall and solve problems using the relationship $F = ma$, appreciating that resultant force and acceleration are always in the same direction. (h) state the principle of conservation of momentum. (i) 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).

Dynamics	**Learning Outcomes** Students should be able to:
	(j) 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. (k) 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.

TOPIC 4: FORCES

Guiding Questions

- What are the different types of forces?
- How do we solve problems involving translational and rotational equilibrium?

Forces	**Learning Outcomes** Students should be able to:
Types of force	(a) recall and apply Hooke's law ($F = kx$, where k is the force constant) to new situations or to solve related problems. (b) describe the forces on a mass, charge and current-carrying conductor in gravitational, electric and magnetic fields, as appropriate. (c) show a qualitative understanding of normal contact forces, frictional forces and viscous forces including air resistance (no treatment of the coefficients of friction and viscosity is required).
Centre of gravity	(d) show an understanding that the weight of a body may be taken as acting at a single point known as its centre of gravity.
Turning effects of forces	(e) define and apply the moment of a force and the torque of a couple. (f) show an understanding that a couple is a pair of forces which tends to produce rotation only. (g) apply the principle of moments to new situations or to solve related problems.
Equilibrium of forces	(h) show an understanding that, when there is no resultant force and no resultant torque, a system is in equilibrium. (i) use a vector triangle to represent forces in equilibrium.
Upthrust	(j) derive, from the definitions of pressure and density, the equation $p = \rho g h$. (k) solve problems using the equation $p = \rho g h$. (l) show an understanding of the origin of the force of upthrust acting on a body in a fluid.

Forces	**Learning Outcomes** Students should be able to:
	(m) state that upthrust is equal in magnitude and opposite in direction to the weight of the fluid displaced by a submerged or floating object. (n) calculate the upthrust in terms of the weight of the displaced fluid. (o) recall and apply the principle that, for an object floating in equilibrium, the upthrust is equal in magnitude and opposite in direction to the weight of the object to new situations or to solve related problems.

TOPIC 5: WORK, ENERGY, POWER

Guiding Questions

- What is energy and how does it relate to work done?
- How does energy get transferred and transformed?

Work, Energy, Power	**Learning Outcomes** Students should be able to:
Work	(a) define and use work done by a force as the product of the force and displacement in the direction of the force. (b) calculate the work done in a number of situations including the work done by a gas which is expanding against a constant external pressure: $W = p\Delta V$.
Energy conversion and conservation	(c) give examples of energy in different forms, its conversion and conservation, and apply the principle of energy conservation.
Efficiency	(d) show an appreciation for the implications of energy losses in practical devices and use the concept of efficiency to solve problems.
Potential energy and kinetic energy	(e) derive, from the equations for uniformly accelerated motion in a straight line, the equation $E_k = \frac{1}{2}mv^2$. (f) recall and use the equation $E_k = \frac{1}{2}mv^2$. (g) distinguish between gravitational potential energy, electric potential energy and elastic potential energy. (h) deduce that the elastic potential energy in a deformed material is related to the area under the force-extension graph. (i) show an understanding of and use the relationship between force and potential energy in a uniform field to solve problems.

Work, Energy, Power	Learning Outcomes Students should be able to:
	(j) derive, from the definition of work done by a force, the equation $E_p = mgh$ for gravitational potential energy changes near the Earth's surface. (k) recall and use the equation $E_p = mgh$ for gravitational potential energy changes near the Earth's surface.
Power	(l) define power as work done per unit time and derive power as the product of a force and velocity in the direction of the force.

TOPIC 6: MOTION IN A CIRCLE

Guiding Questions

- How do we describe the motion of an object moving in a circular path?
- What causes an object to move in a circular path?

Motion in a Circle	Learning Outcomes Students should be able to:
Kinematics of uniform circular motion	(a) express angular displacement in radians. (b) show an understanding of and use the concept of angular velocity to solve problems. (c) recall and use $v = r\omega$ to solve problems.
Centripetal acceleration	(d) describe qualitatively motion in a curved path due to a perpendicular force, and understand the centripetal acceleration in the case of uniform motion in a circle. (e) recall and use centripetal acceleration $a = r\omega^2$, and $a = \frac{v^2}{r}$ to solve problems.
Centripetal force	(f) recall and use centripetal force $F = mr\omega^2$, and $F = \frac{mv^2}{r}$ to solve problems.

TOPIC 7: GRAVITATIONAL FIELD

Guiding Questions

- How do two masses interact? Do they need to be in physical contact to do so?
- What do field lines represent? Do field lines represent similar things for gravitational fields and electric fields?
- How can we understand the motion of planets and satellites? Are we at the centre of the universe?

Gravitational Field	**Learning Outcomes** Students should be able to:
Gravitational field	(a) show an understanding of the concept of a gravitational field as an example of field of force and define the gravitational field strength at a point as the gravitational force exerted per unit mass placed at that point. (b) recognise the analogy between certain qualitative and quantitative aspects of gravitational and electric fields.
Gravitational force between point masses	(c) recall and use Newton's law of gravitation in the form $F = \frac{Gm_1m_2}{r^2}$.
Gravitational field of a point mass	(d) derive, from Newton's law of gravitation and the definition of gravitational field strength, the equation $g = \frac{GM}{r^2}$ for the gravitational field strength of a point mass. (e) recall and apply the equation $g = \frac{GM}{r^2}$ for the gravitational field strength of a point mass to new situations or to solve related problems.
Gravitational field near to the surface of the Earth	(f) show an understanding that near the surface of the Earth, gravitational field strength is approximately constant and is equal to the acceleration of free fall.
Gravitational potential	(g) define the gravitational potential at a point as the work done per unit mass in bringing a small test mass from infinity to that point. (h) solve problems using the equation $\phi = -\frac{GM}{r}$ for the gravitational potential in the field of a point mass.
Circular orbits	(i) analyse circular orbits in inverse square law fields by relating the gravitational force to the centripetal acceleration it causes. (j) show an understanding of geostationary orbits and their application.

2.5 SECTION III: THERMAL PHYSICS

LINKS BETWEEN SECTIONS AND TOPICS

Concepts such as speed, velocity, force and kinetic energy are carefully defined to make the study of mechanics quantitative. Similarly, there needs to be careful definition of terms like temperature, heat and internal energy, which are used in thermal physics. Understanding thermal physics requires us to approach the concepts from both the macroscopic and microscopic lenses.

Heat and temperature are often used interchangeably in everyday language. However, these terms have different and specific meanings in physics. Macroscopically, temperature can be defined in terms of its measurement, while heat refers to the energy transferred between two systems at different temperatures. Linking these two ideas is the zeroth law of thermodynamics, which states that when two objects at different temperature are placed in thermal contact, there will be energy exchange between them until thermal equilibrium is reached. The zeroth law allows the use of thermometers to measure temperature. When thermal equilibrium is achieved, the thermometer reflects its own temperature as well as the temperature of the other body that it is in thermal contact with.

A thermometer is calibrated according to a temperature scale. The Kelvin scale has a privileged status, as it is independent of the exact properties of the material used for temperature measurement. This is unlike the Celsius scale, commonly used for liquid-in-glass thermometers, which is defined based on the properties of water. Energy transfer between two substances in thermal contact usually causes temperature changes in both of them, though this is not guaranteed. Heat capacity and specific heat capacity allows for the calculation of temperature changes in such interactions. Similarly, latent heat is used to calculate the energy required to change the phase of a substance (e.g. from solid to liquid, or from liquid to gas).

The properties of matter depend on temperature, pressure, volume, etc. The condition in which a particular material exists is known as its state, and this could be described by such macroscopic physical quantities, including its mass, which is a measure of the amount of substance. We are particularly interested in the study of gases, as their volumes can be varied much more dramatically than for typical solids and liquids. At very low pressures, most gases behave in much the same way, which is captured by the ideal gas model. While the exact properties of real gases are very complex, most gases at room temperature and atmospheric pressure behave approximately like ideal gases. The ideal gas equation expresses the relationship between state variables for an ideal gas.

These concepts lay the foundation for thermodynamics, the study of relationships involving heat, mechanical work, and other aspects of energy and energy transfer. The first law of thermodynamics is central to understanding thermodynamic processes which involve heat and mechanical work. This law extends the principle of conservation of energy in Newtonian mechanics, by introducing the concept of internal energy.

The really profound and powerful idea that these topics lead on to is the link between microscopic and macroscopic properties. The kinetic theory of gases is a simple example of this, linking macroscopic properties such as pressure, volume, and temperature, with microscopic properties such as the mass and speed of the randomly-moving individual molecules that make up a gas. To a good approximation, we can use Newtonian mechanics to model the microscopic motion of gas molecules, and we can apply concepts from kinematics and dynamics to analyse the average pressure exerted by the randomly-moving molecules.

APPLICATIONS AND RELEVANCE TO DAILY LIFE

Many researchers still actively investigate the behaviour of gases using computer simulation and other techniques. Environmental problems connected with Earth's atmosphere, such as the depletion of the ozone layer, are motivations for such work. A better understanding of the behaviour of gases might lead to an improved characterisation and possible solutions to these problems.

The application of thermodynamics pervades modern society e.g. car engines, air conditioners and power stations. However, an inevitable consequence of this energy conversion is the discharge of heat. This unwanted release of thermal energy into the environment is known as thermal pollution. One approach to reduce this is the development of alternative sources of energy, e.g. solar power. Another approach is to make things more efficient. Reducing the demand for energy should also be a personal and policy priority.

A more complete treatment of thermodynamics involves the concept of entropy, which is central to the second and third laws of thermodynamics. Entropy is linked to disorder and the so-called arrow of time, based on the extreme improbability of events such as un-mixing milk and tea by stirring. The broader framework of statistical mechanics traces its formative roots to classical thermodynamics. Statistical mechanics, which has applications all across the physical sciences and even in the social sciences, is the rigorous science of linking microscopic properties with macroscopic properties, through the application of probability and statistical theory.

Links to Core Ideas		
Systems and Interactions	**Models and Representations**	**Conservation Laws**
• Internal energy is the sum of the random distribution of KE and PE associated with the molecules of a system • Work done and heat are processes which transfer energy	• Kinetic theory of gases • Ideal gas law • Microscopic versus macroscopic description of a gas • Temperature as proportional to the average energy per particle • Common representations: e.g. *P-V* diagrams • Simplifying assumptions: e.g. an ideal gas has no intermolecular forces, negligible heat loss, mean translational KE of a molecule of an ideal gas = 3/2 kT as a useful approximation	• First law of thermodynamics as conservation of energy

TOPIC 8: TEMPERATURE AND IDEAL GASES

Guiding Questions

- What is the difference between temperature and heat? What is internal energy?
- How can we define a simple model of a gas that is valid for real gases under certain assumptions?
- How can we relate microscopic behaviour of gas molecules to the macroscopic properties of a gas?

Temperature and Ideal Gases	**Learning Outcomes** Students should be able to:
Thermal equilibrium	(a) show an understanding that regions of equal temperature are in thermal equilibrium.
Temperature scales	(b) explain how empirical evidence leads to the gas laws and to the idea of an absolute scale of temperature (i.e. the thermodynamic scale that is independent of the property of any particular substance and has an absolute zero). (c) convert temperatures measured in degrees Celsius to kelvin: $T/K = T/°C + 273.15$.
Equation of state	(d) recall and use the equation of state for an ideal gas expressed as $pV = nRT$, where n is the amount of gas in moles. (e) state that one mole of any substance contains 6.02×10^{23} particles and use the Avogadro number $N_A = 6.02 \times 10^{23}$ mol^{-1}.
Kinetic theory of gases	(f) state the basic assumptions of the kinetic theory of gases. (g) explain how molecular movement causes the pressure exerted by a gas and hence derive the relationship $pV = \frac{1}{3}Nm\langle c^2 \rangle$, where N is the number of gas molecules (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).
Kinetic energy of a molecule	(h) recall and apply the relationship that the mean kinetic energy of a molecule of an ideal gas is proportional to the thermodynamic temperature (i.e. $\frac{1}{2}m\langle c^2 \rangle = \frac{3}{2}kT$) to new situations or to solve related problems.

TOPIC 9: FIRST LAW OF THERMODYNAMICS

Guiding Questions

- How can temperature and heat be understood from both macroscopic and microscopic perspectives?
- How does the energy transferred between a system and its environment relate to heat transfer and mechanical work done?

First Law of Thermodynamics	**Learning Outcomes** Students should be able to:
Specific heat capacity and specific latent heat	(a) define and use the concepts of specific heat capacity and specific latent heat.
Internal energy	(b) show an understanding that internal energy is determined by the state of the system and that it can be expressed as the sum of a random distribution of kinetic and potential energies associated with the molecules of a system. (c) relate a rise in temperature of a body to an increase in its internal energy.
First law of thermodynamics	(d) recall and use the first law of thermodynamics expressed in terms of the increase in internal energy, the heat supplied to the system and the work done on the system.

2.6 Section IV: Oscillations and Waves

Links between sections and topics

Periodic motion, where the pattern of movement repeats over time, is ubiquitous, and arises for example when objects are perturbed from a condition of stable equilibrium. While much of the motion we have considered is non-periodic, we have studied uniform circular motion, which is periodic and regular. Even in one spatial dimension, there can be complicated types of periodic motion. Nonetheless, we can gain a deep understanding of periodic motion by analysing the mathematically simplest case of free oscillations, known as simple harmonic motion (SHM). Such sinusoidally varying motion is essentially a projection of uniform circular motion, and provides a mathematical basis upon which to describe more complicated oscillations. Naturally, we revisit concepts in kinematics, dynamics, forces and energy in trying to understand SHM.

When we consider a system of connected particles, the idea of single particles undergoing oscillations is the starting point that leads on to the idea of waves within the system. While we have seen how powerful the particle picture is, it turns out that the wave picture, generalised beyond classical mechanics, is equally fundamental for describing and understanding the physical universe.

With waves, we move conceptually from physics of particles to the physics of continuous media. All waves are disturbances which result in oscillations. The oscillations then spread out as waves, which carry energy and can result in disturbances far away. Waves are a means of transmitting energy without the attendant transfer of matter. Remarkably, one of the many surprises of nature is that electromagnetic waves can travel through a vacuum, an example of field oscillations that do not require particles.

We can also discuss wave mechanics, as waves interact, though in a qualitatively different way from how particles interact. The principle of superposition allows accurate characterisation of interaction of waves. Interference and diffraction are important wave phenomena due to the superposition of waves. However, there is actually no clear distinction between interference and diffraction. The difference in the usage of the terms is mainly historical. Many of the ideas introduced during the study of waves in this section will later be important for appreciating the limitation of classical physics in explaining the behaviour of matter on the atomic scale and understanding quantum wave-particle duality.

Applications and relevance to daily life

Oscillations and waves play important roles in engineering and nature. In nature, molecules in a solid oscillate about their equilibrium position; electromagnetic waves consist of oscillating electric and magnetic fields, and waves are present everywhere, e.g. light travelling from the Sun to Earth, water waves and sound waves. The study and control of oscillation is needed to achieve important goals in engineering, e.g. to prevent the collapse of a building due to waves created by an earthquake. Furthermore, diffraction gratings allow us to determine the frequencies of light sources ranging from lamps to distant stars. Optical engineers also create optically variable graphics (OVG) on credit cards, which incorporate diffraction grating technology, as an anti-counterfeiting measure.

Links to Core Ideas		
Systems and Interactions	**Models and Representations**	**Conservation Laws**
• A wave is a source of disturbance that can transfer energy and momentum through time and space • Interaction of electromagnetic wave with matter (e.g. reflection, refraction, diffraction, absorption, scattering)	• SHM harmonic motion of a mass characterised by a restoring force that is proportional to its displacement • Mechanical wave model • Wave nature of electromagnetic radiation • Superposition principle, which is used to explain wave phenomena (e.g. standing waves, two-source interference, diffraction) • Common representations: e.g. wavefront diagrams, displacement-time graph (characteristic of every particle), displacement-position graph (snapshot of wave in time) • Simplifying assumptions: e.g. ignore dissipative forces like friction and air resistance (negligible attenuation)	• Conservation of mechanical energy in an SHM system • The relationship between intensity and distance for a point source • The intensity distribution of a double-slit interference pattern obeys the conservation of energy

TOPIC 10: OSCILLATIONS

Guiding Questions

- What are the characteristics of periodic motion? How can we study and describe such motion?
- How can circular motion be related to simple harmonic motion?
- How do we analyse simple harmonic motion?

Oscillations	**Learning Outcomes** Students should be able to:
Simple harmonic motion	(a) describe simple examples of free oscillations. (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 and phase difference and express the period in terms of both frequency and angular frequency. (d) recall and use the equation $a = -\omega^2 x$ as the defining equation of simple harmonic motion. (e) recognise and use $x = x_0 \sin \omega t$ as a solution to the equation $a = -\omega^2 x$.

Oscillations	Learning Outcomes Students should be able to:
	(f) recognise and use the equations $v = v_0 \cos \omega t$ and $v = \pm\omega\sqrt{x_0^2 - x^2}$. (g) describe, with graphical illustrations, the changes in displacement, velocity and acceleration during simple harmonic motion.
Energy in simple harmonic motion	(h) describe the interchange between kinetic and potential energy during simple harmonic motion.
Damped and forced oscillations, resonance	(i) describe practical examples of damped oscillations with particular reference to the effects of the degree of damping and to the importance of critical damping in applications such as a car suspension system. (j) describe practical examples of forced oscillations and resonance. (k) describe graphically how the amplitude of a forced oscillation changes with driving frequency near to the natural frequency of the system, and understand qualitatively the factors which determine the frequency response and sharpness of the resonance. (l) show an appreciation that there are some circumstances in which resonance is useful, and other circumstances in which resonance should be avoided.

TOPIC 11: WAVE MOTION

Guiding Questions

- What are waves? How can we study and describe such motion?
- How can oscillatory motion be related to wave motion?
- What do different types of waves have in common, and how are they different?

Wave Motion	Learning Outcomes Students should be able to:
Progressive waves	(a) show an understanding of and use the terms displacement, amplitude, period, frequency, phase difference, wavelength and speed. (b) deduce, from the definitions of speed, frequency and wavelength, the equation $v = f\lambda$. (c) recall and use the equation $v = f\lambda$. (d) show an understanding that energy is transferred due to a progressive wave. (e) recall and use the relationship, *intensity* $\propto$ (amplitude)^2.

Wave Motion	Learning Outcomes Students should be able to:
	(f) show an understanding of and apply the concept that a wave from a point source and travelling without loss of energy obeys an inverse square law to solve problems.
Transverse and longitudinal waves	(g) analyse and interpret graphical representations of transverse and longitudinal waves.
Polarisation	(h) show an understanding that polarisation is a phenomenon associated with transverse waves. (i) 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.
Determination of frequency and wavelength of sound waves	(j) determine the frequency of sound using a calibrated oscilloscope. (k) determine the wavelength of sound using stationary waves.

TOPIC 12: SUPERPOSITION

Guiding Questions

- What happens when two or more waves meet?
- What is a stationary wave and how is it produced?
- What happens when waves meet an obstacle? What if the obstacle is one slit, two slits, or multiple slits?

Superposition	Learning Outcomes Students should be able to:
Principle of superposition	(a) explain and use the principle of superposition in simple applications. (b) show an understanding of the terms interference, coherence, phase difference and path difference.
Stationary waves	(c) show an understanding of experiments which demonstrate stationary waves using microwaves, stretched strings and air columns. (d) explain the formation of a stationary wave using a graphical method, and identify nodes and antinodes.
Diffraction	(e) explain the meaning of the term diffraction. (f) show an understanding of experiments which demonstrate diffraction including the diffraction of water waves in a ripple tank with both a wide gap and a narrow gap.

Superposition	**Learning Outcomes** Students should be able to:
Two-source interference	(g) show an understanding of experiments which demonstrate two-source interference using water waves, sound waves, light waves and microwaves. (h) show an understanding of the conditions required for two-source interference fringes to be observed. (i) recall and solve problems using the equation $\lambda = \frac{ax}{D}$ for double-slit interference.
Single slit and multiple slit diffraction	(j) recall and use the equation $\sin\theta = \frac{\lambda}{b}$ to locate the position of the first minima for single slit diffraction. (k) recall and use the Rayleigh criterion $\theta \approx \frac{\lambda}{b}$ for the resolving power of a single aperture. (l) recall and use the equation $d\sin\theta = n\lambda$ to locate the positions of the principal maxima produced by a diffraction grating. (m) describe the use of a diffraction grating to determine the wavelength of light (the structure and use of a spectrometer are not required).

2.7 SECTION V: ELECTRICITY AND MAGNETISM

LINKS BETWEEN SECTIONS AND TOPICS

There are four fundamental forces in physics: the gravitational, electromagnetic, strong and weak interactions. While the strong and weak interactions explain phenomena at the sub-atomic level, a large number of daily human experiences can be explained by gravitational and electromagnetic interactions.

Electromagnetic interactions involve particles that have a property called electric charge, an attribute that appears to be just as fundamental as mass, or even more so – charge seems to be precisely quantised, while it is not clear if mass is quantised. An object with mass experiences a force in a gravitational field, and electrically-charged objects experience forces in electric and magnetic fields. Like mass-energy, charge obeys a conservation law as well. There are important analogies and distinctions between concepts in the gravitational field and in the electrical field topics.

A charge produces an electric field in the space around it, and a second charge placed in this field experiences a force due to this field. The electric force between two isolated point charges is governed by Coulomb's law, which is mathematically similar to Newton's law of gravitation for isolated point masses. We can use the concepts of work done and energy in the context of electrical interactions as well, and these ideas provide another route to solving problems that can in certain cases bring out the simplicity of the situation. Terms like electric potential and electric potential energy are defined similarly as with gravitational potential and gravitational potential energy.

Practical use of electricity often occurs in circuits rather than in free space. Circuits provide a means of conveying energy and information from one place to another. Within a circuit, the complicated effects of forces and electric fields at the microscopic level result in a macroscopic description where consideration of energy and electric potentials mostly suffices. The collective movement of charges results in electrical current, driven by potential differences (also known as voltages). Both current and voltage can be experimentally measured. Applying the principles of charge and energy conservation provide powerful tools to analyse a variety of electrical circuits.

The mystery of magnetism was first discovered in magnetic stones by the ancients. Today, we understand magnetism as an effect inseparable from electricity, summarised by Maxwell's laws of electromagnetism. Unlike electric forces, which act on electric charges whether moving or stationary, magnetic forces act only on moving charges. Moving charges produce a magnetic field, and another moving charge or current placed in this magnetic field experiences a force. This apparent asymmetry in electromagnetic phenomena contributed to the development of the theory of relativity, and Einstein's 1905 paper on relativity begins with the following description:

> *It is known that Maxwell's electrodynamics – as usually understood at the present time – when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable*

phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighborhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighborhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise – assuming equality of relative motion in the two cases discussed – to electric currents of the same path and intensity as those produced by the electric forces in the former case.

— A. Einstein, On the electrodynamics of moving bodies (1905)

APPLICATIONS AND RELEVANCE TO DAILY LIFE

Technologies harnessing electrical and magnetic properties pervade modern society. Converting energy into electrical energy traditionally involves the induced electromotive force and current produced by a changing magnetic flux or a time-varying magnetic field. Transmitting electrical energy over long distances is made feasible by the use of alternating current and voltage transformers. Semiconductor devices in computers and smartphones are the product of our deep understanding of the physics of electricity and magnetism in solid state materials. Innovations are also pushing on the quantum frontier.

Even more fundamentally, elastic forces in springs and contact forces between surfaces arise from electrical forces at the atomic level. In biology, electricity is also important in signalling and control. The heart rhythms are maintained by waves of electrical excitation, from nerve impulses that spread through special tissue in the heart muscles.

Links to Core Ideas		
Systems and Interactions	**Models and Representations**	**Conservation Laws**
• F_E as the interaction between a charge and an external *E*-field • F_B as the interaction between a moving charge and an external *B*-field	• Microscopic model of the flow of charges • Ohm's law (for ohmic conductors) • Faraday's law • Common representations: diagrams of electric circuits, field lines and equipotential lines, magnetic flux density patterns, etc • Simplifying assumptions: e.g. point charges, negligible internal resistance, infinitely extended planes	• Conservation of charges in circuits • Conservation of energy in circuits • Lenz's law as conservation of energy

TOPIC 13: ELECTRIC FIELDS

Guiding Questions

- What is electric charge? How do charges interact?
- What do field lines represent? Do field lines represent similar things for gravitational fields and electric fields?

Electric Fields	**Learning Outcomes** Students should be able to:
Concept of an electric field	(a) show an understanding of the concept of an electric field as an example of a field of force and define electric field strength at a point as the electric force exerted per unit positive charge placed at that point. (b) represent an electric field by means of field lines. (c) recognise the analogy between certain qualitative and quantitative aspects of electric and gravitational fields.
Electric force between point charges	(d) recall and use Coulomb's law in the form $F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$ for the electric force between two point charges in free space or air.
Electric field of a point charge	(e) recall and use $E = \frac{Q}{4\pi\varepsilon_0 r^2}$ for the electric field strength of a point charge in free space or air.
Uniform electric fields	(f) calculate the electric field strength of the uniform field between charged parallel plates in terms of the potential difference and plate separation. (g) calculate the forces on charges in uniform electric fields. (h) describe the effect of a uniform electric field on the motion of charged particles.
Electric potential	(i) define the electric potential at a point as the work done per unit positive charge in bringing a small test charge from infinity to that point. (j) state that the field strength of the electric field at a point is numerically equal to the potential gradient at that point. (k) use the equation $V = \frac{Q}{4\pi\varepsilon_0 r}$ for the electric potential in the field of a point charge, in free space or air.

TOPIC 14: CURRENT OF ELECTRICITY

Guiding Questions

- How does the macroscopic phenomenon of current flow relate to the movement of microscopic charges?
- How are current, voltage, and resistance related in an electrical circuit?
- What happens to energy in an electrical circuit?

Current of Electricity	**Learning Outcomes** Students should be able to:
Electric current	(a) show an understanding that electric current is the rate of flow of charge. (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 $Q = It$.
Potential difference	(d) recall and solve problems using the equation $V = \frac{W}{Q}$. (e) recall and solve problems using the equations $P = VI$, $P = I^2R$ and $P = \frac{V^2}{R}$.
Resistance and resistivity	(f) define the resistance of a circuit component as the ratio of the potential difference across the component to the current passing through it, and solve problems using the equation $V = IR$. (g) sketch and explain the I-V characteristics of various electrical components such as an ohmic resistor, a semiconductor diode, a filament lamp and a negative temperature coefficient (NTC) thermistor. (h) sketch the resistance-temperature characteristic of an NTC thermistor. (i) recall and solve problems using the equation $R = \frac{\rho l}{A}$.
Electromotive force	(j) distinguish between electromotive force (e.m.f.) and potential difference (p.d.) using energy considerations. (k) 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.

TOPIC 15: D.C. CIRCUITS

Guiding Questions

- How are symbols and diagrams used to represent real circuits?
- How are the principles of charge and energy conservation applied to analyse circuits?

D.C. Circuits	**Learning Outcomes** Students should be able to:
Circuit symbols and diagrams	(a) recall and use appropriate circuit symbols as set out in the ASE publication *Signs, Symbols and Systematics (The ASE Companion to 16–19 Science, 2000)*. (b) draw and interpret circuit diagrams containing sources, switches, resistors, ammeters, voltmeters, and/or any other type of component referred to in the syllabus.
Series and parallel arrangements	(c) solve problems using the formula for the combined resistance of two or more resistors in series. (d) solve problems using the formula for the combined resistance of two or more resistors in parallel. (e) solve problems involving series and parallel circuits for one source of e.m.f.
Potential divider	(f) show an understanding of the use of a potential divider circuit as a source of variable p.d. (g) explain the use of thermistors and light-dependent resistors in potential divider circuits to provide a potential difference which is dependent on temperature and illumination respectively.
Balanced potentials	(h) recall and solve problems by using the principle of the potentiometer as a means of comparing potential differences.

TOPIC 16: ELECTROMAGNETISM

Guiding Questions

- What is a magnet? Are there “magnetic” charges?
- Do magnetic fields have effects on electric charges?
- What do field lines represent? Do field lines represent similar things for electric fields and magnetic fields?
- Why is the word “flux” used when talking about a magnetic field?

Electromagnetism	**Learning Outcomes** Students should be able to:
Concept of a magnetic field	(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.

Electromagnetism	Learning Outcomes Students should be able to:
Magnetic fields due to currents	(b) sketch flux patterns 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 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.
Force on a current-carrying conductor	(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. (h) show an understanding of how the force on a current-carrying conductor can be used to measure the flux density of a magnetic field using a current balance.
Force between current-carrying conductors	(i) explain the forces between current-carrying conductors and predict the direction of the forces.
Force on a moving charge	(j) predict the direction of the force on a charge moving in a 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 and uniform magnetic fields. (m) explain how electric and magnetic fields can be used in velocity selection for charged particles.

TOPIC 17: ELECTROMAGNETIC INDUCTION

Guiding Questions

- If an electric current produces a magnetic field, can a magnetic field produce an electric current? What is required for this?
- Can we achieve perpetual motion by invoking the magic of electromagnetism?

Electromagnetic Induction	Learning Outcomes Students should be able to:
Magnetic flux	(a) define magnetic flux as the product of an area and the component of the magnetic flux density perpendicular to that area.

Electromagnetic Induction	**Learning Outcomes** Students should be able to:
	(b) recall and solve problems using $\Phi = BA$. (c) define magnetic flux linkage.
Laws of electromagnetic induction	(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.

TOPIC 18: ALTERNATING CURRENT

Guiding Questions

- How is alternating current different from direct current?
- How can we describe alternating current, e.g. mathematically and graphically?
- Why is alternating current used in the generation and transmission of electricity?

Alternating Current	**Learning Outcomes** Students should be able to:
Characteristics of alternating currents	(a) 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. (b) deduce that the mean power in a resistive load is half the maximum (peak) power for a sinusoidal alternating current. (c) represent an alternating current or an alternating voltage by an equation of the form $x = x_0 \sin \omega t$. (d) distinguish between r.m.s. and peak values and recall and solve problems using the relationship $I_{\text{r.m.s.}} = \frac{I_0}{\sqrt{2}}$ for the sinusoidal case.
The transformer	(e) 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.
Rectification with a diode	(f) explain the use of a single diode for the half-wave rectification of an alternating current.

2.8 SECTION VI: MODERN PHYSICS

LINKS BETWEEN SECTIONS AND TOPICS

This section deals with physics developed from 1900 onwards, focusing on quantum physics and nuclear physics. 'Modern' physics in this context provides the physical basis for much of chemistry, and was developed to explain the behaviour of matter on the atomic scale. Such behaviour was observed to be quite different from what was expected in the Newtonian view of the world.

While interference, diffraction and polarisation demonstrated the wave nature of electromagnetic (EM) radiation, the photoelectric effect and the emission and absorption spectra of atoms suggested instead a particulate model for EM radiation. We now consider EM radiation as composed of discrete 'quantised' packets of energy known as photons. Quantisation also manifested in the unique energy levels of atoms. The particle nature and the wave nature of EM radiation are linked – the energy of a single photon is proportional to the frequency of the radiation.

The basic ideas of photons and atomic energy levels allowed for the explanation of a variety of otherwise puzzling experimental observations, such as the production and scattering of X-rays, and led to the development of lasers. Quantum mechanics traces its development to these early ideas, and gradually the notion of a clockwork universe now appeared to collapse at the sub-atomic scale into a bizarre many-worlds situation filled with probabilities and even complex numbers. The idea of wave-particle duality applies not just to EM radiation but even particles like electrons were shown to have wave properties and an associated de Broglie's wavelength. Nonetheless, the unity of physics as a discipline only grew stronger through this quantum revolution – the deep ideas of classical physics provided some basis for the radical new ideas, and the quantum formalism naturally agreed with the classical one when applied in the realm of macroscopic systems.

Nuclear physics and relativity were also developed during the early 1900s. Nuclear physics started with the observations of radioactivity in uranium. The study of radioactivity is an attempt to understand the nature of radiation emitted by radioactive nuclei. Radioactivity can be explained as the result of decay or disintegration of unstable nuclei. The stability or instability of a particular nucleus is affected by the competition between the attractive nuclear forces among the protons and neutrons and the repulsive electrical interactions among the protons. A nucleus might be induced to decay by colliding it with an energetic particle. Ultimately, these are all quantum processes.

Nuclear reactions can generally be classified as fusion or fission. While we have harnessed fission for the generation of nuclear energy, research laboratories around the world are still working on fusion reactors that promise to provide abundant clean energy and create an 'artificial sun'. Conservation laws are a powerful way to analyse nuclear reactions, and the conservation of mass-energy is an especially important conservation law introduced in this topic. In 1905, the so-called 'miracle year' for Einstein, he also published a paper on mass-energy equivalence, which we now know as the famous equation $E = mc^2$.

APPLICATIONS AND RELEVANCE TO DAILY LIFE

Quantum mechanics is the key to understanding atoms and molecules, including their structure, emission/absorption spectra, chemical behaviour and other properties. The development of quantum mechanics provided the basis for many modern advances in chemistry. Quantum technologies could revolutionise the world – quantum computing for example is an interdisciplinary field bringing together physicists, computer scientists, and mathematicians with the promise of creating computers that use qubits instead of bits.

The applications of nuclear physics have had enormous effects on humankind – some beneficial, some catastrophic. Radioactive dating using carbon-14 and nuclear energy produced through fission are some examples of beneficial applications, while the world now lives with global stockpiles of nuclear warheads that can destroy the Earth many times over. Accidents at nuclear energy reactors, such as those at Chernobyl and Fukushima, also show the dangers associated with nuclear energy.

Links to Core Ideas		
Systems and Interactions	**Models and Representations**	**Conservation Laws**
• Interaction of electromagnetic radiation (or photons) with matter (e.g. absorption, emission, scattering)	• Particulate nature of electromagnetic radiation and wave nature of particles (wave-particle duality) • Models of the atom • Exponential form of radioactive decay as a random process with a fixed probability • Common representations: e.g. energy level diagrams • Simplifying assumptions: e.g. Planck's quantum hypothesis	• Einstein's photoelectric effect as conservation of energy • Conservation of nucleon number, proton number and mass-energy in nuclear processes • The use of conservations laws of energy and momentum to predict the existence of the neutrino

TOPIC 19: QUANTUM PHYSICS

Guiding Questions

- What roles do experiments play in constructing knowledge about the photoelectric effect, the discrete energy levels in atoms, and wave-particle duality?
- How does the wave model of light fail to explain the photoelectric effect? What does the existence of atomic line spectra suggest about light?
- How does quantum physics modify our ideas about matter?
- How can we use conservation laws to analyse the photoelectric effect?
- What is the significance of Heisenberg's uncertainty principle?

Quantum Physics	**Learning Outcomes** Students should be able to:
Energy of a photon	(a) show an appreciation of the particulate nature of electromagnetic radiation.

Quantum Physics	**Learning Outcomes** Students should be able to:
	(b) recall and use the equation $E = hf$ for the energy of a photon.
The photoelectric effect	(c) show an understanding that the photoelectric effect provides evidence for the particulate nature of electromagnetic radiation while phenomena such as interference and diffraction provide evidence for the wave nature. (d) recall the significance of threshold frequency. (e) recall and use the equation $\frac{1}{2}mv_{\max}^2 = eV_s$, where V_s is the stopping potential. (f) explain photoelectric phenomena in terms of photon energy and work function energy. (g) explain why the stopping potential is independent of intensity whereas the photoelectric current is proportional to intensity at constant frequency. (h) recall, use and explain the significance of the equation $hf = \Phi + \frac{1}{2}mv_{\max}^2$.
Wave-particle duality	(i) describe and interpret qualitatively the evidence provided by electron diffraction for the wave nature of particles. (j) recall and use the relation for the de Broglie wavelength $\lambda = \frac{h}{p}$.
Energy levels in atoms	(k) show an understanding of the existence of discrete electronic energy levels in isolated atoms (e.g. atomic hydrogen) and deduce how this leads to the observation of spectral lines.
Line spectra	(l) distinguish between emission and absorption line spectra. (m) recall and solve problems using the relation $hf = E_2 - E_1$.
X-ray spectra	(n) explain the origins of the features of a typical X-ray spectrum.
The uncertainty principle	(o) show an understanding of and apply $\Delta p \Delta x \gtrsim h$ as a form of the Heisenberg position-momentum uncertainty principle to new situations or to solve related problems.

TOPIC 20: NUCLEAR PHYSICS

Guiding Questions

- Why are some nuclei radioactive? What happens during radioactive decay? Where does the energy come from?
- What is emitted during radioactive decay, and is it harmful? How do decay products interact with matter?
- What are the uses of radioactivity?
- How are nuclear reactions different from chemical reactions? How are they similar?
- What can conservation laws tell us about nuclear processes?

Nuclear Physics	**Learning Outcomes** Students should be able to:
The nucleus	(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).
Isotopes	(c) show an understanding that an element can exist in various isotopic forms each with a different number of neutrons in the nucleus.
Nuclear processes	(d) use the usual notation for the representation of nuclides and represent simple nuclear reactions by nuclear equations of the form $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$. (e) state and apply to problem solving the concept that nucleon number, charge and mass-energy are all conserved in nuclear processes.
Mass defect and nuclear binding energy	(f) show an understanding of the concept of mass defect. (g) recall and apply the equivalence between energy and mass as represented by $E = mc^2$ to solve problems. (h) show an understanding of the concept of nuclear binding energy and its relation to mass defect. (i) sketch the variation of binding energy per nucleon with nucleon number. (j) explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.
Radioactive decay	(k) show an understanding of the spontaneous and random nature of nuclear decay. (l) infer the random nature of radioactive decay from the fluctuations in count rate. (m) show an understanding of the origin and significance of background radiation.

Nuclear Physics	**Learning Outcomes** Students should be able to:
	(n) show an understanding of the nature of α, β and γ radiations (knowledge of positron emission is not required). (o) show an understanding of how the conservation laws for energy and momentum in β decay were used to predict the existence of the neutrino (knowledge of antineutrino and antiparticles is not required). (p) define the terms activity and decay constant and recall and solve problems using the equation $A = \lambda N$. (q) infer and sketch the exponential nature of radioactive decay and solve problems using the relationship $x = x_0 \exp(-\lambda t)$ where x could represent activity, number of undecayed particles or received count rate. (r) define and use half-life as the time taken for a quantity x to reduce to half its initial value. (s) solve problems using the relation $\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$.
Biological effects of radiation	(t) discuss qualitatively the effects, both direct and indirect, of ionising radiation on living tissues and cells.

3. PEDAGOGY

The starting point for the science curriculum is that every child wants to and can learn. The science curriculum nurtures students as inquirers and taps on their innate curiosity and desire to seek answers to questions or solve problems relating to science. Besides developing a strong conceptual understanding of scientific models and theories, students' curiosity is stimulated and they are encouraged to see the value of science and its applications and connection to their everyday lives.

3.1 DEVELOPING CONCEPTUAL UNDERSTANDING

Conceptual understanding is more than factual knowledge which is commonly associated with the memorising of facts and definitions. Conceptual understanding is built by using facts as tools to discern patterns, connections, and deeper, transferable understanding. One approach to develop students' conceptual understanding is through conceptual change that occurs when they are dissatisfied with a prior conception and the available replacement conception is logical, reasonable and/or meaningful.

3.2 ENGAGING IN THE PRACTICES OF SCIENCE

Science is not just a body of knowledge, but also a way of knowing and doing. The 'ways of thinking and doing' refer to a discipline's distinctive mode of inquiry and approach to working with the observations and knowledge about the world. Through the Practices of Science, students should appreciate the following:

- **Nature of scientific knowledge:** Students understand the nature of scientific knowledge implicitly through the process of 'doing science'. To complement this, an explicit approach may be used. This approach utilises elements from the history of science or the processes in science to improve students' views of the nature of scientific knowledge.

- **Science as an inquiry:** Scientific inquiry refers to the different approaches by which scientists study and develop an understanding of the natural and physical world around us. Inquiry-based instruction could be used to develop the different aspects of the Practices of Science together with the understanding of science concepts as well as the dispositions and attitudes associated with science. Inquiry-based strategies could include questioning, demonstrations, use of technology, as well as models and modelling.

- **Relating science and society:** Students should appreciate how science and technology are used in daily life. They should apply and experience the potential of science to generate creative solutions to solve a wide range of real-world problems, ranging from those affecting everyday lives to complex problems affecting humanity, while appreciating the values and ethical implications of these applications. Science education needs to equip students with the ability to articulate their ethical stance as they participate in discussions about socio-scientific issues that involve ethical dilemmas, with no single right answers.

3.3 Practical Work

Science practical work supports the teaching and learning of science through developing the Practices of Science, experimental techniques, practical manipulative skills and conceptual understanding. It also cultivates interest in science and in learning science. In addition, attitudes like objectivity and integrity, which are important in the learning of the discipline of science, are reinforced.

3.4 The Singapore Student Learning Space (SLS)

The Singapore Student Learning Space (SLS) is an online platform that supports teaching and learning, it

- **enables our students to learn anytime, anywhere**
  As SLS is available to all students and teachers in every school it can be a key lever to bring about more pervasive and seamless integration of technology in teaching and learning at schools. Students can access SLS through different devices and learn at their own pace.

- **allows our students to take greater ownership of their learning and work collaboratively**
  Students can do self-directed learning by accessing the resources in SLS on their own or complete learning packages assigned by teachers. Quizzes are auto-graded to give immediate feedback to students. These resources complement other teaching and learning resources such as lecture notes, tutorials, physical manipulatives, etc. There are learning tools available on SLS that enable students to curate and organise information, connect with peers and to create works to demonstrate their learning.

- **complements classroom teaching**
  Teachers can use the MOE curriculum-aligned resources in the SLS, curate own resources from the world-wide-web or develop own resources to complement their teaching. In addition, teachers are supported by visualisation tools in SLS to easily monitor students' learning progress and check for understanding.

- **is collectively shaped by schools and owned by all**
  As SLS is accessible by teachers across all Singapore schools, it provides a unique opportunity for teachers to work collectively to co-develop, adapt and share lessons. Teachers can make use of the co-editing and sharing capabilities in SLS to curate and share lesson designs.

Students can access the SLS through *https://vle.learning.moe.edu.sg/login*.

4. ASSESSMENT

Assessment is the process of gathering and analysing evidence about student learning. This information is used to make decisions about students, curricula and programmes. Assessment for Learning (AfL) is assessment conducted constantly during classroom instruction to support teaching and learning. With the feedback about the state of students' learning, teachers then adapt their teaching strategies and pace based on the students' needs. Assessment of Learning (AoL) aims to summarize how much or how well students have achieved at the end of a course of study over an extended period of time. The A-level examination is an example of AoL.

4.1 A-LEVEL EXAMINATION

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.

This syllabus is designed to place less emphasis on factual material and greater emphasis on the understanding and application of scientific concepts and principles. This approach has been adopted in recognition of the need for students to develop skills that will be of long term value in an increasingly technological world rather than focusing on large quantities of factual material which may have only short term relevance.

Experimental work is an important component and should underpin the teaching and learning of Physics.

4.2 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 and 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 materials that candidates need to recall and explain. Questions testing the objectives above will often begin with one of the following words: *define, state, name, describe, explain* or *outline* (see Section 4.7 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, interpret 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. present reasoned explanations for phenomena, patterns, trends and relationships
5. make comparisons that may include the identification of similarities and differences
6. analyse and evaluate information to identify patterns, report trends, draw inferences, report conclusions and construct arguments
7. justify decisions, make predictions and propose hypotheses
8. apply knowledge, including principles, to novel situations
9. use skills, knowledge and understanding from different areas of Physics to solve problems
10. organise and present information, ideas and arguments clearly and coherently, using appropriate language.

These assessment objectives above cannot be precisely specified in the syllabus content because questions testing such skills are often based on information which 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 may begin with one of the following words: *discuss, predict, suggest, calculate* or *determine* (see Section 4.7 Glossary of Terms).

C ***Experimental skills and investigations***

Candidates should be able to:

1. follow a detailed sequence of instructions or apply standard techniques
2. devise and plan investigations which may include constructing and/or testing a hypothesis and select techniques, apparatus and materials
3. use techniques, apparatus and materials safely and effectively
4. make and record observations, measurements and estimates
5. interpret and evaluate observations and experimental data
6. evaluate methods and techniques, and suggest possible improvements.

4.3 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	80
3	Longer Structured Questions	2 h	35	80
4	Practical	2 h and 30 min	20	55

Paper 1 (1 h, 30 marks)
This paper will consist of 30 compulsory multiple-choice questions. All questions will be of the direct-choice type with four options.

Paper 2 (2 h, 80 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, 80 marks)
This paper will consist of 2 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 60 marks, consisting of a variable number of structured questions, all compulsory; and
- Section B, worth 20 marks, consisting of a choice of one from two 20-mark questions.

Paper 4 (2 h and 30 min, 55 marks)
This paper will assess appropriate aspects of assessment 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 5%. The assessment of skill areas MMO, PDO and ACE will have a weighting of 15%.

The assessment of PDO and ACE may also include questions on data-analysis which do not require practical equipment and apparatus. Candidates will be allocated a specified time for access to apparatus and materials of specific questions. Candidates will **not** be permitted to refer to books and laboratory notebooks during the assessment.

Weighting of Assessment Objectives

Assessment Objective		Weighting (%)	Assessment Components
A	Knowledge with understanding	32	Papers 1, 2, 3
B	Handling, applying and evaluating information	48	Papers 1, 2, 3
C	Experimental skills and investigations	20	Paper 4

4.4 ADDITIONAL INFORMATION

Disallowed Subject Combinations
Candidates may not simultaneously offer physics at H1 and H2 levels.

Mathematical Requirements
The mathematical requirements are given in Section 4.6.

Data and Formulae
Data and Formulae, given in Section 4.9, will appear as pages 2 and 3 in Papers 1, 2 and 3.

Symbols, Signs and Abbreviations
Symbols, signs and abbreviations used in examination papers will follow the recommendations made in *Signs, Symbols and Systematics* (The ASE Companion to 16-19 Science, 2000). The units kWh, atmosphere, eV and unified atomic mass unit (u) may be used in examination papers without further explanation.

Geometrical Instruments
Candidates should have geometrical instruments with them for all papers.

For more information on assessment, please refer to the Singapore Examinations and Assessment Board https://www.seab.gov.sg/.

4.5 PRACTICAL ASSESSMENT

Scientific subjects are, by their nature, experimental. It is therefore important that, wherever possible, candidates carry out appropriate practical work to support the learning of this subject and develop the expected practical skills.

Paper 4 Practical Paper
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 conclusion(s) 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, and explain how they affect the final result(s)
- state and explain how significant errors/limitations 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 the treatment of given experimental data in drawing relevant conclusions and conducting analysis of a proposed plan.

The assessment of skill areas MMO, PDO and ACE will also be set in the context of the syllabus. The assessment of PDO and ACE may also include questions on data analysis that do not require practical equipment and apparatus.

Within the Scheme of Assessment, Paper 4 is weighted to 20% of the Higher 2 assessment. 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 *A-Level Physics Practical Skills Handbook*, which has been published separately, provides examples of relevant practical activities.

Candidates will **not** be permitted to refer to books and laboratory notebooks during the assessment.

Apparatus List

The list in Table 4.1 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 at least sufficient for half the candidates to undertake that particular experiment at the same time; some spare sets should also be provided.

Candidates will be told that they will have access to the apparatus and materials for specific questions for a specified time. Candidates will be told which question(s) to attempt first.

Table 4.1: Apparatus List for H2 Physics (9749)

Electricity and Magnetism	**Mechanics and General Items**
Ammeter (analogue): f.s.d. 500 mA and 1 A	Pendulum bob
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)	Stand, boss and clamp **x 3** (rod lengths: 60 cm **x 2**, 90 cm **x 1**)
	G-clamp **x 2**
	Pivot
	Pulley
Voltmeter (analogue): f.s.d. 3 V	Tuning forks (set of 8 pc): (1 set per 4–6 candidates)
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)	Newton-meter: 1 N, 10 N
	Rule with millimeter scale (1 m **x 2**, 0.5 m **x 1**, 300 mm **x 1**)
Galvanometer (analogue): centre-zero, f.s.d. ±35 mA, reading to 1 mA or better	Micrometer screw gauge (1 per 4–6 candidates)
	Vernier calipers (1 per 4–6 candidates)
Power supply: 12 V d.c. (low resistance)	Stopwatch (reading to 0.1 s or better)
Cells: 1.5 V **x 2** (with holder), 2 V **x 1**	Protractor
Lamp and holder: 6 V, 300 mA; 2.5 V, 0.3 A	Balance to 0.01 g (1 per 8–12 candidates)
Rheostat: max resistance 22 Ω, rating: at least 3.3 A	Beakers: 100 cm^3 **x 1**, 250 cm^3 **x 2**
	Plasticine
Switch	Blu-Tack
Jockey	Wire cutters
Leads and crocodile clips	Bare copper wire: 18, 26 s.w.g.
Wire: constantan 26, 28, 30, 32, 36, 38 s.w.g. or metric equivalents	Springs
	Spirit level (1 per 4–6 candidates)
Magnets and mounting: magnadur magnets **x 2** plus small iron yoke for mounting, bar magnets **x 2**	Stout pin or round nail
	Optical pin
	Slotted masses: 5 g **x 1**, 10 g **x 1**, 20 g **x 2**, 50 g **x 4**; 50 g hanger **x 1**
Compasses (small) **x 2**	
	Slotted masses: 100 g **x 4**; 100 g hanger **x 1**
Heat	

Electricity and Magnetism	Mechanics and General Items
Long stem thermometer: range –10 °C to 110 °C, at 1 °C intervals	Cork
	String/thread/twine
Metal calorimeter	Scissors
Measuring cylinder: 50 cm^3, 100 cm^3	Adhesive tape
Plastic or polystyrene cup 200 cm^3	Card (assorted sizes)
Means to heat water safely to boiling point	Sand and tray
Heating mat	Wood (assorted sizes, for various uses, e.g. to support)
Stirrer	
	Bricks **x 2** (each approx. 22 cm x 10 cm x 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.

4.6 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 $<, >, \ll, \gg, \approx, /, \propto, \langle x \rangle (= \bar{x}), \Sigma, \Delta x, \delta x, \surd$.

<u>Geometry and trigonometry</u>

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.

<u>Vectors</u>

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.

<u>Graphs</u>

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 $\frac{1}{x}, x^2, \frac{1}{x^2}, \sin x, \cos x, e^{-x}$.

(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 $\frac{dy}{dx}$ 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.

4.7 GLOSSARY OF TERMS

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. **Calculate** is used when a numerical answer is required. In general, working should be shown.
2. **Compare** requires candidates to provide both similarities and differences between things or concepts.
3. **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 from an earlier part of the question.
4. **Define (the term(s) ...)** is intended literally. Only a formal statement or equivalent paraphrase, such as the defining equation with symbols identified, is required.
5. **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 needed should be interpreted in light of the indicated mark value.
6. **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.
7. **Discuss** requires candidates to give a critical account of the points involved in the topic.
8. **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.
9. **Explain** may imply reasoning or some reference to theory, depending on the context.
10. **List** requires a number of points with no elaboration. Where a given number of points is specified, this should not be exceeded.

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. **Predict**: (see **Deduce**).

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

14. **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.

15. **Sketch**, when applied to diagrams, implies that a simple freehand drawing is acceptable; nevertheless, care should be taken to ensure that proportions are correct and that important details are clearly shown.

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

17. **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 that may not be formally included in the syllabus.

18. **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.

4.8 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
<u>Base Quantities</u>		
mass	m	kg
length	l	m
time	t	s
electric current	I	A
thermodynamic temperature	T	K
amount of substance	n	mol
<u>Other Quantities</u>		
distance	d	m
displacement	s, x	m

Quantity	Usual symbols	Usual unit
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	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	$rad\ s^{-1}$
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
electric field strength	E	$N\ C^{-1}$, $V\ m^{-1}$

Quantity	**Usual symbols**	**Usual unit**
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	°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	$t_{1/2}$	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
proton number	Z	
nucleon number	A	
neutron number	N	

4.9 DATA AND FORMULAE

The following data and formulae will appear as pages 2 and 3 in Papers 1, 2 and 3.

Data

speed of light in free space	c	$= 3.00 \times 10^{8}$ m s^{-1}
permeability of free space	μ_0	$= 4\pi \times 10^{-7}$ H m^{-1}
permittivity of free space	ε_0	$= 8.85 \times 10^{-12}$ F m^{-1}
		$= \frac{1}{36\pi} \times 10^{-9}$ F m^{-1}
elementary charge	e	$= 1.60 \times 10^{-19}$ C
the Planck constant	h	$= 6.63 \times 10^{-34}$ J s
unified atomic mass constant	u	$= 1.66 \times 10^{-27}$ kg
rest mass of electron	m_e	$= 9.11 \times 10^{-31}$ kg
rest mass of proton	m_p	$= 1.67 \times 10^{-27}$ kg
molar gas constant	R	$= 8.31$ J K^{-1} mol^{-1}
the Avogadro constant	N_A	$= 6.02 \times 10^{23}$ mol^{-1}
the Boltzmann constant	k	$= 1.38 \times 10^{-23}$ J K^{-1}
gravitational constant	G	$= 6.67 \times 10^{-11}$ N m^{2} kg^{-2}
acceleration of free fall	g	$= 9.81$ 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	$W = p\Delta V$
hydrostatic pressure	$p = \rho g h$
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 molecule	$E = \frac{3}{2}kT$
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	$I = Anvq$
resistors in series	$R = R_1 + R_2 + \cdots$
resistors in parallel	$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$
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	$B = \mu_0 n I$
radioactive decay	$x = x_0 \exp(-\lambda t)$
decay constant	$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$

5. TEXTBOOKS AND REFERENCES

Students may find the following references helpful.

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