PHYSICS

SYLLABUS

Pre-University

Higher 1 / 2 / 3

Syllabus 8867 / 9478 / 9814

Implementation starting with the 2025 Pre-University 1 cohort

Ministry of Education
SINGAPORE

CONTENTS

SECTION 1:
INTRODUCTION

1. INTRODUCTION

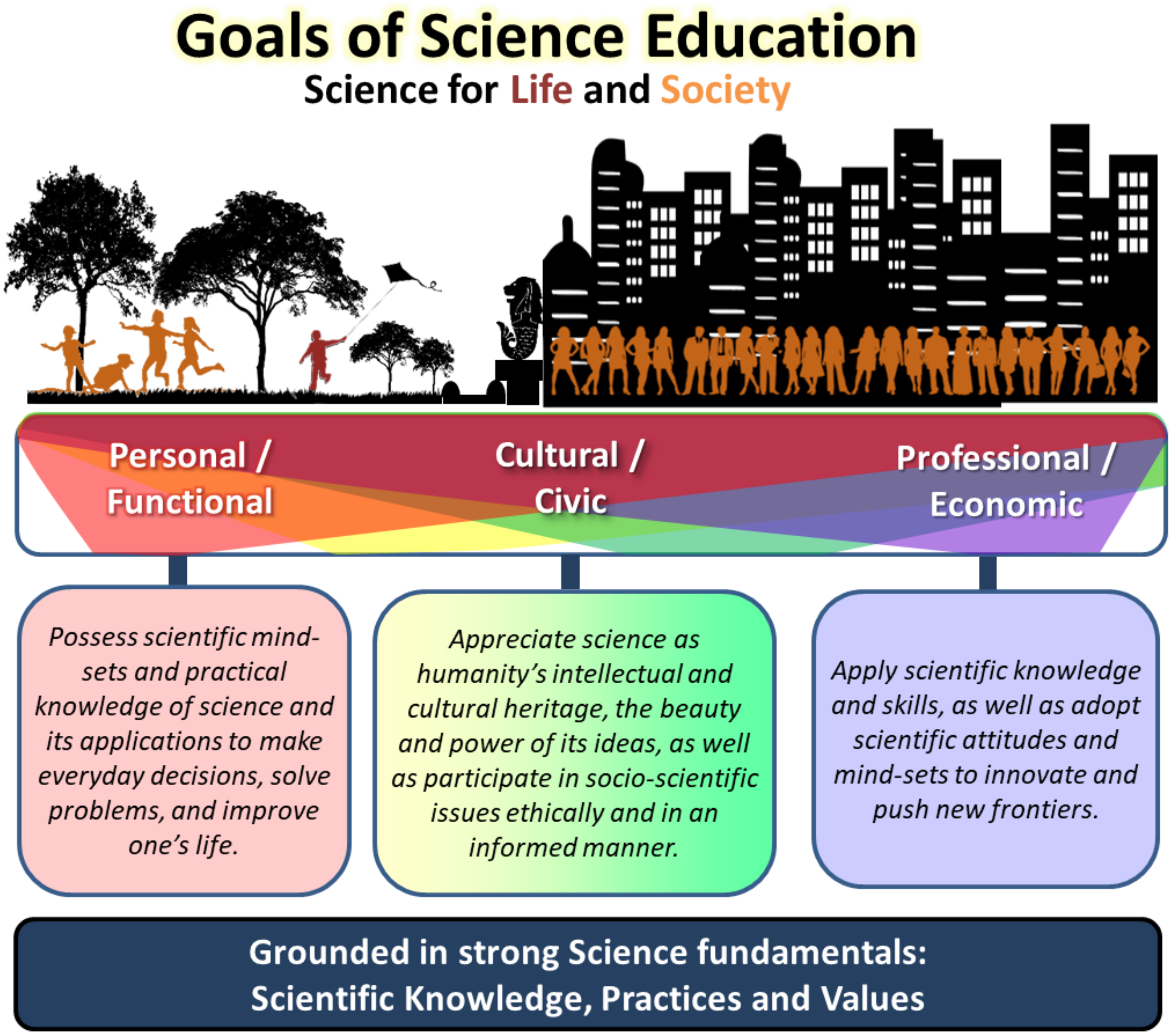
1.1 GOALS AND VISION OF SCIENCE EDUCATION

Our science students are diverse, with different needs, interests and aptitudes for science. Given the diversity of our science students and the needs of Singapore, the twin goals of science education are to:

a. Enthuse and nurture all students to be scientifically literate, so that they are able to make informed decisions and take responsible actions in their daily lives; and

b. Provide strong science fundamentals for students to innovate and pursue Science, Technology, Engineering, Math (STEM) for future learning and work.

The goals of science education, which serve the interwoven needs of the individual and society, can be unpacked into three dimensions: *personal/functional, cultural/civic* and *professional/economic*, as shown in **Figure 1.1**. *Science for Life and Society* is the tagline to capture the essence of these goals of science education, which can be achieved through developing strong fundamentals in scientific knowledge, practices and values.



Possess scientific mind-sets and practical knowledge of science and its applications to make everyday decisions, solve problems, and improve one's life.

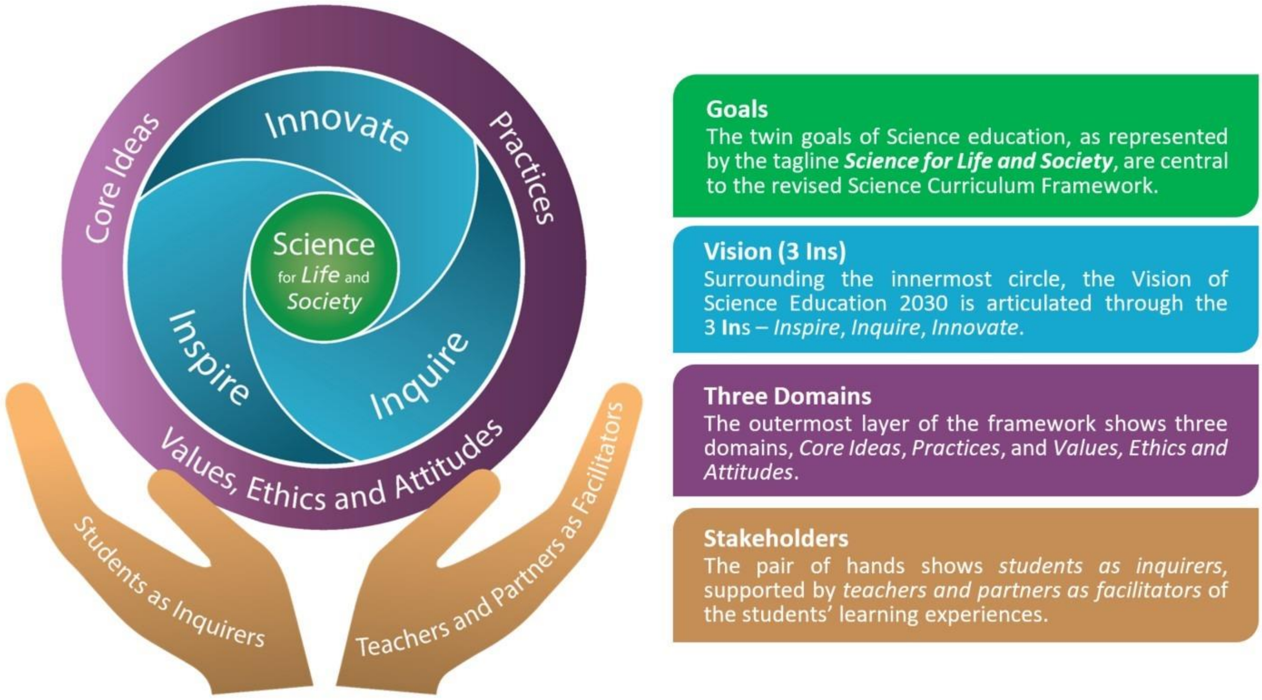
Appreciate science as humanity's intellectual and cultural heritage, the beauty and power of its ideas, as well as participate in socio-scientific issues ethically and in an informed manner.

Apply scientific knowledge and skills, as well as adopt scientific attitudes and mind-sets to innovate and push new frontiers.

Grounded in strong Science fundamentals: Scientific Knowledge, Practices and Values

Figure 1.1: Overview of Goals of Science Education in Singapore

The *Science Curriculum Framework*, as shown in **Figure 1.2**, encapsulates the thrust of science education in Singapore to provide students with strong fundamentals in science for life, learning, citizenry and work.



Goals
The twin goals of Science education, as represented by the tagline ***Science for Life and Society***, are central to the revised Science Curriculum Framework.

Vision (3 Ins)
Surrounding the innermost circle, the Vision of Science Education 2030 is articulated through the 3 **In**s – *Inspire*, *Inquire*, *Innovate*.

Three Domains
The outermost layer of the framework shows three domains, *Core Ideas*, *Practices*, and *Values, Ethics and Attitudes*.

Stakeholders
The pair of hands shows *students as inquirers*, supported by *teachers and partners as facilitators* of the students' learning experiences.

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Figure 1.2: Science Curriculum Framework

The twin goals of science education, as represented by the tagline ***Science for Life and Society***, are central to the Science Curriculum Framework. Surrounding the innermost circle, the Vision of Science Education 2030 is articulated through the 3 **In**s – *Inspire*, *Inquire*, *Innovate*. The outermost layer of the framework shows three domains, *Core Ideas*, *Practices*, and *Values, Ethics and Attitudes*. The pair of hands shows *students as inquirers*, supported by *teachers and partners as facilitators* of the students' learning experiences.

The term *Core Ideas* refers to the fundamental ideas that are essential for the understanding of science. The term *Practices* signals the importance of "Ways of thinking and doing in science" and emphasises science as a human endeavour guided by *Values, Ethics and Attitudes* embedded within society. In addition, teaching and learning involves not just the students and teachers but other partners who can facilitate learning in various contexts to help students appreciate the application of science in their daily lives, society and the environment.

Our vision for science education, manifested through the three **In**-s, encapsulates the overall experience of our students in science education:

a. Inspired by science. Students enjoy learning science and are fascinated by how everyday phenomena have scientific connections and how science helps solve many of our global challenges. They regard science as relevant and meaningful, and appreciate how science and technology have transformed the world and improved our lives. Students are open to the possibility of pursuing science-related careers to serve the good of society.

b. Inquire like scientists. Students have strong fundamentals in science, and possess the spirit of scientific inquiry. They are able to engage confidently in the *Practices of Science* and are grounded in the knowledge, issues and questions that relate to the roles played by science in daily life, society and the environment. They can discern, weigh alternatives and evaluate claims and ideas critically, based on logical scientific evidence and arguments, while consciously suspending judgement where there is lack of evidence.

c. Innovate using science. Students apply science to generate creative solutions to solve real-world problems, ranging from those affecting everyday lives to complex problems affecting humanity. It is envisaged that there will be a strong pipeline of students who can contribute towards STEM research, innovation and enterprise.

The goals and vision of science education are aligned with the broader MOE framework of 21st Century Competencies (21CC). Inspired students, who inquire and innovate through the Practices of Science (POS), develop future-ready competencies such as critical, adaptive and inventive thinking. The 21CC framework shown in **Figure 1.3** guides the purposive development, through the total curriculum, of key competencies and mindsets for students to be successful in the future.

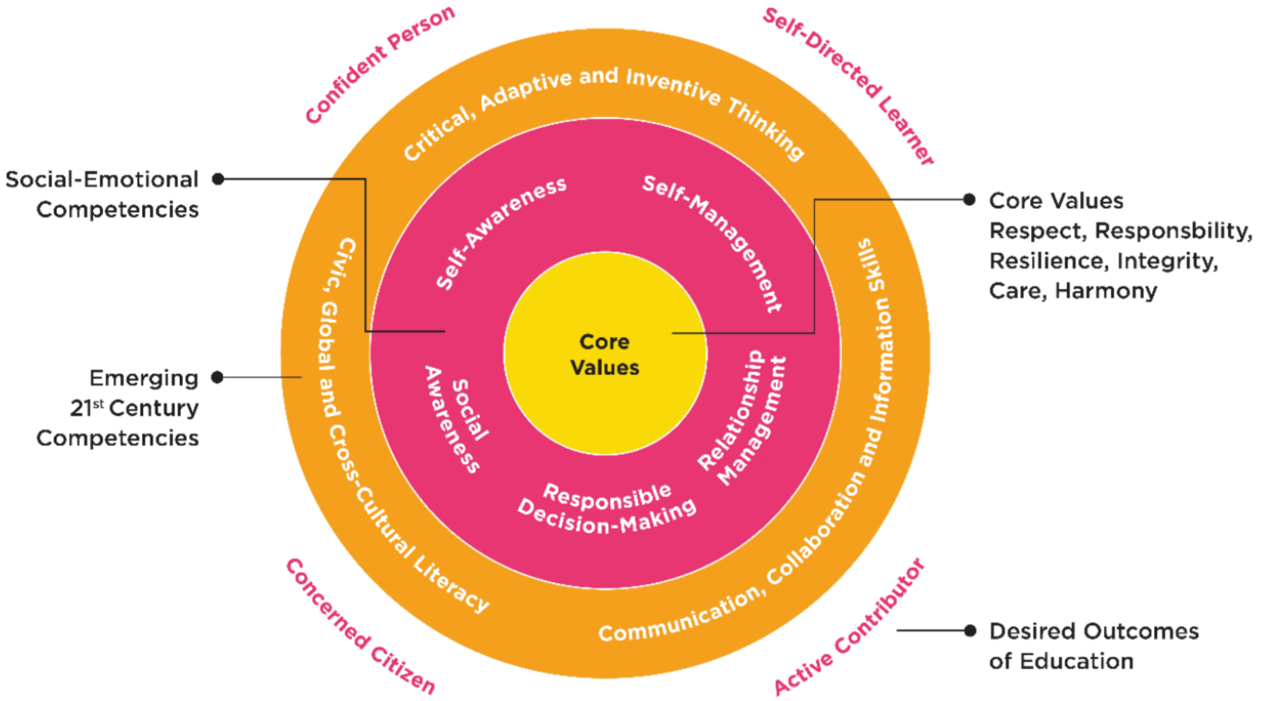

Figure 1.3: Framework for 21st Century Competencies and Student Outcomes

The teaching and learning of science naturally serve the larger goal of developing 21CC in students. The emerging 21CC domains that can be most naturally developed through the process of scientific inquiry, such as engaging in scientific investigation, reasoning, modelling and problem-solving, are **Critical, Adaptive and Inventive Thinking,** as well as **Communication**. The development of the other emerging 21CC domains (e.g. Collaboration, Information Skills, Civic and Global Literacy) depends on the context of the lesson. Intentional development of 21CC through science makes learning meaningful and facilitates the transfer of learning.

1.2 BACKGROUND ON THE 2025 A-LEVEL SCIENCE CURRICULUM

The A-Level science curriculum review ensures the continued relevance of the curriculum in laying a strong foundation of knowledge, skills and attitudes in order to prepare our students well for university, work and life in the future. The review is guided by internal and external scans, and also took into consideration broader MOE emphases on learning for life, and the development of 21st Century Competencies (21CC) and digital literacy (DL) in our students.

The key curricular shifts are to:

1. Strengthen Practices of Science (POS)[1], through enhancing digital literacy. The learning of science should reflect the evolving nature of the scientific disciplines as they are practised. Data collection, analysis, modelling, and interpreting data and evidence are important areas of the POS that can be strengthened and made more authentic with the use of information and communications technology. Digital literacy (DL),[2] including data competencies (DC) and computational thinking (CT), could also be naturally built up through the curriculum as students encounter opportunities to make use of a variety of hardware and software to investigate and model the world.
2. Maintain strong disciplinary fundamentals while layering in compelling real-world applications and interdisciplinary connections. Timely refreshing of the curricular content retains the focus on learning key concepts and core ideas in science, while embedding Science, Technology, Society and Environment (STSE) and Science, Technology, Engineering and Mathematics (STEM) contexts and applications more deliberately. This can help bring out the relevance and impact of science for more students.[3] To encourage debate and discussion, contexts could involve socio-scientific issues that prompt the exploration of values, ethics, and attitudes in science. Contexts related to sustainability will also feature to a greater extent across the science syllabuses in view of Singapore's commitment to the 2030 Agenda for Sustainable Development.[4]
3. Broaden practical work learning experiences beyond the confines of the laboratory and include more open-ended tasks to promote greater student agency, experimentation and authenticity. As pre-university students are building their "science identity", challenging them to take up an open-ended group investigative task increases student agency and forms an important part of their overall learning experience in science. The task design should encourage curiosity, problem-posing and inventive thinking, thus providing opportunities for students to embrace uncertainty and ambiguity, and to learn through iteration and from failures. Such activities could include science investigations and/or engineering design challenges where students plan and carry out their own group investigative tasks and deepen their understanding of POS.

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[1] The *Practices of Science* (POS) 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.

[2] DC refers to the handling and analysis of data. CT can be taught in the context tackling complex problems in scientific domains, and comprises four elements: decomposition, pattern recognition, abstraction, and algorithmic thinking.

[3] Bennett, J., Lubben, F., & Hogarth, S. (2007). Bringing science to life: A synthesis of the research evidence on the effects of context-based and STS approaches to science teaching. *Sci. Ed.*, 91(3): 347–370.

[4] See report Towards a sustainable and resilient Singapore.

One of the strategic thrusts in the Educational Technology (EdTech) Masterplan 2030[5] is to strengthen the development of students' DL and technological skills. In curricular shift 1 above, the use of digital sensors for data collection and the use of spreadsheet to analyse and visualise larger authentic data sets in the revised H2 Physics Practical is well aligned to the "find", "think" and "create" components of the National Digital Literacy Programme (NDLP), as launched by MOE in 2020 (see **Figure 1.4**). Enhanced DL skills through the A-level science curriculum empowers students to become technologically-adept innovators who can "discover" needs and "develop" solutions to real-world problems.

Find

Critically gather and evaluate information from, and use digital resources (including social media) in a safe, secure, responsible and ethical manner.

....

- Digital Safety & Security
- Digital Information Management
- Digital Responsibility

Think

Interpret and analyse data, and solve problems systemically.

....

- Data Competencies
- Computational Thinking

Apply

Use software and devices effectively and productively; facilitate the use of knowledge and skills in new contexts; keep up with technological developments.

....

- Device & Software Operations
- Digital Knowledge Currency

Create

Produce content and artefacts and collaborate with others digitally.

....

- Coding & Programming
- Digital Communication, Collaboration & Participation

Figure 1.4: MOE Framework for Strengthening Digital Literacy[6]

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[5] See https://www.moe.gov.sg/education-in-sg/educational-technology-journey/edtech-masterplan.

[6] "A Guide to the Development of Digital Literacy and Technological Skills" (Sep 2024) https://intranet.moe.gov.sg/etd/edtechmp2030/Pages/Resources.aspx

1.3 PURPOSE AND VALUE OF PHYSICS EDUCATION AT PRE-UNIVERSITY

Broadly, we can think about the purpose and value of studying physics in terms of *what* we know, *how* we know, and the "so what?" questions.

> *What we know*: Physics is a fundamental science 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 much of modern technology, as the foundational basis upon which practical applications are built through various fields of science and engineering.
>
> *How we know*: Studying A-Level Physics exposes learners 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 reasoning, a curious and inquiring mind, and the ability to solve problems and grasp complex concepts. These students will gain a firm foundation to prepare them for university studies not just in physics but also various fields of engineering and technology, and relevant careers that place a premium on clear, critical, and creative thinking.
>
> *So what*? 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.[7] Models should be tested through experiments and must be consistent with available evidence. Hence, they can change and evolve with new evidence.[8] 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.[9] 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.

The syllabuses have been designed to build on and extend the content coverage and skills development at the secondary school (O-Level / G3). Students will be assumed to have knowledge and understanding of physics at the secondary level.

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[7] Gilbert, J. K. (2004). Models and modelling: Routes to more authentic science education. *International Journal of Science and Mathematics Education,* 2*:* 115–130.

[8] Krajcik, J., & Merritt, J. (2012). Engaging students in scientific practices: what does constructing and revising models look like in the science classroom? Understanding a framework for K-12 science education. *The Science Teacher, 3,* 38.

[9] Etkina, E., Warren, A., & Gentile, M. (2006). The role of models in physics instruction. *The Physics Teacher*, *44*, 34–39.

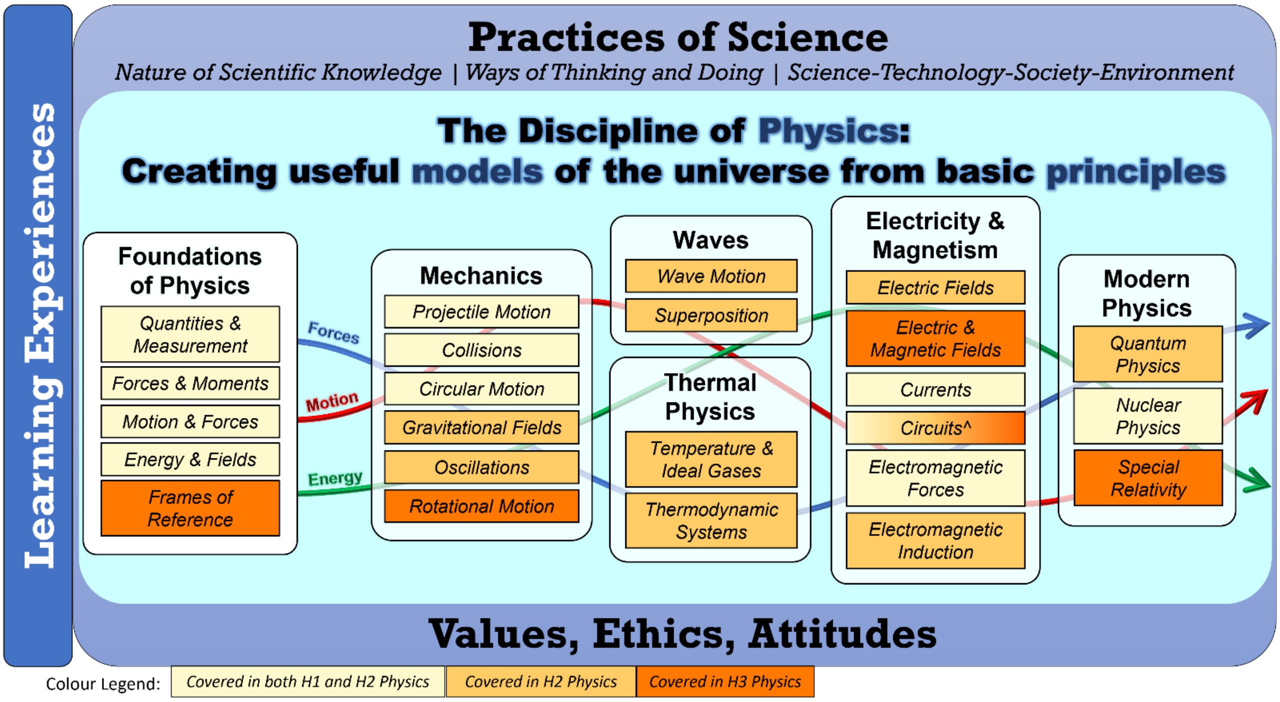
The aims of a course based on these syllabuses are shown in **Table 1.1**. Students may not offer physics at both the H1 and H2 levels, though if they offer H3 Physics they must offer H2 Physics simultaneously.

Table 1.1: Aims of A-Level Physics Syllabuses

<table>
<tr><th>Aims</th><th>H1 Physics</th><th>H2 Physics</th><th>H3 Physics</th></tr>
<tr><td>Twin Goals of Science Education</td><td>• provide students with an experience that develops interest in physics and builds the knowledge, skills and attitudes necessary for them to become scientifically literate citizens who are well-prepared for the challenges of the 21st century</td><td>• provide students with an experience that develops interest in physics and builds the knowledge, skills and attitudes necessary for them to become scientifically literate citizens who are well-prepared for the challenges of the 21st century
• to equip students with the knowledge and skills for further studies in related fields</td><td>• provide students with an experience that deepens their knowledge and skills in physics, and foster attitudes necessary for further studies in related fields</td></tr>
<tr><td>Practices of Science & Values, Ethics, Attitudes</td><td colspan="2">• develop in students the understanding, skills, ethics and attitudes relevant to the <i>Practices of Science</i>, including the following:
A. demonstrating the ways of thinking and doing
B. understanding the nature of scientific knowledge
C. relating science, technology, society and environment</td><td>• develop in students the appreciation of the practice, value and rigour of physics as a discipline</td></tr>
<tr><td>Disciplinary Ways of Thinking and Doing</td><td colspan="2">• 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</td><td>• develop in students the skills to analyse physical situations, and to apply relevant concepts and techniques, including calculus, to solve problems</td></tr>
</table>

1.4 A-LEVEL PHYSICS CURRICULUM FRAMEWORK

The *Values, Ethics, Attitudes*, the *Practices of Science*, the *Disciplinary Content* and *Learning Experiences* are put together in a framework (see **Figure 1.5**) to guide the design and implementation of the A-level Physics curriculum.



Colour Legend: Covered in both H1 and H2 Physics | Covered in H2 Physics | Covered in H3 Physics

^Circuits is in H1, H2 (includes capacitors), and H3 Physics (includes inductors)

Figure 1.5: A-Level Physics Curriculum Framework

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

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

The *Disciplinary Content* is the Physics syllabuses that are organised around four *Core Ideas* of Physics. For each Core Idea, pertinent and open-ended guiding questions are listed to help students frame the concepts and promote inquiry, while narratives allow links between concepts, both within and between *Core Ideas* to be made.

The *Learning Experiences (LEs)* refer to a range of learning opportunities that enhance students' learning of physics. Real-world contexts can help illustrate the application of physics concepts and bring the subject to life. These *LEs* would include experimental (practical work) activities and ICT tools that can be used to build students' understanding.

1.4.1 VALUES, ETHICS, ATTITUDES

Although science uses objective methods to arrive at evidence-based conclusions, it is in fact a human enterprise conducted in some social contexts, which thus involves consideration of values and ethics. The intent of fostering an awareness and appreciation of these values in the curriculum is to sensitise our students to the ethical implications of the application of science in society.

Humanity will face challenges in the upcoming centuries that require the development of scientific and technological solutions, alongside other approaches, but these solutions have complex outcomes and there is a need to consider their impact in terms of their benefits and drawbacks to humanity and the ethical issues involved. This is complicated by a myriad of beliefs and value systems. Thus, science education needs to equip students with attitudes (see **Table 1.2**) and the ability to articulate their ethical stance as they participate in discussions about socio-scientific issues[10] that involve ethical dilemmas, with no single right answers.

Table 1.2: Values, Ethics, Attitudes

Values, Ethics, and Attitudes	**Brief Description**
Curiosity	Desiring to explore the environment and question what is found.
Creativity	Seeking innovative and relevant ways to solve problems.
Integrity	Handling and communicating data and information with complete honesty.
Objectivity	Seeking data and information to validate observations and explanations without bias.
Open-mindedness	Accepting all knowledge as tentative and suspending judgment. Tolerance for ambiguity. Willingness to change views if the evidence is convincing.
Resilience	Not giving up on the pursuit for answers / solutions. Willingness to take risks and embrace failure as part of the learning process.
Responsibility	Showing care and concern for living things and awareness of our responsibility for the quality of the environment.
Healthy Scepticism	Questioning the observations, methods, processes and data, as well as trying to review one's own ideas.

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[10] Examples of socio-scientific issues are genetic engineering (e.g. cloning and gene therapy), reproductive technology, climate change and the adoption of nuclear energy.

1.4.2 CORE IDEAS

Our science curriculum is organised around *Core Ideas*, which are distilled ideas central to the discipline of science. The selection of Core Ideas is guided by the two principles of

- **Centrality:** Ideas which are important to the understanding of the discipline, and are generative, with the potential to add breadth, depth and make connections); and
- **Coherence**: Ideas which are aligned to overall goals, developmentally appropriate, timely and timeless.

Core Ideas help students appreciate the connectedness and the conceptual links within and across the different sub-disciplines of science (i.e. biology, chemistry and physics). The **Unifying Ideas** across science (biology, chemistry and physics) are described in **Table 1.3**, and the **Disciplinary Ideas** within physics are listed in **Table 1.4**.

Table 1.3: Unifying Ideas across science subjects

Unifying Idea	Description
Pattern	A pattern is an observed sequence or repetition in nature. A way to make sense of the world around us is to organise its diversity through classification based on similarities and differences, and recognising deviations. Understanding patterns helps us to also predict events and processes that occur in the natural world
Diversity	Diversity refers to the variety of living and non-living things around us. Such diversity in the natural and man-made worlds helps to maintain a balance in the ecosystem and provide us with useful resources to develop solutions to real world problems. We have to use the resources in nature responsibly and sustainably.
System	A system comprises parts which interact with one another within a boundary. Interactions within and between systems can be explored at different scales. Studying systems allow us to understand how different parts with different functions, may work together for a common purpose.
Structure	Structure refers to the arrangement of and relations between parts of a system. Making sense of the structure of systems and their parts leads to a deeper understanding of their functions and properties, which allow us to make and test predictions of their behaviours.
Energy	Energy is required for things to work. The total amount of energy within a chosen system is always the same (i.e. conserved). While energy cannot be created or destroyed, it can be transferred from one energy store to another during an event or process. In these processes some energy may become less useful.
Matter	Matter is anything that has mass and occupies space. All matter in the Universe, living and non-living, is made up of very small particles called atoms. The behaviour and arrangement of the atoms explain the properties of different materials. We can better appreciate nature by understanding the structure and properties of matter.
Balance	Balance is achieved when opposing forces or influences act on a system to allow the system to be in equilibrium or in a steady state. Maintaining balance is important in

Unifying Idea	Description
	living things and in ecosystems. We are able to design stable systems through understanding the mechanisms by which balance is achieved.
Change	Change is caused by interactions within and across systems, which may involve forces or the flow of matter and energy. Different types of interactions allow us to understand the behaviour of systems and make predictions on how changes in one factor affects the other factors in a system.

Table 1.4: Disciplinary Ideas within Physics

Disciplinary Ideas
1. Matter and energy make up the Universe. 2. Matter interacts through forces and fields. 3. Forces help us understand motion. 4. Waves can transfer energy without transferring matter. 5. Conservation laws constrain the changes in systems. 6. Microscopic models can explain macroscopic phenomena.

For physics, to mindfully balance conceptual understanding and appreciation of real-world applications, broad contextual themes have been identified for each of the content sections (see **Table 1.5**). While these themes help focus and guide the development of exciting and relevant learning experiences to bring physics to life, they are in no way meant to exclude equally compelling contexts that illustrate the beauty of the workings of the universe.

Table 1.5: Contextual Themes for Physics

"How might we understand the universe, and shape our place in the world?"		
Section	**Contextual Theme**	**Examples of Applications**
Foundations of Physics	The Universe	astronomical units to everyday to microscopic units, observational astronomy, precision measurements
Mechanics	Transport	bicycles, e-scooters, automobiles, mass transport (trains, buses), canoes and ships, space travel (rockets, satellites)
Waves	Communication	sound waves, radio/WiFi/Bluetooth, GPS, Internet
Thermal Physics	The Industrial Age	environmental heating and cooling, engines and heat pumps, large-scale infrastructure and systems (e.g. LNG transport, storage, distribution)
Electricity & Magnetism	Electronics	capacitive touchscreens, circuit design, computer storage, powering and charging devices including electric vehicles, electrical grid
Modern Physics	Modern Technology	quantum dots, electron microscopes, quantum information, cryptography, metrology, radiation diagnostics, cancer treatments

1.4.3 PRACTICES OF SCIENCE (POS)

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.

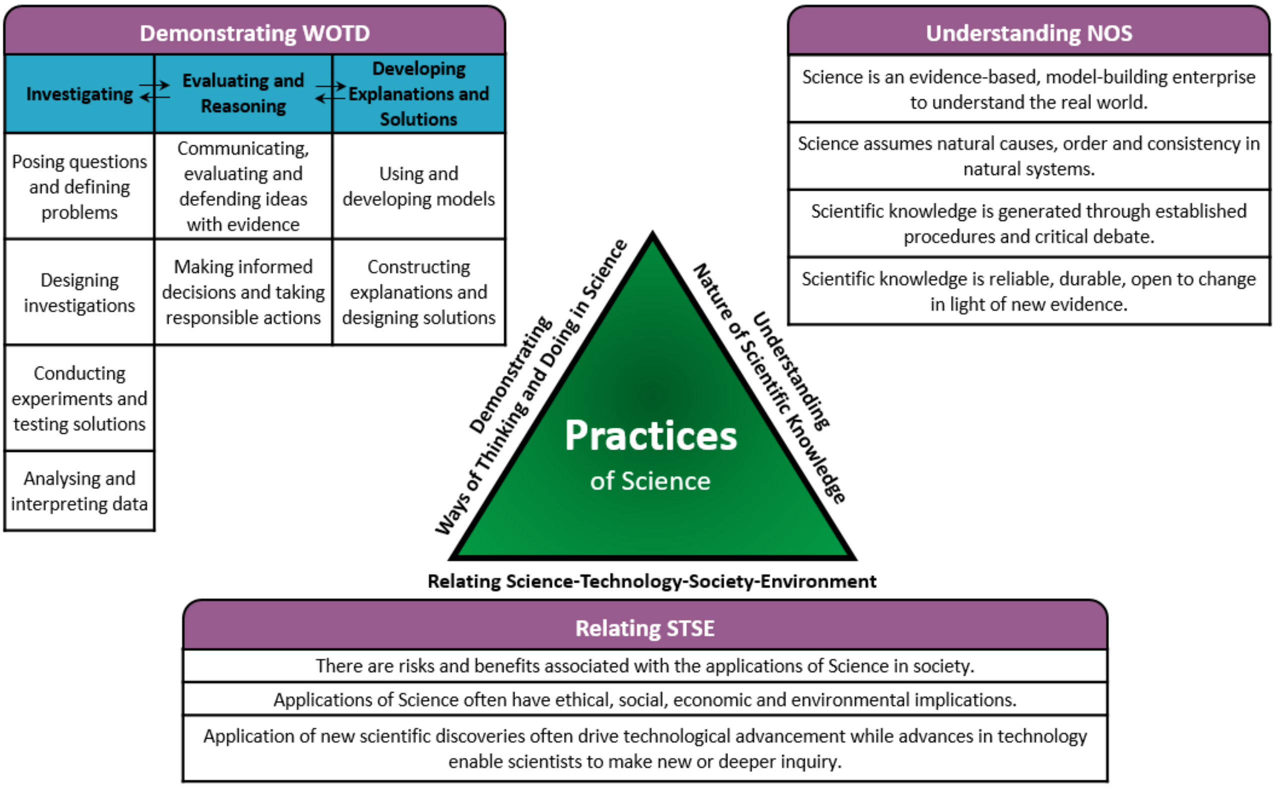
Teaching students the nature of science (NOS) helps them develop an accurate understanding of what science is and how it is practised and applied in society. Students should be encouraged to consider relevant ethical issues, how scientific knowledge is developed, and the strengths and limitations of science. Teaching the NOS 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* which are explicitly articulated in the syllabus to allow teachers to embed them as learning objectives in their lessons. The 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 should be emphasised in the teaching of these practices where appropriate.

Time should be set aside to allow students to reflect on how the POS contribute to the accumulation of scientific knowledge. This means, for example, that when students pose questions, plan and conduct investigations, develop models or engage in arguments, they should have opportunities to think about what they have done and why.

The use of technology and tools are essential to doing and learning science. Just as the slide rule has given way to pocket calculators, the use of computer software for data analysis and visualisation has become common practice today. Thus, the POS described here include the use of digital technology in teaching and learning science where appropriate.

See **Figure 1.6** for the components of POS, which will be discussed in **Table 1.6**.



Demonstrating WOTD

Investigating	Evaluating and Reasoning	Developing Explanations and Solutions
Posing questions and defining problems	Communicating, evaluating and defending ideas with evidence	Using and developing models
Designing investigations	Making informed decisions and taking responsible actions	Constructing explanations and designing solutions
Conducting experiments and testing solutions		
Analysing and interpreting data		

Understanding NOS

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

Relating STSE

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

Figure 1.6: Practices of Science

Table 1.6: Components of the Practices of Science (POS)

Demonstrating WOTD
WOTD in Science illustrates a set of established practices associated with scientific inquiry to gather evidence and test ideas on how the natural world works. The three broad, iterative domains of scientific activity are:
Investigating
Posing questions and defining problems. Scientific questions initiate the drive to find out more about the natural and man-made world(s), such as what is and how it works. The applications of Science are motivated by finding solutions to problems. This also involves asking questions and scoping the problem so that it may be solved through the application of science and technology.
Designing investigations. Scientific investigations are often carried out as part of scientific inquiry into a phenomenon or testing of a theory or model that explains the world. In the applications of science, investigations are also conducted to identify the most appropriate solution or determine ways to improve on a technological system. Various criteria are considered in planning investigations, including the general approach, the apparatus and type of data needed.
Conducting experiments and testing solutions. This involves the application of techniques, methods, understanding on a range of apparatus and equipment (including sensors and dataloggers) and/or apply methods.
Analysing and interpreting data. Scientists are actively involved in organising and interpreting data to reveal any patterns and relationships that may serve as evidence for communicating to others. Students learning science should be introduced to the use of technology as an aid in practical work or as a tool for the interpretation of experimental and theoretical results. The use of digital tools can allow a great volume of data to be systematically and efficiently analysed, to decide on and/or predict the efficacy of a model.
Evaluating and Reasoning
Communicating, evaluating and defending ideas with evidence. Practices in Science and technology involve clear and persuasive communication of ideas in various forms (e.g. orally, written, visual) and media (e.g. journals, newspaper, news). In the process, reasoning, argumentation and critique of ideas are practiced, based on evidence, such that explanations and design solutions become acceptable within the scientific and technological communities.
Making informed decisions and taking responsible actions. This involves identifying and analysing a situation competently and reflect upon the implication of decisions made based on various considerations (e.g. economic, social, environmental and ethical).
Developing Evaluations and Solutions
Using and developing models. Models are approximations of phenomena or systems that are based on evidence and hold potential for describing, explaining and predicting phenomena to aid scientific inquiry and/or analyse technological systems.
Constructing explanations and designing solutions. Science strives to explain the causes of phenomena while scientific applications endeavour to solve problems. The process of constructive explanations and designing solutions are iterative and systematic.

Understanding NOS

Science is an epistemic endeavour to build a better understanding of reality. What kinds of knowledge can scientists build?

Science is an evidence-based, model-building enterprise to understand the real world. Science is a unique way of knowing which uses empirical standards, logical arguments, and sceptical reviews. It consists of both a body of knowledge of natural systems and the processes used to refine, elaborate, revise, and extend this knowledge.

Science assumes natural causes, order and consistency in natural systems. Scientists often use hypotheses to develop and test theories and explanations for physical phenomena. Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through measurement and observation. Scientific knowledge is based on the assumption that natural laws operate today as they did in the past and they will continue to do so in the future[11]. Theories are validated by the scientific community before they are accepted.

Scientific knowledge is generated through established procedures and critical debate. Collaboration by students in their science learning echoes the social NOS for practising scientists. By presenting their work and ideas to others as part of the scientific community, they develop multiple ways to observe and measure, suggest predictions and propose inferences.

Scientific knowledge is reliable, durable, open to change in light of new evidence. Scientific explanations are tentative and open to revision if sufficient evidence or arguments can be provided. Scientific knowledge advances as old ideas are replaced by better explanations.

Relating STSE

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

There are risks and benefits associated with the applications of science in society. Science and its applications have the potential to bring about both benefits and harm to society.

Applications of science often have ethical, social, economic, and environmental implications. It is useful to be able to predict some of these implications while appreciating the possibility of unintended consequences.

Applications of new scientific discoveries often drive technological advancements while advances in technology enable scientists to make new or deeper inquiry. Science and technology can exist in a virtuous cycle, with new science inspiring new technology, and advances in engineering allowing the successful execution of challenging experiments (e.g. achieving greater precision in measurements, carrying out complex investigations or analysis).

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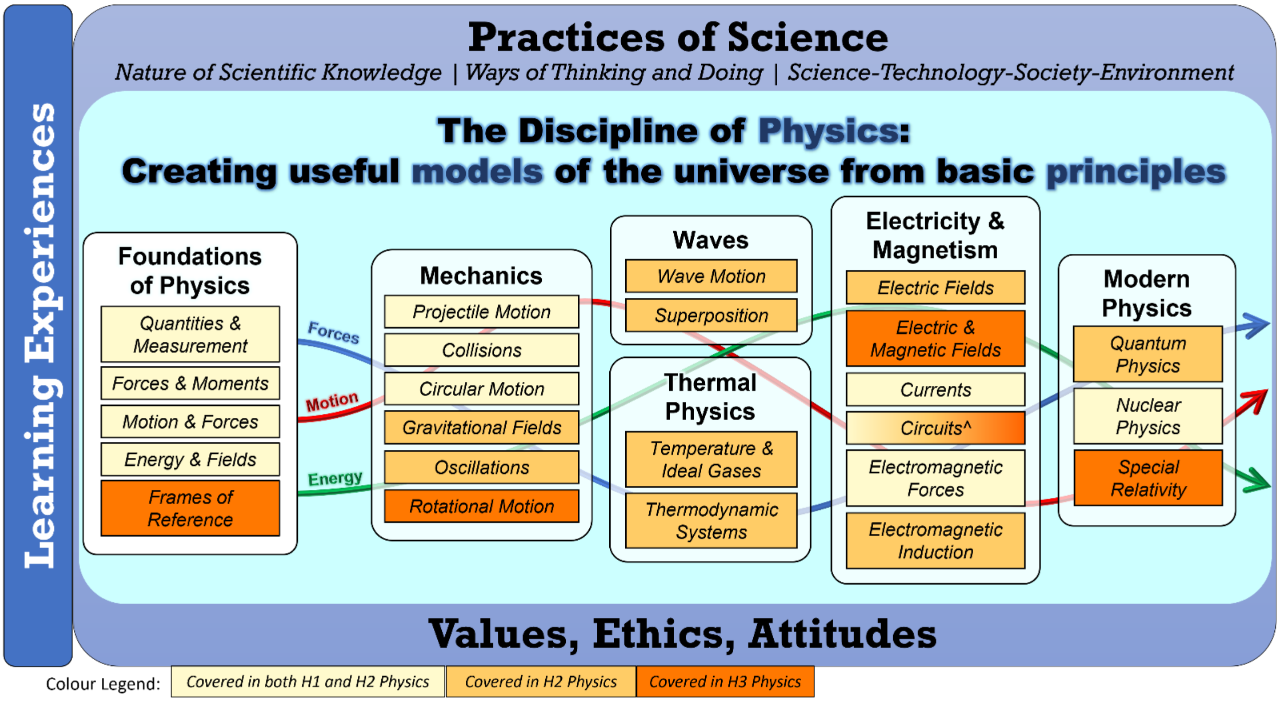
[11] Laws are regularities or descriptions of natural phenomena. A scientific theory is a substantiated explanation of an aspect of the natural world, based on a body of facts that has been repeatedly verified through observation and experiment.

SECTION 2:
CONTENT

2. CONTENT

The syllabus for H1 Physics is a *subset* of the H2 Physics syllabus. The syllabus for H3 Physics builds on that for H2 Physics and *includes* the whole of the H2 Physics syllabus. Candidates who offer H3 Physics should have a strong foundation in H2 Physics and would be expected to tackle more sophisticated problems than candidates who only offer H2 Physics.



Colour Legend: Covered in both H1 and H2 Physics | Covered in H2 Physics | Covered in H3 Physics

^Circuits is in H1, H2 (includes capacitors), and H3 Physics (includes inductors)

2.1 SYLLABUS NARRATIVE

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

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

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

Several revolutionary paradigms have emerged in the historical development of the discipline of physics. While each paradigm considers a different set of principles as fundamental, the older paradigms like *Newtonian Mechanics* remain relevant – coherent application of its principles produces excellent agreement between theory and experiment in many cases. Still, the universe is a tremendously complex place. Science and physics are not quite “finished” as no paradigm has yet proven fully satisfactory as a “theory of everything”. There is much we know, and much more to find out.

The core content selected for the Singapore Advanced-Level Physics Curriculum provide rich contexts and applications to spark the joy of learning, and is organised into six[12] sections:

Foundations of Physics:

- This introductory section is designed to strengthen the framework and approach to physics that learners bring along from secondary school. An appreciation for measurement and uncertainty anchors the *Ways of Thinking and Doing* articulated in the *Practices of Science*. Physical quantities are modelled as mathematical objects like scalars and vectors, and simple examples are used to illustrate the key conceptual strands of **motion**, **forces**, and **energy** that thread through the syllabus.
- In **H3 Physics**, learners explore and wonder about the role of the observer in physical descriptions.

Mechanics:

- Each topic in mechanics is built around real-world contexts to deepen learners' understanding of **motion**, **forces**, and **energy**. Learners will sharpen their quantitative and analytical skills as they bridge real-world observations and theory by conducting investigations and experiments to study the mechanics of **systems**. Think about how gravity affects the vertical motion but not the horizontal motion of a thrown ball. In collisions, careful consideration of *before* and *after* allows us to **model** and extract information about the dramatic and short-lived impact event. Why does Earth maintain a circular orbit around the Sun? Is there acceleration when moving with constant speed?
- In **H2 Physics**, learners encounter oscillatory perturbations from stable equilibrium, which also recalls the regularity and **pattern** of circular motion.
- In **H3 Physics**, learners unlock possibilities for modelling rigid bodies by realising the analogy between translational and rotational **motion**.

Waves:

- In **H2 Physics**, the collective behaviour of synchronised oscillators is modelled as **waves**. These ripples in space and time can transfer **energy** without transferring **matter**. To describe and represent wave motion, learners first need to pick up the necessary mathematical language and terminology, focusing initially on visualising waves in one spatial and one temporal dimension. Using the principle of linear superposition, a wide range of phenomena involving wave interference can be explained, predicting complex **patterns** with the aid of geometric reasoning.

Thermal Physics:

- In **H2 Physics**, the everyday concepts of heat and temperature are re-examined. Single-particle mechanics is applied to **model** an ideal gas, which is one of the simplest many-body **systems**. A crucial purpose of this section is to connect the **microscopic** behaviour of individual constituents with the **macroscopic** properties of the collective **system**, for learners to *simultaneously* see the forest *and* the trees. The strand of **energy** provides insight into physical processes like melting and boiling for material substances generalised beyond ideal gases. The overlap with what learners might have encountered in chemistry provides opportunities for teachers to discuss cross-curricular connections.

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

Electricity & Magnetism

- In this section, learners explore the **diversity** of phenomena related to the fundamental physical property of (electric) charge, which experiences **forces** when interacting with electric and magnetic **fields**. There is a close analogy between mass in a gravitational fields and charge in an electric field. Electromagnetic forces can cause the kinds of **motion** studied in the earlier mechanics topics, and the **microscopic** behaviour of individual charges is connected to **macroscopic** property of current in circuit **systems**. The principle of **conservation** of **energy** guides the analysis of circuits containing resistors and e.m.f. sources.
- In **H2 Physics**, the consideration of charge storage in capacitors deepens learners' appreciation of applications in electronics. The mathematics of oscillations and **waves** prove useful here for describing alternating currents in the electrical grid.
- In **H3 Physics**, the laws of electromagnetism are recast in integral form, which emphasises their geometrical nature, and allows characterisation of more complex field **patterns**. Learners explore the rotational **motion** of electric and magnetic dipoles, as well as the modification of electromagnetic fields in dielectric and ferromagnetic media, which is crucial for technological applications. In electrical circuits, the analogy with mechanical oscillations is established when inductive components are added to resistive and capacitive components.

Modern Physics

- This final section interrogates the **structure** of atoms – peering past their vast electronic shells into their central cores, the incredibly dense nuclear regions. In that secret heart of atoms, the electrical repulsion of like charges is overwhelmed by mysterious nuclear **forces**, which act as an invisible hand causing random and spontaneous disintegration for radioactive substances. **Conservation** laws also guide the analysis of nuclear reactions such as fusion and fission, which humanity has exploited in times of peace but also in times of war.
- In **H2 Physics**, learners catch glimpses into a paradigm shift that famously rocked the foundations of physics – the quantum revolution. **Waves** are particle-like particles are wave-like; nature at its smallest scales does not behave in accordance with a deterministic classical clockwork conception, requiring a new framework to harmonise both particle-like and wave-like properties into a coherent theory expressed in terms of probability, complex numbers, and linear algebra.
- In **H3 Physics**, learners are challenged with yet another paradigm shift – the theory of relativity that questioned accepted wisdom about the absolute nature of space and time. Space and time do not exist independently of each other, and the relative **motion** of observers distorts their assignments of space and time coordinates. Simultaneity is not as obvious as we naïvely expect because of the universal limiting speed of light. To truly appreciate physical reality, we need the courage and tenacity to experiment, the humility and skepticism to question even our most basic assumptions, and the creativity and imagination to build alternative theories.

H1 CONTENT

2.2 SECTIONS AND TOPICS IN H1 PHYSICS

The 11 topics in H1 Physics are organised into four main sections, as listed in **Table 2.1**. For each section, a section narrative outlines the conceptual development and the contextual relevance. For each topic, we provide a topic narrative, followed by examinable learning outcomes.

Table 2.1: Main sections and topics for H1 Physics

Sections	**Topics**
I. Foundations of Physics	1. Quantities & Measurement 2. Forces & Moments 3. Motion & Forces 4. Energy & Fields
II. Mechanics	5. Projectile Motion 6. Collisions 7. Circular Motion & Gravitation
III. Electricity & Magnetism	8. Currents 9. Circuits 10. Electromagnetism
IV. Modern Physics	11. Nuclear Physics

This introductory section conveys a broad sweep of the core ideas in physics, attempting to focus on conceptual understanding while minimising demands on technical proficiency.

Concepts

One key concept in *Quantities & Measurement* is that measurement **systems** with suitably defined units enable the progress of science and technology. This leads naturally into a discussion of measurement uncertainty and the mathematics of propagating uncertainty, to quantify ideas around precision and accuracy. As many physical quantities are vectorial, this topic includes techniques for analysing vectors geometrically and by resolution into components.

The topic on *Forces & Moments* provides concrete practice with vectors and diagrammatic representations (e.g. free-body diagrams) to reason about the possible **forces** and interactions that arise in various situations. This topic focuses on the translational and rotational effects of forces in equilibrium situations.

The third topic on *Motion & Forces* establishes the key principles of the Newtonian paradigm of mechanics, summarised in the three laws of **motion**. The main ideas of kinematics (*describing* motion) and dynamics (*explaining* motion) can be illustrated using motion in a straight line, before more complex types of motion are introduced in later topics.

The final topic of this section shows how the essential strand of **energy** weaves in with **forces** and **motion**. Energy can be put under a pedagogical framework of energy stores and transfers, where forces that "do work" transfer energy across energy stores. An introductory discussion of (conservative) **fields** is included to describe long-range forces and the idea of potential energy.

Contexts

An overarching contextual theme of "The Universe" provides a fitting way to introduce the syllabus content. Zooming across length scales from the astronomical to the human to the microscopic provides a grand visual sweep of the wonders of the universe. This also naturally sets the context for discussing units[13] and prefixes, as well as making order-of-magnitude estimates. Another compelling reason for the theme of exploring the universe and space travel is that demonstrations and experiments conducted in "zero gravity" directly illustrate Newton's laws of motion.

The James Webb Space Telescope and Mars missions by NASA are recent high-profile and exciting applications of STEM. History also provides sobering examples of relevance to this topic, such as the Mars Climate Orbiter disaster where an elementary mistake in the choice of units was not caught in time.

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[13] The historic redefinition of the SI in 2019 showcases how local expertise (see https://www.a-star.edu.sg/nmc/About-NMC/si-redefinition) contributed to global efforts.

[H1 Physics] Topic 1: Quantities & Measurement

As an experimental science, physics requires the measurement of quantities that we use to build our **models** of nature. Observational and experimental data is tested against theoretical predictions, spurring the development and refinement of physical theories. Scientific knowledge continues to evolve as data from new or improved measurements helps us better characterise and understand the natural world.

We now use the International System of Units (SI) as a **system** of measurement. In this topic, the SI base quantities and units are introduced, then used to check the homogeneity of equations. As all measurements involve a degree of uncertainty and can thus affect the drawing of conclusions, being able to estimate the extent to which uncertainty limits precision and accuracy is important. Mathematics can provide guidance through simple rules-of-thumb[14] for propagating uncertainty. Learners would also need to routinely work with scalar and vectors quantities throughout the syllabus, so the last sub-topic focuses on these mathematical objects.

Learning Outcomes Students should be able to:
1.1 Physical quantities and SI units
1(a) recall and use the following SI base quantities and their units: mass (kg), length (m), time (s), current (A), temperature (K), amount of substance (mol)
1(b) recall and use the following prefixes and their symbols to indicate decimal sub-multiples or multiples of both base and derived units: pico (p), nano (n), micro (μ), milli (m), centi (c), deci (d), kilo (k), mega (M), giga (G), tera (T)
1(c) express derived units as products or quotients of the SI base units and use the named units listed in 'Summary of Key Quantities, Symbols and Units' as appropriate
1(d) use SI base units to check the homogeneity of physical equations
1(e) make reasonable estimates of physical quantities included within the syllabus
1.2 Errors and uncertainties
1(f) show an understanding of the distinction between random and systematic errors (including zero error) which limit precision and accuracy
1(g) assess the uncertainty in derived quantities by adding absolute or relative (i.e. fractional or percentage) uncertainties or by numerical substitution (rigorous statistical treatment is not required)
1.3 Scalars and vectors
1(h) distinguish between scalar and vector quantities, and give examples of each
1(i) add and subtract coplanar vectors
1(j) represent a vector as two perpendicular components.

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[14] This can be explained using simple arithmetic and substitution of values; a more rigorous statistical treatment is beyond the scope of the syllabus though certainly important and likely to be required of learners who progress to university and professional fields.

[H1 Physics] Topic 2: Forces & Moments

This topic is rich in both physics and mathematics. The physics focus is on the nature and existence of various types of forces experienced in everyday life, and how a combination of forces can result in an absence of motion (including the lack of a turning effect). Dynamics will be explored in the next topic.

Learning Outcomes Students should be able to:
2.1 Types of forces
2(a) describe the forces on a mass, charge and current-carrying conductor in gravitational, electric and magnetic fields, as appropriate
2(b) show a qualitative understanding of forces including normal force, frictional force, and viscous force, e.g. air resistance (knowledge of the concepts of coefficients of friction and viscosity is not required)
2(c) recall and apply Hooke's law ($F = kx$, where k is the force constant) to new situations or to solve related problems
2.2 Moment and torque
2(d) define and apply the moment of a force and the torque of a couple
2(e) show an understanding that a couple is a pair of forces which tends to produce rotation only
2(f) show an understanding that the weight of a body may be taken as acting at a single point known as its centre of gravity
2.3 Translational and rotational equilibrium
2(g) apply the principle of moments to new situations or to solve related problems
2(h) show an understanding that, when there is no resultant force and no resultant torque, a system is in equilibrium
2(i) use free-body diagrams and vector triangles to represent forces on bodies that are in rotational and translational equilibrium.

The link between **motion** and **forces** is surprisingly nuanced, managing to evade the grasp of many of the greatest thinkers and philosophers. The Aristotelian (mis)conception that motion requires forces might still seem very reasonable that "everything moved must be moved by something". If translational equilibrium implies that there is zero resultant force on a body, surely the resultant force must be non-zero if a body is moving? The subtlety is that (resultant) force is related to the rate of change of momentum. For bodies of constant mass, this is proportional to acceleration. Galileo came up with a thought experiment involving ramps to imagine how, in the absence of resistance to motion, forces are not needed to maintain velocity – inertia and momentum suffice.

Learning Outcomes Students should be able to:
3.1 Kinematics
3(a) show an understanding of and use the terms position, distance, displacement, speed, velocity, and acceleration
3(b) use graphical methods to represent distance, displacement, speed, velocity, and acceleration
3(c) identify and use the physical quantities from the gradients of position-time or displacement-time graphs, and areas under and gradients of velocity-time graphs, including cases of non-uniform acceleration
3.2 Uniformly accelerated linear motion
3(d) derive, from the definitions of velocity and acceleration, equations which represent uniformly accelerated motion in a straight line
3(e) solve problems using equations which represent uniformly accelerated motion in a straight line, e.g. for bodies falling vertically without air resistance in a uniform gravitational field
3.3 Mass and linear momentum
3(f) show an understanding that mass is the property of a body which resists change in motion (inertia)
3(g) define and use linear momentum as the product of mass and velocity
3.4 Laws of motion
3(h) state and apply each of Newton's laws of motion: 1st law: a body at rest will stay at rest, and a body in motion will continue to move at constant velocity, unless acted on by a resultant external force; 2nd law: the rate of change of momentum of a body is (directly) proportional to the resultant force acting on the body and is in the same direction as the resultant force; and 3rd law: the force exerted by one body on a second body is equal in magnitude and opposite in direction to the force simultaneously exerted by the second body on the first body
3(i) recall the relationship resultant force $F = ma$ for a body of constant mass, and use this to solve problems.

[H1 Physics] Topic 4: Energy & Fields

Applying the lens of **energy** to study **motion** is often a worthwhile and complementary approach to analysing forces. The connections and distinctions between **force** and **energy** are key disciplinary understandings. Forces are simultaneously produced pairwise in interactions within a **system** – that's Newton's third law of motion – with the overall vector sum for the entire system remaining zero because of the equal magnitudes in opposite directions. Energy is a **conserved** scalar quantity for a closed system and can be pedagogically modelled within a framework of energy stores and transfers. The basic concepts of (conservative) **fields** are also introduced here so that the concept of potential energy is properly framed.

Learning Outcomes Students should be able to:
4.1 Energy stores and transfers
4(a) show an understanding that physical systems can store energy, and that energy can be transferred from one store to another
4(b) give examples of different energy stores and energy transfers, and apply the principle of conservation of energy to solve problems
4.2 Work done by a force
4(c) show an understanding that work is a mechanical transfer of energy, and define and use work done by a force as the product of the force and displacement in the direction of the force
4.3 Kinetic energy
4(d) derive, from the definition of work done by a force and the equations for uniformly accelerated motion in a straight line, the equation $E_k = \frac{1}{2}mv^2$
4(e) recall and use the equation $E_k = \frac{1}{2}mv^2$ to solve problems
4.4. Concept of a field
4(f) show an understanding of the concept of a field as a region of space in which bodies may experience a force associated with the field
4(g) define gravitational field strength at a point as the gravitational force per unit mass on a mass placed at that point, and define electric field strength at a point as the electric force per unit charge on a positive charge placed at that point
4(h) represent gravitational fields and electric fields by means of field lines (e.g. for uniform and radial field patterns)
4.5 Potential energy
4(i) show an understanding that the force on a mass in a gravitational field (or the force on a charge in an electric field) acts along the field lines, and the work done by the field in moving the mass (or charge) is equal to the negative of the change in potential energy
4(j) distinguish between gravitational potential energy, electric potential energy and elastic potential energy
4(k) recall that the elastic potential energy stored in a deformed material is given by the area under its force-extension graph and use this to solve problems
4.6 Power and efficiency
4(l) define power as the rate of energy transfer
4(m) show an understanding that mechanical power is the product of a force and velocity in the direction of the force

Learning Outcomes Students should be able to:
4(n) show an appreciation for the implications of energy losses in practical devices, and solve problems using the concept of efficiency of an energy transfer as the ratio of useful energy output to total energy input.

Classical mechanics provides a powerful paradigm for introductory physics, elegantly explaining the **motion** of bodies with **forces** and flows (transfers) of **energy**. Classical mechanics is a key foundation of contemporary science and a basis for much of engineering and applied science. For example, it is of paramount importance for a civil engineer to understand the effects of various internal and external forces acting on structures such as tunnels or bridges.

Each topic in this section gives the learner greater mastery of how the world works, and opportunities to notice, think about, and experiment in real-world contexts. Key ideas from *Foundations* are revisited with deepening sophistication, applied to archetypal **motions** produced by **forces** in 1D and 2D, seen also through the **energy** lens. Making observations and conducting experimental investigations encourage practice with concepts related to measurement and uncertainty. The use of computer simulations and numerical methods can enable rich modelling of motion.

Concepts

The strands of **motion**, **forces** and **energy** are highlighted across all topics in this section – kinematics as language for describing motion (including graphical and mathematical descriptions), dynamics as theory linking to forces and causes, and energy as a useful abstraction for analysing **systems**. To scope the syllabus, we usually restrict ourselves to modelling the motion of bodies where effects such as rotation or changes in mass distribution of the body are insignificant, and hence such bodies are assumed to be well-described as point masses.

The *Projectile Motion* topic builds on one-dimensional motion. In the absence of air resistance, the horizontal and vertical **motions** (these directions are defined by the acceleration of free fall) are coordinated (in time) but otherwise independent one-dimensional motions. Learners should appreciate, based on **forces** and acceleration, why resolving into perpendicular motions is useful, and also appreciate, based on **energy** and work done, why potential energy changes are only coupled to motion parallel to the **field** lines. The velocity-dependence of air resistance complicates matters, but as such provides an impetus for exploration using computational tools.

The second topic on *Collisions* accepts the premise that events can be very dramatic and short-lived, yet we might be able to analyse such events using **conservation** laws and looking carefully at the *before* and *after*. The concept of impulse is defined as the integral over time of a **force** and linked to momentum change, like how work done is the integral of a force over space (the latter involves taking scalar products since both force and displacement are vectors) and linked to **energy** change. Collisions provide simple examples of two-body **systems** to start to sharpen the way learners reason about parts in relation to the whole. There is plenty of scope for teachers and learners to create and capture collisions in all sorts of real-world contexts.

The final topic in this section on *Circular Motion & Gravitation* takes the idea from *Projectile Motion* of resolving **motion** into horizontal and vertical components, then adapts it to resolving motion into radial and tangential components in situations where the concept of a “radial direction” is possible. A key focus in this topic is centripetal acceleration and centripetal **force** – the latter is either mistaken as a physical force or confused with a fictitious force (“centrifugal force”) that is an artifact of analysing motion from a rotating frame of reference. The kinematics to describe angular motion is introduced to deal with simple examples of circular motion. Gravitational **fields** provide a natural context to discuss radial **forces** and circular motion in satellite applications and celestial mechanics.

Learners can connect their imagination of the world from the human scale to the astronomical scale.

Contexts

The overarching contextual theme of “Transport” provides a wide variety of ways to link the ideas in this section with everyday life. Space travel links to the contextual theme in *Foundations*. Closer to earth, planes and helicopters move people by moving air. On the surface of the earth, friction is employed to push vehicles relative to the ground. When we walk or run, contact friction is also necessary. On water or underwater, the strategy for motion is to push water powerfully towards the back while pushing it as little as possible in the forward direction.

The scope for the theme need not be limited to moving people from one point to another – tossing a durian moves matter from one place to another. Circular motion and oscillatory motion are also basic ways to obtain repeated motion paths – of practical importance as we often need to do things gradually and repeatedly rather than all at once.

[H1 Physics] Topic 5: Projectile Motion

Objects tend to exhibit projectile **motion** when dropped or thrown, since we live in a uniform gravitational **field**. In free fall, without resistive forces and other complications, the horizontal motion has *constant velocity*, while the vertical motion has *constant acceleration*. These perpendicular components of motion are coordinated (synchronised) yet otherwise independent. Through the **energy** lens, learners should appreciate how the potential energy changes in the vertical direction parallel to the field lines, and to relate speed with kinetic energy.

Learning Outcomes Students should be able to:
5.1 Free fall
5(a) describe and use the concept of weight as the force experienced by a mass in a gravitational field
5(b) describe and explain motion due to a uniform velocity in one direction and a uniform acceleration in a perpendicular direction
5.2 Gravitational potential energy in a uniform field
5(c) derive, from the definition of work done by a force, the equation $\Delta E_p = mg\Delta h$ for gravitational potential energy changes in a uniform gravitational field (e.g. near the Earth's surface)
5(d) recall and use the equation $\Delta E_p = mg\Delta h$ to solve problems
5.3 Effects of air resistance
5(e) describe qualitatively, with reference to forces and energy, the motion of bodies falling in a uniform gravitational field with air resistance, including the phenomenon of terminal velocity.

[H1 Physics] Topic 6: Collisions

How do we know what happened if it happened too fast? The important idea in this topic is that we can use **conservation** laws and look carefully at the *before* and *after* to extract valuable information about the **interaction**. Newton's third law of **motion** provides the conceptual underpinning – the simultaneous pair-wise nature of **forces** guarantees that impulses (i.e. the integral of force over time) have a vector sum of zero and thus momentum is **conserved** in the **system**, provided external forces are neglected.

This topic thus develops critical thinking about **systems** and parts of systems, and to reconcile the application of principles of momentum **conservation** and conservation of **energy** (especially when the latter principle *seems* to be "broken" for inelastic collisions between **macroscopic** bodies).

Learning Outcomes Students should be able to:
6.1 Impulse
6(a) recall that impulse is given by the area under the force-time graph for a body and use this to solve problems
6.2 Conservation of momentum and energy
6(b) state the principle of conservation of momentum
6(c) apply the principle of conservation of momentum to solve simple problems including inelastic and (perfectly) elastic interactions between two bodies in one dimension (knowledge of the concept of coefficient of restitution is not required)
6(d) show an understanding that, for a (perfectly) elastic collision between two bodies, the relative speed of approach is equal to the relative speed of separation
6(e) show an understanding that, whilst the momentum of a closed system is always conserved in interactions between bodies, some change in kinetic energy usually takes place.

[H1 Physics] Topic 7: Circular Motion & Gravitation

The curved path in projectile **motion** could be achieved with a constant **force**. In this topic, we consider turning around a circle due to a force that is constant in magnitude but constantly changing in direction. This has a lot of real-world relevance in mechanisms like spinning fan blades, the orbit of the moon around the Earth (and of planets around the Sun), as well as the feeling of being flung “outwards” when a vehicle makes a turn at high speed, which is a “feeling” that could be discussed as the *absence* or *lack* of a physical force required to *maintain* circular motion.

The key concepts for learners would be to relate linear velocity and acceleration to angular velocity in circular **motion** (kinematics), and to apply Newton’s laws of motion to relate centripetal acceleration to the component of the resultant **force** in the radial direction (dynamics).

Discussion of gravitational **fields** introduces radial field **patterns** and builds on concepts like field strength and potential **energy** from *Foundations*. Linking back to the earlier topics in mechanics, Newton’s cannonball is a classic thought experiment that provides a context to bring together parabolic **motion**, circular motion, and even unbounded trajectories.

Learning Outcomes Students should be able to:
7.1 Kinematics of uniform circular motion
7(a) express angular displacement in radians
7(b) show an understanding of and use the concept of angular velocity
7(c) recall and use $v = r\omega$ to solve problems
7.2 Centripetal acceleration
7(d) show an understanding of centripetal acceleration in the case of uniform motion in a circle, and qualitatively describe motion in a curved path (arc) as due to a resultant force that is both perpendicular to the motion and centripetal in direction
7(e) recall and use centripetal acceleration $a = r\omega^2$and $a = \frac{v^2}{r}$ to solve problems
7(f) recall and use $F = mr\omega^2$ and $F = \frac{mv^2}{r}$ to solve problems
7.3 Newton’s law of gravitation
7(g) recall and use Newton’s law of gravitation in the form $F = G\frac{m_1 m_2}{r^2}$
7(h) show an understanding that near the surface of the Earth, gravitational field strength is approximately constant and equal to the acceleration of free fall
7.4 Circular orbits
7(i) analyse circular orbits in inverse square law fields by relating the gravitational force to the centripetal acceleration it causes
7(j) show an understanding of satellites in geostationary orbit and their applications.

The topics in this section explore the implications of the existence of electric charge. The constituents of **matter** commonly possess the property of charge in addition to mass. Both mass and charge are scalar quantities, but charge differs from mass in that it is either positive or negative – so while gravitational **forces** are always attractive, electrostatic forces can be attractive or repulsive. In terms of **energy**, the gravitational potential is always negative but the electric potential can be positive or negative.

Charge in an electric **field** experiences a **force**. If there is a magnetic field *and* the charge is moving, then the moving charge experiences an electromagnetic force. In this section, we continue to use the language of **forces**, **fields**, and **energy** to discuss **motion** and **systems**.

Concepts

Conceptually, this section contains content that falls under one of two categories: (i) thinking in terms of **fields** and single-particle mechanics; and (ii) thinking in terms of **systems** and parts. In the first category, electric fields are treated like a *doppelgänger* of gravitational fields, and then magnetic fields are introduced as a contrasting complement to electric fields. In the second category, the **microscopic** appreciation for **forces** and more of **energy** is applied to **macroscopic** components that are assembled into circuits.

In the first topic on *Currents*, we take the perspective of **systems** where the collective **microscopic** behaviour of charges produces **macroscopic** currents and voltages that can be measured. Current and voltage characterise the flow of charge and **energy** respectively, which are **conserved** quantities.

In the topic on *Circuits*, we then see how various electronic components can be put together for practical applications. By considering the **system** and its components, the principle of charge and energy **conservation** guides the analysis of circuits containing resistors, and e.m.f. sources. In this topic, we interpret resistance graphically using I-V characteristics. We discuss how resistivity is affected by drift velocity and the number density of charges. Learners are also taught to analyse series and parallel combinations of resistors (including internal resistance). Exploratory investigations and design tasks can be built around these.

The final topic on *Electromagnetism* provides further opportunities to revisit ideas about **fields**, **force** and (potential) **energy**. Nonetheless, because charge has a valence, complications will arise that require careful consideration of negative signs and directions when dealing with scalars and vectors. Learners should also gain some familiarity with the relevant constants (e.g. permittivity, permeability) and units (e.g. coulomb, tesla). Based on the topics in *Mechanics*, learners would also be expected to analyse the **motion** of charges in a uniform electric field. Magnetic field **patterns** can produce **forces** on moving charge and current. Electromagnetic forces have applications such as velocity selection and in a current balance (including versions of a Kibble balance).

Contexts

The theme of “Electronics” can cover many technological applications that pervade modern society – from the tiny integrated circuits densely packed into our handheld smartphones to large-scale power transformers and particle accelerators. Our understanding of the science behind electricity and magnetism was an important enabler for the accelerated (and accelerating) technological evolution of human society.

Electronics is a relevant and hands-on context to introduce concepts associated with currents and circuits. Basic electronics using LEDs, resistors, diodes, capacitors, sensors, and actuators can be assembled with microcontrollers and programming to serve as simple *Internet of Things* (IoT) devices. Semiconductor devices in computers and smartphones are the engineered inventions based on our deep understanding of electricity and magnetism in solid-state materials. We live in exciting times with innovations in information technology also pushing on the quantum frontier (e.g. using superconducting circuits, ultracold atoms, and even diamonds) to harness quantum information by manipulating qubits in quantum computers.

Electric power generation and transmission is a great context at an industrial scale to introduce electromagnetic induction (and the historic "battle of the currents"), which can be extended to discuss the existential issue of harnessing clean and sustainable sources of energy for human society. Electromagnetic field concepts are central to particle accelerators like cyclotrons – circular accelerators use both magnetic and electric fields while linear accelerators use electric fields only. While accelerators (e.g. the Large Hadron Collider at CERN) are commonly associated with advanced particle physics research, cyclotrons are also used in medical physics – with important applications like cancer treatment.

Plenty of natural phenomena showcase the beauty and power of electricity and magnetism. Singapore experiences one of the highest incidences of lightning strikes in the world – the meteorological phenomenon of thunderstorms provides a natural context to introduce the concepts of charges, electric fields, electric potential, and capacitance. The rapid movement of clouds during the formation of a thunderstorm leads to frictional charging, which sets up an electric field between the cloud and the ground. The system of cloud and ground acts as a large capacitor that discharges through the air in the form of lightning.

Auroras at the Earth's poles present another remarkable natural phenomenon due to electromagnetic interaction of the solar wind (highly energetic charged particles from the Sun) with gases in Earth's atmosphere. The charged particles are constrained to move in helical paths through the Earth's magnetic field (magnetosphere), colliding with gas particles in our atmosphere and creating colourful displays in the night sky.

In biology, electricity is also important in signalling and control, complementing neurochemical transmission and reception. The heart rhythms are maintained by waves of electrical excitation, from nerve impulses that spread through special tissue in the heart muscles. Heart rhythms can be electrically monitored, and even "rebooted" using a defibrillator in life-threatening situations.

[H1 Physics] Topic 8: Currents

Electricity is an essential part of modern living. We rely heavily on electrical appliances and electronic gadgets daily – water heaters, refrigerators, air-conditioners, smartphones, laptops – which are all powered with electric current.

In this topic, we consider how the collective **motion** of **microscopic** charges produces **macroscopic** measurable currents and voltages. Current and voltage characterise the flow of charge and **energy** respectively, which are **conserved** quantities. While an applied **field** establishes a potential difference that in free space would cause charges to accelerate, the loss of **energy** through heating in a resistor is analogous to the "drag" experienced by a falling parachutist, resulting in a low average *drift velocity* for charge that is akin to "terminal velocity" (though the individual charges really move quickly and in essentially random directions).

The **energy** lens is used heavily since it is a reliable principle that we can apply even in complicated **systems**. Learners who might have studied electrode potentials in electrochemistry might realise that this is essentially the concept of e.m.f. for chemical batteries.

Learning Outcomes Students should be able to:
8.1 Current and drift velocity
8(a) show an understanding that electric current is the rate of flow of charge and solve problems using $I = Q/t$
8(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
8.2 Potential difference and power
8(c) recall and solve problems using the equation for potential difference in terms of electrical work done per unit charge, $V = \frac{W}{Q}$
8(d) recall and solve problems using the equations for electrical power $P = VI$, $P = I^2R$ and $P = \frac{V^2}{R}$.
8(e) distinguish between electromotive force (e.m.f.) and potential difference (p.d.) using energy considerations.

[H1 Physics] Topic 9: Circuits

In this topic, we dive deeper into electrical **systems** created out of various circuit components. Circuits are everywhere, from the large-scale power grid supplying **energy** to our cities and homes, to the tiny integrated circuit chips in our electronic gadgets and smart devices. We can expect to see increased use of the *Internet of Things* (IoT), integrated sensors and circuits in automation, optimisation, monitoring and much more, bringing greater efficiency and convenience to our lives.

In analysing circuits, the **conservation** principles for charge and **energy** (also known as Kirchoff's circuit laws) allow us to **model** and predict **system** behaviour, e.g. for series and parallel combinations of resistors (including internal resistance). By understanding resistance graphically using I-V characteristics, learners would be better able to design circuits for practical applications, incorporating other common circuit components such as light-dependent resistors and thermistors, which can serve as sensors in integrated circuits.

Learning Outcomes Students should be able to:
9.1 Circuit symbols and diagrams
9(a) recall and use appropriate circuit symbols
9(b) draw and interpret circuit diagrams containing sources, switches, resistors (fixed and variable), ammeters, voltmeters, lamps, thermistors, light-dependent resistors, diodes and any other type of component[15] referred to in the syllabus
9.2 Resistance, resistivity, and internal resistance
9(c) define the resistance of a circuit component as the ratio of the potential difference across the component to the current in it, and solve problems using the equation $V = IR$
9(d) recall and solve problems using the equation relating resistance to resistivity, length and cross-sectional area, $R = \frac{\rho l}{A}$.
9(e) sketch and interpret the I-V characteristics of various electrical components in a d.c. circuit, such as an ohmic resistor, a semiconductor diode, a filament lamp and a negative temperature coefficient (NTC) thermistor
9(f) explain the temperature dependence of the resistivity of typical metals (e.g. in a filament lamp) and semiconductors (e.g. in an NTC thermistor) in terms of the drift velocity and number density of charge carriers respectively
9(g) show an understanding of the effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power
9.3 Resistors in series and in parallel
9(h) solve problems using the formula for the combined resistance of two or more resistors in series
9(i) solve problems using the formula for the combined resistance of two or more resistors in parallel
9(j) solve problems involving series and parallel arrangements of resistors for one source of e.m.f., including potential divider circuits which may involve NTC thermistors and light-dependent resistors.

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[15] Capacitors are not included in the H2 Physics syllabus, and diagrams including capacitors are not expected.

[H1 Physics] Topic 10: Electromagnetism

Charge is a fundamental property of **matter**. The valence of charge (positive versus negative) affects the directions of electric and magnetic **forces** experienced, as well as the sign of the electric potential **energy**. Charged particles can set up electric and magnetic **fields** in the region of space around them. These fields mediate long-range **interactions** with other charges. Unlike gravitational fields, electric fields allow both attractive and repulsive interactions. Earth's magnetic **field** forms a natural protective shield against the harmful high-energy solar wind and cosmic rays, giving rise to colourful auroras in the polar regions.

This topic is an important opportunity to revisit **field** line representations and 2D/3D visualisations with appropriate graphs. One of the challenges in this topic is the spatial visualisation needed for the 3D nature of magnetic field **patterns** and the associated **forces** on moving charges and currents.

Just like in *Mechanics* topics, we can analyse the **motion** of a charge by considering **forces** and **energy**. We revisit parabolic motion in uniform electric fields and circular motion in uniform magnetic fields. We will also explore the use of electromagnetic forces in standard applications like a current balance. Everyday applications include motors, and more sophisticated applications can be found in mass spectrometers for identification of ions, in particle accelerators for cancer therapy or for research into elementary particles and the formation of the **universe**.

Learning Outcomes Students should be able to:
10.1 Uniform electric fields
10(a) calculate the force on a charge in a uniform electric field
10(b) describe the effect of a uniform electric field on the motion of a charged particle
10.2 Magnetic fields and magnetic flux density due to currents
10(c) 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
10(d) sketch magnetic field lines due to currents in a long straight wire, a flat circular coil, and a long solenoid
10.3 Force on a current-carrying conductor
10(e) show an understanding that a current-carrying conductor placed in a magnetic field might experience a force
10(f) recall and solve problems using the equation $F = BIl\sin\theta$, with directions as interpreted by Fleming's left-hand rule
10(g) define magnetic flux density as the force acting per unit current per unit length on a conductor placed perpendicular to the magnetic field
10(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
10.4 Force on a moving charge
10(i) predict the direction of the force on a charge moving in a uniform magnetic field
10(j) recall and solve problems using the equation $F = BQv\sin\theta$
10(k) describe and analyse deflections of beams of charged particles by uniform electric fields and uniform magnetic fields
10(l) explain how perpendicular electric and magnetic fields can be used in velocity selection for charged particles.

More than 100 years ago, at the turn of the 20th century, landmark discoveries in physics brought into question well-established concepts from classical physics (such as in mechanics and electrodynamics). Inspired by these experimental results, new paradigms of the physical world emerged, forming the foundation of what we know today as quantum physics and relativity. Despite these advancements in our **model** of the physical world, classical physics continues to provide very accurate descriptions on the length scales and speeds we typically encounter in daily life.

Some knowledge of quantum physics is critical for understanding present-day technologies that pervade daily life. Nuclear physics is also important for scientific literacy – while the quantum theory of the strong and weak nuclear forces extends well beyond the syllabus, we should have some basic understanding of phenomena like thermonuclear fusion that powers the sun and other stars, spontaneous radioactive decay that contributes to background radiation, nuclear fission that can be harnessed to meet some of our energy needs but also to destroy the world many times over, radioactive medicine, therapy and diagnostics, and other industrial applications of radiation including in food safety.

Concepts

While it is often emphasised that the development of *Modern Physics* involved revolutionary paradigm shifts in thinking, these developments were still anchored to concepts in classical physics (mechanics, waves, thermodynamics, electromagnetism, etc.). In this section, we attempt to highlight the continuity with *Foundations* while giving learners a rich taste and appreciation of some important ideas that go beyond classical physics.

The *Nuclear Physics* topic begins with a discussion of experimental evidence for the small, massive[16], charged atomic nucleus. Next, the phenomenon of radioactive decay is explored, with a focus on modelling the decay rate using concepts like half-life. The randomness in nuclear processes is an indication that quantum mechanics is at play. We also place emphasis on understanding the characteristics of nuclear radiation and appreciating the applications and hazards of radioactivity. This topic concludes with the study of nuclear reactions such as fusion and fission, which have major technological applications. We are reminded of the utility of the **conservation** laws, with a focus on nuclear binding **energy** and mass defect that are related as a consequence of mass-energy equivalence (predicted by special relativity).

Contexts

The theme of “Modern Technology” provides a wide scope for discussing relevant applications range from food safety (irradiation of food to destroy viruses and bacteria) to medical uses (positron emission tomography “PET” and radioactive tracers for diagnostics, gamma knife and proton therapy for treatments) to energy production (nuclear fission, thermonuclear fusion). Learners should also be aware of the many low-level radiation sources in their daily lives, and to contextualise the health hazards of radiation appropriately.

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[16] Here, “massive” should be taken literally as having a (relatively) large mass.

[H1 Physics] Topic 11: Nuclear Physics

It is important to learn about nuclear physics as part of scientific literacy. Learners should appreciate that while the fallout from nuclear disaster can be extremely hazardous, life on Earth has coped with an environmental level of background radiation. There are many creative applications that we have found to use nuclear radiation productively. Discussing such socio-scientific issues provides opportunities to situate scientific and technological understanding in the context of humanistic and economic concerns.

In terms of the physics concepts, this topic builds from *Electromagnetism* when discussing Rutherford scattering of alpha particles from the atomic nucleus, as well as for understanding the characteristics of nuclear radiation. The rest of the topic is otherwise descriptive or involves data handling and simple mathematical modelling, such as the exponential curve in simple examples of radioactive decay, as well as applying **conservation** laws (including the famous mass-energy equivalence) in nuclear reactions and processes.

Learning Outcomes Students should be able to:
11.1 The nuclear atom
11(a) infer from the results of the Rutherford α-particle scattering experiment the existence and small size of the atomic nucleus
11(b) distinguish between nucleon number (mass number) and proton number (atomic number)
11(c) show an understanding that an element can exist in various isotopic forms, each with a different number of neutrons in the nucleus, and use the notation $^{A}_{Z}X$ for the representation of nuclides
11(d) state that one mole of any substance contains 6.02×10^{23} particles, and use the Avogadro constant $N_A = 6.02 \times 10^{23}$ mol^{-1}
11.2 Radioactive decay
11(e) show an understanding of the spontaneous and random nature of nuclear decay, and use the term activity
11(f) infer the random nature of radioactive decay from the fluctuations in count rate
11(g) show an understanding of the origin and significance of background radiation
11(h) show an understanding of the nature and properties of α, β and γ radiations (knowledge of positron emission is not required)
11(i) define half-life as the time taken for a quantity x to reduce to half its initial value, and use the term to solve problems which might involve information in tables or decay curves
11(j) discuss qualitatively the applications (e.g. medical and industrial uses) and hazards of radioactivity based on: i. half-life of radioactive materials, ii. penetrating abilities and ionising effects of radioactive emissions
11.3 Nuclear processes and conservation laws
11(k) represent simple nuclear reactions by nuclear equations of the form $^{14}_{7}\text{N} + ^{4}_{2}\text{He} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H}$
11(l) state and apply to problem solving the concept that nucleon number, charge and mass-energy are all conserved in nuclear processes
11.4 Mass defect and nuclear binding energy
11(m) show an understanding of the concept of mass defect

Learning Outcomes Students should be able to:
11(n) recall and apply the equivalence between energy and mass as represented by $E = mc^2$ to solve problems
11(o) show an understanding of the concept of nuclear binding energy and its relation to mass defect
11(p) sketch the variation of binding energy per nucleon with nucleon number
11(q) explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.

H2 CONTENT

2.3 SECTIONS AND TOPICS IN H2 PHYSICS

The 20 topics in H2 Physics are organised into six main sections, as listed in **Table 2.3**. For each section, a section narrative outlines the conceptual development and the contextual relevance. For each topic, we provide a topic narrative, followed by examinable learning outcomes.

Table 2.3: Main sections and topics for H2 Physics

Sections	Topics
I. Foundations of Physics	1. Quantities & Measurement 2. Forces & Moments 3. Motion & Forces 4. Energy & Fields
II. Mechanics	5. Projectile Motion 6. Collisions 7. Circular Motion 8. Gravitational Fields 9. Oscillations
III. Waves	10. Wave Motion 11. Superposition
IV. Thermal Physics	12. Temperature & Ideal Gases 13. Thermodynamic Systems
V. Electricity & Magnetism	14. Electric Fields 15. Currents 16. Circuits 17. Electromagnetic Forces 18. Electromagnetic Induction
VI. Modern Physics	19. Quantum Physics 20. Nuclear Physics

This introductory section conveys a broad sweep of the core ideas in physics, attempting to focus on conceptual understanding while minimising demands on technical proficiency.

Concepts

One key concept in *Quantities & Measurement* is that measurement **systems** with suitably defined units enable the progress of science and technology. This leads naturally into a discussion of measurement uncertainty and the mathematics of propagating uncertainty, to quantify ideas around precision and accuracy. As many physical quantities are vectorial, this topic includes techniques for analysing vectors geometrically and by resolution into components.

The topic on *Forces & Moments* provides concrete practice with vectors and diagrammatic representations (e.g. free-body diagrams) to reason about the possible **forces** and interactions that arise in various situations. This topic focuses on the translational and rotational effects of forces in equilibrium situations.

The third topic on *Motion & Forces* establishes the key principles of the Newtonian paradigm of mechanics, summarised in the three laws of **motion**. The main ideas of kinematics (*describing* motion) and dynamics (*explaining* motion) can be illustrated using motion in a straight line, before more complex types of motion are introduced in later topics.

The final topic of this section shows how the essential strand of **energy** weaves in with **forces** and **motion**. Energy can be put under a pedagogical framework of energy stores and transfers, where forces that "do work" transfer energy across energy stores. An introductory discussion of (conservative) **fields** is included to describe long-range forces and the idea of potential energy.

Contexts

An overarching contextual theme of "The Universe" provides a fitting way to introduce the syllabus content. Zooming across length scales from the astronomical to the human to the microscopic provides a grand visual sweep of the wonders of the universe. This also naturally sets the context for discussing units[17] and prefixes, as well as making order-of-magnitude estimates. Another compelling reason for the theme of exploring the universe and space travel is that demonstrations and experiments conducted in "zero gravity" directly illustrate Newton's laws of motion.

The James Webb Space Telescope and Mars missions by NASA are recent high-profile and exciting applications of STEM. History also provides sobering examples of relevance to this topic, such as the Mars Climate Orbiter disaster where an elementary mistake in the choice of units was not caught in time.

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[17] The historic redefinition of the SI in 2019 showcases how local expertise (see https://www.a-star.edu.sg/nmc/About-NMC/si-redefinition) contributed to global efforts.

As an experimental science, physics requires the measurement of quantities that we use to build our **models** of nature. Observational and experimental data is tested against theoretical predictions, spurring the development and refinement of physical theories. Scientific knowledge continues to evolve as data from new or improved measurements helps us better characterise and understand the natural world.

We now use the International System of Units (SI) as a **system** of measurement. In this topic, the SI base quantities and units are introduced, then used to check the homogeneity of equations. As all measurements involve a degree of uncertainty and can thus affect the drawing of conclusions, being able to estimate the extent to which uncertainty limits precision and accuracy is important. Mathematics can provide guidance through simple rules-of-thumb[18] for propagating uncertainty. Learners would also need to routinely work with scalar and vectors quantities throughout the syllabus, so the last sub-topic focuses on these mathematical objects.

Learning Outcomes Students should be able to:
1.1 Physical quantities and SI units
1(a) recall and use the following SI base quantities and their units: mass (kg), length (m), time (s), current (A), temperature (K), amount of substance (mol)
1(b) recall and use the following prefixes and their symbols to indicate decimal sub-multiples or multiples of both base and derived units: pico (p), nano (n), micro (μ), milli (m), centi (c), deci (d), kilo (k), mega (M), giga (G), tera (T)
1(c) 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
1(d) use SI base units to check the homogeneity of physical equations
1(e) make reasonable estimates of physical quantities included within the syllabus
1.2 Errors and uncertainties
1(f) show an understanding of the distinction between random and systematic errors (including zero error), which limit precision and accuracy
1(g) assess the uncertainty in derived quantities by adding absolute or relative (i.e. fractional or percentage) uncertainties or by numerical substitution (rigorous statistical treatment is not required)
1.3 Scalars and vectors
1(h) distinguish between scalar and vector quantities, and give examples of each
1(i) add and subtract coplanar vectors
1(j) represent a vector as two perpendicular components.

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[18] This can be explained using simple arithmetic and substitution of values; a more rigorous statistical treatment is beyond the scope of the syllabus though certainly important and likely to be required of learners who progress to university and professional fields.

[H2 Physics] Topic 2: Forces & Moments

This topic is rich in both physics and mathematics. The focus is on the nature and existence of various types of forces experienced in everyday life, and how a combination of forces can result in an absence of motion (including the lack of a turning effect). Dynamics will be explored in the next topic.

Learning Outcomes Students should be able to:
2.1 Types of forces
2(a) describe the forces on a mass, charge and current-carrying conductor in gravitational, electric and magnetic fields, as appropriate
2(b) show a qualitative understanding of forces including normal force, frictional force, buoyant force (upthrust), and viscous force, e.g. air resistance (knowledge of the concepts of coefficients of friction and viscosity is not required)
2(c) recall and apply Hooke's law ($F = kx$, where k is the force constant) to new situations or to solve related problems
2.2 Moment and torque
2(d) define and apply the moment of a force and the torque of a couple
2(e) show an understanding that a couple is a pair of forces which tends to produce rotation only
2(f) show an understanding that the weight of a body may be taken as acting at a single point known as its centre of gravity
2.3 Translational and rotational equilibrium
2(g) apply the principle of moments to new situations or to solve related problems
2(h) show an understanding that, when there is no resultant force and no resultant torque, a system is in equilibrium
2(i) use free-body diagrams and vector triangles to represent forces on bodies that are in rotational and translational equilibrium.

The link between **motion** and **forces** is surprisingly nuanced, managing to evade the grasp of many of the greatest thinkers and philosophers. The Aristotelian (mis)conception that motion requires forces might still seem very reasonable that “everything moved must be moved by something”. If translational equilibrium implies that there is zero resultant force on a body, surely the resultant force must be non-zero if a body is moving? The subtlety is that (resultant) force is related to the rate of change of momentum. For bodies of constant mass, this is proportional to acceleration. Galileo came up with a thought experiment involving ramps to imagine how, in the absence of resistance to motion, forces are not needed to maintain velocity – inertia and momentum suffice.

Learning Outcomes Students should be able to:
3.1 Kinematics
3(a) show an understanding of and use the terms position, distance, displacement, speed, velocity, and acceleration
3(b) use graphical methods to represent distance, displacement, speed, velocity, and acceleration
3(c) identify and use the physical quantities from the gradients of position-time or displacement-time graphs, and areas under and gradients of velocity-time graphs, including cases of non-uniform acceleration
3.2 Uniformly accelerated linear motion
3(d) derive, from the definitions of velocity and acceleration, equations which represent uniformly accelerated motion in a straight line
3(e) solve problems using equations which represent uniformly accelerated motion in a straight line, e.g. for bodies falling vertically without air resistance in a uniform gravitational field
3.3 Mass and linear momentum
3(f) show an understanding that mass is the property of a body which resists change in motion (inertia)
3(g) define and use linear momentum as the product of mass and velocity.
3.4 Laws of motion
3(h) state and apply each of Newton’s laws of motion: 1st law: a body at rest will stay at rest, and a body in motion will continue to move at constant velocity, unless acted on by a resultant external force; 2nd law: the rate of change of momentum of a body is (directly) proportional to the resultant force acting on the body and is in the same direction as the resultant force; 3rd law: the force exerted by one body on a second body is equal in magnitude and opposite in direction to the force simultaneously exerted by the second body on the first body.
3(i) recall the relationship resultant force $F = ma$ for a body of constant mass, and use this to solve problems.

[H2 Physics] Topic 4: Energy & Fields

Applying the lens of **energy** to study **motion** is often a worthwhile and complementary approach to analysing forces. The connections and distinctions between **force** and **energy** are key disciplinary understandings. Forces are simultaneously produced pairwise in interactions within a **system** – that's Newton's third law of motion – with the overall vector sum for the entire system remaining zero because of the equal magnitudes in opposite directions. Energy is a **conserved** scalar quantity for a closed system and can be pedagogically modelled within a framework of energy stores and transfers. The basic concepts of (conservative) **fields** are also introduced here so that the concept of potential energy is properly framed.

Learning Outcomes Students should be able to:
4.1 Energy stores and transfers
4(a) show an understanding that physical systems can store energy, and that energy can be transferred from one store to another
4(b) give examples of different energy stores and energy transfers, and apply the principle of conservation of energy to solve problems
4.2 Work done by a force
4(c) show an understanding that work is a mechanical transfer of energy, and define and use work done by a force as the product of the force and displacement in the direction of the force
4.3 Kinetic energy
4(d) derive, from the definition of work done by a force and the equations for uniformly accelerated motion in a straight line, the equation $E_k = \frac{1}{2}mv^2$
4(e) recall and use the equation $E_k = \frac{1}{2}mv^2$ to solve problems
4.4. Concept of a field
4(f) show an understanding of the concept of a field as a region of space in which bodies may experience a force associated with the field
4(g) define gravitational field strength at a point as the gravitational force per unit mass on a mass placed at that point, and define electric field strength at a point as the electric force per unit charge on a positive charge placed at that point
4(h) represent gravitational fields and electric fields by means of field lines (e.g. for uniform and radial field patterns), and show an understanding of the relationship between equipotential surfaces and field lines
4.5 Potential energy
4(i) show an understanding that the force on a mass in a gravitational field (or the force on a charge in an electric field) acts along the field lines, and the work done by the field in moving the mass (or charge) is equal to the negative of the change in potential energy
4(j) distinguish between gravitational potential energy, electric potential energy and elastic potential energy
4(k) recall that the elastic potential energy stored in a deformed material is given by the area under its force-extension graph and use this to solve problems
4.6 Power and efficiency
4(l) define power as the rate of energy transfer
4(m) show an understanding that mechanical power is the product of a force and velocity in the direction of the force

Learning Outcomes Students should be able to:
4(n) show an appreciation for the implications of energy losses in practical devices, and solve problems using the concept of efficiency of an energy transfer as the ratio of useful energy output to total energy input.

Classical mechanics provides a powerful paradigm for introductory physics, elegantly explaining the **motion** of bodies with **forces** and flows (transfers) of **energy**. Classical mechanics is a key foundation of contemporary science and a basis for much of engineering and applied science. For example, it is of paramount importance for a civil engineer to understand the effects of various internal and external forces acting on structures such as tunnels or bridges.

Each topic in this section gives the learner greater mastery of how the world works, and opportunities to notice, think about, and experiment in real-world contexts. Key ideas from *Foundations* are revisited with deepening sophistication, applied to archetypal **motions** produced by **forces** in 1D and 2D, seen also through the **energy** lens. Making observations and conducting experimental investigations encourage practice with concepts related to measurement and uncertainty. The use of computer simulations and numerical methods can enable rich modelling of motion. Learners with a solid foundation in mechanics would be well-positioned to move on to advanced mechanics at university.

Concepts

The strands of **motion**, **forces** and **energy** are highlighted across all topics in this section – kinematics as language for describing motion (including graphical and mathematical descriptions), dynamics as theory linking to forces and causes, and energy as a useful abstraction for analysing **systems**. To scope the syllabus, we usually restrict ourselves to modelling the motion of bodies where effects such as rotation or changes in mass distribution of the body are insignificant, and hence such bodies are assumed to be well-described as point masses.

The *Projectile Motion* topic builds on one-dimensional motion. In the absence of air resistance, the horizontal and vertical **motions** (these directions are defined by the acceleration of free fall) are coordinated (in time) but otherwise independent one-dimensional motions. Learners should appreciate, based on **forces** and acceleration, why resolving into perpendicular motions is useful, and also appreciate, based on **energy** and work done, why potential energy changes are only coupled to motion parallel to the **field** lines. The velocity-dependence of air resistance complicates matters, but as such provides an impetus for exploration using computational tools.

The second topic on *Collisions* accepts the premise that events can be very dramatic and short-lived, yet we might be able to analyse such events using **conservation** laws and looking carefully at the *before* and *after*. The concept of impulse is defined as the integral over time of a **force** and linked to momentum change, like how work done is the integral of a force over space (the latter involves taking scalar products since both force and displacement are vectors) and linked to **energy** change. Collisions provide simple examples of two-body **systems** to start to sharpen the way learners reason about parts in relation to the whole. There is plenty of scope for teachers and learners to create and capture collisions in all sorts of real-world contexts.

The next topic on *Circular Motion* takes the idea from *Projectile Motion* of resolving **motion** into horizontal and vertical components, then adapts it to resolving motion into radial and tangential components in situations where the concept of a "radial direction" is possible. A key focus in this topic is centripetal acceleration and centripetal **force** – the latter is either mistaken as a physical force or confused with a fictitious force ("centrifugal force") that is an artifact of analysing motion from a rotating frame of reference. The kinematics to describe angular motion is introduced to deal with simple examples of circular motion – extensions to angular dynamics (e.g. moment of inertia, angular momentum) are explored further in H3 Physics.

The *Gravitational Fields* topic provides a natural context to discuss radial **fields** and **forces**, and to apply concepts from *Circular Motion* to satellite applications and celestial mechanics. Discussing gravity in detail helps to deepen ideas about fields and equipotentials introduced in *Foundations*, while also allowing learners to connect their imagination of the world from the human scale to the astronomical scale. Contexts related to escape velocity and orbital energy again showcase the usefulness of the **energy** lens; modelling more complicated dynamics through forces and momentum can also be explored with computational tools.

The final topic in this section is *Oscillations*, which has a nice link to *Circular Motion* and segues naturally into the next section on *Waves*. Vibrations and oscillations are ubiquitous in **systems** near configurations of stable equilibrium. Concretely, the **forces** in a horizontal spring-mass system could be used to obtain the equations of **motion**, which can then be shown to also apply when the spring is vertical. In both scenarios, the **energy** changes also display interesting **patterns**. These simple examples can provide physical intuition for qualitative discussions of oscillations involving driving (forcing) and damping – which are fertile areas for further mathematical and computational exploration.

Contexts

The overarching contextual theme of "Transport" provides a wide variety of ways to link the ideas in this section with everyday life. Space travel links to the contextual theme in *Foundations*. Closer to earth, planes and helicopters move people by moving air. On the surface of the earth, friction is employed to push vehicles relative to the ground. When we walk or run, contact friction is also necessary. On water or underwater, the strategy for motion is to push water powerfully towards the back while pushing it as little as possible in the forward direction.

The scope for the theme need not be limited to moving people from one point to another – tossing a durian moves matter from one place to another. Circular motion and oscillatory motion are also basic ways to obtain repeated motion paths – of practical importance as we often need to do things gradually and repeatedly rather than all at once.

Objects tend to exhibit projectile **motion** when dropped or thrown, since we live in a uniform gravitational **field**. In free fall, without resistive forces and other complications, the horizontal motion has *constant velocity*, while the vertical motion has *constant acceleration*. These perpendicular components of motion are coordinated (synchronised) yet otherwise independent. Through the **energy** lens, learners should appreciate how the potential energy changes in the vertical direction parallel to the field lines, and to relate speed with kinetic energy. Learners should have sufficient opportunities to make sense of various mathematical and graphical representations.

Including air resistance complicates the mathematics quite a bit, though this can be seen as an opportunity for numerical modelling – bridging data, theory, and computation.

Learning Outcomes Students should be able to:
5.1 Free fall
5(a) describe and use the concept of weight as the force experienced by a mass in a gravitational field
5(b) describe and explain motion due to a uniform velocity in one direction and a uniform acceleration in a perpendicular direction
5.2 Gravitational potential energy in a uniform field
5(c) derive, from the definition of work done by a force, the equation $\Delta E_p = mg\Delta h$ for gravitational potential energy changes in a uniform gravitational field (e.g. near the Earth's surface)
5(d) recall and use the equation $\Delta E_p = mg\Delta h$ to solve problems
5.3 Effects of air resistance
5(e) describe qualitatively, with reference to forces and energy, the motion of bodies falling in a uniform gravitational field with air resistance, including the phenomenon of terminal velocity.

How do we know what happened if it happened too fast? The important idea in this topic is that we can use **conservation** laws and look carefully at the *before* and *after* to extract valuable information about the **interaction**. Newton's third law of **motion** provides the conceptual underpinning – the simultaneous pair-wise nature of **forces** guarantees that impulses (i.e. the integral of force over time) have a vector sum of zero and thus momentum is **conserved** in the **system**, provided external forces are neglected.

This topic thus develops critical thinking about **systems** and parts of systems, and to reconcile the application of principles of momentum **conservation** and conservation of **energy** (especially when the latter principle *seems* to be "broken" for inelastic collisions between **macroscopic** bodies).

Learning Outcomes Students should be able to:
6.1 Impulse
6(a) recall that impulse is given by the area under the force-time graph for a body and use this to solve problems
6.2 Conservation of momentum and energy
6(b) state the principle of conservation of momentum
6(c) apply the principle of conservation of momentum to solve simple problems including inelastic and (perfectly) elastic interactions between two bodies in one dimension (knowledge of the concept of coefficient of restitution is not required)
6(d) show an understanding that, for a (perfectly) elastic collision between two bodies, the relative speed of approach is equal to the relative speed of separation
6(e) show an understanding that, whilst the momentum of a closed system is always conserved in interactions between bodies, some change in kinetic energy usually takes place.

The curved path in projectile **motion** could be achieved with a constant **force**. In this topic, we consider turning around a circle due to a force that is constant in magnitude but constantly changing in direction. This has a lot of real-world relevance in mechanisms like spinning fan blades, the orbit of the moon around the Earth (and of planets around the Sun), as well as the feeling of being flung "outwards" when a vehicle makes a turn at high speed, which is a "feeling" that could be discussed as the *absence* or *lack* of a physical force required to *maintain* circular motion.

The key concepts for learners would be to relate linear velocity and acceleration to angular velocity in circular **motion** (kinematics), and to apply Newton's laws of motion to relate centripetal acceleration to the component of the resultant **force** in the radial direction (dynamics). A natural extension of this topic, covered in H3 Physics, would be to also consider the moments of forces to **model** more complicated rigid body motion that has both translational and rotational aspects (e.g. ball rolling down a slope).

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

This topic of gravitational **fields** introduces radial field **patterns** and builds on concepts like field strength and potential from *Foundations*. Linking back to the earlier topics in mechanics, Newton's cannonball is a classic thought experiment that provides a context to bring together parabolic **motion**, circular motion, and even unbounded trajectories.

This topic invites a universal perspective of physics across astronomical distances, and brings in exciting contexts such as satellite deployment and space travel. Conceptually, it brings together various kinds of **motion**, **forces**, and **energy**, which will be revisited again when considering electric and magnetic **fields**. Simulations and computational tools can again be used to explore more complex dynamics.

Learning Outcomes Students should be able to:
8.1 Newton's law of gravitation
8(a) recall and use Newton's law of gravitation in the form $F = G\frac{m_1 m_2}{r^2}$
8.2 Gravitational field strength
8(b) derive, from Newton's law of gravitation and the definition of gravitational field strength, the field strength due to a point mass $g = G\frac{M}{r^2}$
8(c) recall and use $g = G\frac{M}{r^2}$ for the gravitational field strength due to a point mass to solve problems
8(d) show an understanding that near the surface of the Earth, gravitational field strength is approximately constant and equal to the acceleration of free fall
8.3 Gravitational potential and energy
8(e) define gravitational potential at a point as the work done per unit mass by an external force in bringing a small test mass from infinity to that point
8(f) solve problems using the equation $\phi = -G\frac{M}{r}$ for the gravitational potential in the field due to a point mass
8(g) show an understanding that the gravitational potential energy of a system of two point masses is $U_G = -G\frac{Mm}{r}$
8(h) recall that gravitational field strength at a point is equal to the negative potential gradient at that point and use this to solve problems
8.4 Escape velocity and circular orbits
8(i) analyse problems related to escape velocity by considering energy stores and transfers
8(j) analyse circular orbits in inverse square law fields by relating the gravitational force to the centripetal acceleration it causes
8(k) show an understanding of satellites in geostationary orbit and their applications.

A particle in circular **motion** never physically goes through the "centre". For oscillations, the "centre" has physical relevance as the position of stable equilibrium, such that any perturbation away from the centre causes a resultant *restoring* **force** back towards the centre. For one-dimensional oscillation, such as for a spring-mass **system**, there are changes in both the magnitude and direction of the resultant force as the particle moves. If this restoring force is (directly) proportional to the displacement from the equilibrium position, the oscillation is termed *simple harmonic*.

Physically, the lens of **energy** is an important focus for this topic. In a mechanical context, e.g. for a mass on a spring or a marble rolling around in a bowl, the repeated transfer of energy back and forth between the potential and kinetic stores is a key feature of oscillations. The recurring motion in an oscillatory system also means that small energy transfers can have a cumulative effect – without energy input, a damped oscillator eventually slows down and stops, so a driving force is needed in order to establish a steady state.

Learning Outcomes Students should be able to:
9.1 Simple harmonic motion
9(a) describe simple examples of free oscillations, where particles periodically return to an equilibrium position without gaining energy from or losing energy to the environment
9(b) investigate the motion of an oscillator using experimental and graphical methods
9(c) show an understanding of and use the terms amplitude, period, frequency, angular frequency, phase and phase difference, and express the period in terms of both frequency and angular frequency
9(d) show an understanding that $a = -\omega^2 x$ is the defining equation of simple harmonic motion, where acceleration is (directly) proportional to displacement from an equilibrium position and acceleration is always directed towards the equilibrium position
9(e) recognise and use $x = x_0 \sin \omega t$ as a solution to the equation $a = -\omega^2 x$
9(f) recognise and use the equations $v = v_0 \cos \omega t$ and $v = \pm\omega\sqrt{x_0^2 - x^2}$
9(g) describe, with graphical illustrations, the relationships between displacement, velocity, and acceleration during simple harmonic motion
9.2 Energy in oscillations
9(h) describe the interchange between kinetic and potential energy during simple harmonic motion
9(i) describe practical examples of damped oscillations, with particular reference to the effects of the degree of damping (light/under, critical, heavy/over), and to the importance of critical damping in applications such as a car suspension system
9(j) describe graphically how the amplitude of a forced oscillation changes with driving frequency, resulting in maximum amplitude at resonance when the driving frequency is close to or at the natural frequency of the system
9(k) show a qualitative understanding of the effects of damping on the frequency response and sharpness of the resonance
9(l) describe practical examples of forced oscillations and resonance, and show an appreciation that there are some circumstances in which resonance is useful, and other circumstances in which resonance should be avoided.

Complex real-world phenomena in a **system** can often be considered as arising from the emergent behaviour of simple **interactions** between its constituent parts. Waves are a key example of this in physics – their collective **macroscopic** properties arise from the **microscopic** behaviour of oscillations in space and time, but are also distinct.

In this section, we study multiple layers of emergent behaviour. Simple waves are large-scale **patterns** of coordinated oscillations across regions of space and time. Unlike classical bodies that collide with one another, waves **interact** in a "ghostly" manner – they can "pass through" the same position in space at the same time with a resultant *interference* that is governed by the principle of linear superposition. In other words, oscillations form **waves**, and waves interfere to form more complex patterns.

Concepts

The first topic on *Wave Motion* discusses how **waves** are composed of the **motion** of many coordinated **microscopic** oscillations, then introduces the language and terminology to describe and represent the **macroscopic** properties of waves.

The second topic on *Superposition* is anchored on the principle of linear superposition. This principle is repeatedly and consistently applied to various interference phenomena. Starting with standing **waves** in one spatial dimension, we move on to **patterns** in two spatial dimensions – with waves from two point sources (two-source interference), from multiple point sources (diffraction grating), and from a finite-width source (single-slit diffraction).

Contexts

Using the contextual theme of "Communication", we can consider the many ways for information to be passed from source to receiver using wave disturbances, most of which also involve resonance to maximise energy transfer so that the signal is picked up effectively. For example, speaking works through the transmission of sound waves, and the eardrum is structured to detect different frequencies of sound. Radio transmission uses electromagnetic waves to send coded messages over long distances, with the receiver's antenna tuned to respond to specific bands of wavelength. Cellular data, WiFi, Bluetooth, Global Positioning System (GPS), and near-field communication (NFC) technology are all essentially based on radio technology (similar to that used for traditional television and radio transmission), though they typically use higher frequency waves in the microwave band.

There are many other uses of wave superposition in science, engineering and technology. Diffraction gratings allow us to determine the frequencies of light sources ranging from terrestrial lamps to distant stars; observing variations in interference patterns allows us to precisely detect changes in distances, such as in the famous Michelson-Morley interferometer experiment to test the "ether model" for light. Optically variable devices (OVD) based on diffraction can be used on banknotes and credit cards as an anti-counterfeiting measure.

Waves are also commonly found in nature. The "patterning" of waves can be experienced as things of beauty, such as musical tones produced by our voices or by instruments, and vibrant blue colours in certain bird feathers and butterfly wings arising from the scattering of light by microscopic structures.

[H2 Physics] Topic 10: Wave Motion

In the study of waves, we move conceptually from physics of particles to the physics of continuous media. All **waves** involve disturbances that result in oscillations at specific points. These oscillations influence other positions within space at later times, thus spreading and carrying **energy** without net transport of **matter**. Different types of oscillations, and their **interactions**, result in different types of waves.

Just as the study of **motion** began with kinematics and description, we begin also with describing waves using common terminology like amplitude, frequency, wavelength. Simulations that allow users to step-through slowly are useful for deriving the formula for wave speed in terms of frequency and wavelength. Relating intensity to amplitude can be motivated by referencing the quadratic dependence on amplitude for the **energy** of an oscillator. The inverse-square decay of intensity with distance for a point source is an important result that can be experimentally investigated and links with the mathematical result of the surface area of a sphere. There are many amazing demonstrations of polarisation and interesting applications, which can serve as a powerful way to end off this topic.

Learning Outcomes Students should be able to:
10.1 Properties of waves
10(a) show an understanding that mechanical waves involve the oscillations of particles within a material medium, such as a string or a fluid, and electromagnetic waves involve the oscillations of electromagnetic fields in space and time
10(b) show an understanding of and use the terms displacement, amplitude, period, frequency, phase, phase difference, wavelength, and speed
10(c) deduce, from the definitions of speed, frequency and wavelength, the equation $v = f\lambda$
10(d) recall and use the equation $v = f\lambda$
10(e) analyse and interpret graphical representations of transverse and longitudinal waves with respect to variations in time and position (space)
10.2 Energy transfer by progressive waves
10(f) show an understanding that energy is transferred due to a progressive wave without matter being transferred
10(g) recall and use the term intensity as the power transferred (radiated) by a wave per unit area, and the relationship $\text{intensity} \propto (\text{amplitude})^2$ for a progressive wave
10(h) show an understanding of and apply the concept, that the intensity of a wave from a point source and travelling without loss of energy obeys an inverse square law to solve problems
10.3 Polarisation
10(i) show an understanding that polarisation is a phenomenon associated with transverse waves
10(j) recall and use Malus' law ($\text{intensity} \propto \cos^2\theta$) to calculate the amplitude and intensity of a plane-polarised electromagnetic wave after transmission through a polarising filter.

Oscillations can form **waves**. Waves can **interact** with one another. In this topic, we seek to understand the behaviour of waves as they pass through and around stuff. The key to unlock this is the principle of linear superposition. At every point in space and time, the resultant wave arises from the superposition (e.g. a vector sum) of displacements due to the waves meeting at that space-time coordinate.

Similarly to how ideas of **force** and **energy** were deepened through application to selected types of **motion**, in this topic we apply the principle of superposition first to standing waves in one-dimension before considering two-dimensional patterns. The techniques used are essentially the same, yet are powerfully able to account for a variety of phenomena from two-source interference, diffraction gratings, and single-slit diffraction.

Learning Outcomes Students should be able to:
11.1 Principle of superposition
11(a) explain and use the principle of superposition in simple applications
11.2 Standing waves
11(b) show an understanding of experiments which demonstrate standing (stationary) waves using microwaves, stretched strings and air columns
11(c) explain the formation of a standing (stationary) wave using a graphical method, and identify nodes and antinodes, differentiating between pressure and displacement nodes and antinodes for sound waves
11(d) determine the wavelength of sound using standing (stationary) waves
11.3 Interference of two or more point sources
11(e) show an understanding of the terms diffraction, interference, coherence, phase difference and path difference
11(f) show an understanding of phenomena which demonstrate two-source interference using water waves, sound waves, light and microwaves
11(g) show an understanding of the conditions required for two-source interference fringes to be observed
11(h) recall and use the equation $\frac{ax}{D} = \lambda$ to solve problems for double-slit interference, where a is the slit separation and x is the fringe separation
11(i) recall and use the equation $a \sin\theta = n\lambda$ to solve problems involving the principal maxima of a diffraction grating, where a is the slit separation
11(j) describe the use of a diffraction grating to determine the wavelength of light (knowledge of the structure and use of a spectrometer is not required)
11.4 Diffraction through a finite-size gap
11(k) show an understanding of phenomena which demonstrate diffraction through a single slit or aperture, or across an edge, such as the diffraction of water waves in a ripple tank with both a wide gap and a narrow gap, or the diffraction of sound waves from loudspeakers or around corners
11(l) recall and use the equation $b \sin\theta = \lambda$ to solve problems involving the positions of the first minima for diffraction through a single slit of width b
11(m) recall and use the Rayleigh criterion $\theta \approx \frac{\lambda}{b}$ for the resolving power of a single aperture, where b is the width of the aperture.

Complex real-world phenomena in a **system** can often be considered as arising from the emergent behaviour of simple **interactions** between its constituent parts. In this section, we study simple phenomena in thermal physics that showcase this idea – the (stable) **macroscopic** properties of the collective systems are often quite fundamentally different from the (chaotic) **microscopic** behaviours.

In this section, we explore simple examples (e.g. classical ideal gases) to understand how **system** properties arise from the behaviour of individual particles. Building on *Foundations* and *Mechanics*, we **model** particles as point masses and use their **motion** and collisions to discuss **forces**, momentum, and **energy**. For more complicated systems, it gets harder to consider force-vectors but the energy lens remains useful for analysis. We explore some everyday ideas linked to energy – heat and temperature – which are governed by the laws of thermodynamics.

Concepts

We start the section with *Temperature & Ideal Gases*. This topic begins by reviewing the equation of state for an ideal gas and the concept of absolute zero. A key focus of the topic is to **model** the ideal gas with kinetic theory, which links particle speed to pressure and temperature. The collective **macroscopic** properties of the **system** come from taking suitable averages of physical quantities from single-particle mechanics.

The next topic on *Thermodynamic Systems* expands the discussion to cover general **systems**, including real-world substances. The zeroth and first laws of thermodynamics summarise the main ideas around **energy** in this context. The zeroth law links temperature to thermal equilibrium, while the first law helps distinguish between internal energy, heating and (mechanical) work done. These concepts provide the theoretical underpinning for empirical material characteristics like specific heat capacity and specific latent heat for processes like melting and boiling.

Contexts

"The Industrial Age" is a theme well-suited to discuss large-scale applications of thermodynamics.[19] The transport, storage, and use of liquefied natural gas (LNG) is important for meeting Singapore's energy needs; these processes involve many considerations and calculations from thermal physics. Internal combustion engines are *heat engines* that produce mechanical work to make things move. Air conditioners and refrigerators are *heat pumps*, which are heat engines "run in reverse" – work is done to transfer heat *against* a temperature gradient. Many other contexts relatable to everyday life can also be suitably discussed, from boiling a kettle to pumping a bicycle tire.

Extensive modelling of the atmosphere and relevant large-scale systems is needed to characterise and deal with climate change. Even the simplest **models** will involve and incorporate many aspects of physics. Tackling climate change is an existential question for human society – a huge issue that provides plenty of scope for discussion and possible action at global and local scales, at policy and personal levels.

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[19] The second and third laws of thermodynamics, dealing with entropy, are not in the syllabus. Nonetheless, a qualitative appreciation of entropy could be useful for understanding aspects of thermodynamics, especially in relation to limits to the efficiency of heat engines and heat pumps, or in relation to predicting the spontaneity of chemical reactions using the concept of free energy.

[H2 Physics] Topic 12: Temperature & Ideal Gases

In this topic, we consider constant-volume gas thermometers, which extrapolate to a common temperature at zero pressure for different gases. With this empirical motivation, the concept of an absolute zero for temperature can be introduced, along with the **model** of an ideal gas. Some discussion here of the Avogadro constant and the Boltzmann constant is useful for conveying a sense of the relevant scales.

A mechanical **model** of elastically colliding point particles moving ballistically between collisions – the kinetic theory of gases – is used to connect the **microscopic** parameters of the particles (e.g. momentum, root mean square speed) with the **macroscopic** properties (e.g. pressure and temperature) of the gas. There is such a large number of particles in a gas that these collisions are essentially random and unpredictable; yet precisely *because* there is such a large number of particles, the average effect becomes very predictable and regular.

Learning Outcomes Students should be able to:
12.1 Empirical gas laws
12(a) show an understanding that a thermodynamic scale of temperature has an absolute zero and is independent of the property of any particular substance
12(b) convert temperatures measured in degrees Celsius to kelvin: $T/\mathrm{K} = \theta/{}^\circ\mathrm{C} + 273.15$
12(c) recall and use the equation of state for an ideal gas expressed as $pV = NkT$, where N is the number of particles
12(d) state that one mole of any substance contains 6.02×10^{23} particles, and use the Avogadro constant $N_A = 6.02 \times 10^{23}$ mol^{-1} as well as the relationship $Nk = nR$ between the Boltzmann constant and the molar gas constant where n is the number of moles and $N = nN_A$
12.2 Kinetic theory of gases
12(e) state the basic assumptions of the kinetic theory of gases
12(f) explain how the random motion of gas particles exert mechanical pressure and hence derive, using the definition of pressure as force per unit area, the relationship $pV = \frac{1}{3}Nm\langle c^2\rangle$ (a simple model considering one-dimensional collisions and then extending to three dimensions using $\langle c_x^2\rangle = \frac{1}{3}\langle c^2\rangle$ is sufficient)
12(g) recall and use the relationship that the mean translational kinetic energy of a particle of an ideal gas is (directly) proportional to the thermodynamic temperature (i.e. $\frac{1}{2}m\langle c^2\rangle = \frac{3}{2}kT$) to solve problems.

In this topic, learners explore concepts to do with **energy** in thermodynamic **systems**. The zeroth law of thermodynamics states the transitive property of thermal equilibrium as a basis for thermometry. The first law of thermodynamics expresses the principle of energy **conservation** in thermodynamic systems, with careful attention to the meaning of quantities like internal energy, heating, and (mechanical) work done.

These laws find application in the analysis of thermal processes, including phase transitions such as melting and boiling. The **energy** changes associated with these thermal processes are empirically characterised in terms of specific heat capacity and specific latent heat for various material substances.

Learning Outcomes Students should be able to:
13.1 Internal energy
13(a) show an understanding that the macroscopic state of a system determines the internal energy of the system, and that internal energy can be expressed as the sum of a random distribution of microscopic kinetic and potential energies associated with the particles of the system
13(b) show an understanding that the thermodynamic temperature of a system is (directly) proportional to the mean microscopic kinetic energy of particles
13.2 Heating and work done
13(c) show an understanding that when two systems are placed in thermal contact, energy is transferred (by heating) from the system at higher temperature to the system at lower temperature, until they reach the same temperature and achieve thermal equilibrium (i.e. no net energy transfer)
13(d) show an understanding of the difference between the work done by a gas and the work done on a gas, and calculate the work done by a gas in expanding against a constant external pressure: $W = p\Delta V$
13.3 Laws of thermodynamics
13(e) recall and apply the zeroth law of thermodynamics that if two systems are both in thermal equilibrium with a third system, then they are also in thermal equilibrium with each other
13(f) recall and apply the first law of thermodynamics, $\Delta U = Q + W$, that the increase in internal energy of a system is equal to the sum of the energy transferred to the system by heating and the work done on the system
13.4 Specific heat capacity and specific latent heat
13(g) define and use the concepts of specific heat capacity and specific latent heat.

The topics in this section explore the implications of the existence of electric charge. The constituents of **matter** commonly possess the property of charge in addition to mass. Both mass and charge are scalar quantities, but charge differs from mass in that it is either positive or negative – so while gravitational **forces** are always attractive, electrostatic forces can be attractive or repulsive. In terms of **energy**, the gravitational potential is always negative but the electric potential can be positive or negative.

Charge in an electric **field** experiences a **force**. If there is a magnetic field *and* the charge is moving, then the moving charge experiences an electromagnetic force. In this section, we continue to use the language of **forces**, **fields**, and **energy** to discuss **motion** and **systems**.

Concepts

Conceptually, this section contains content that falls under one of two categories: (i) thinking in terms of **fields** and single-particle mechanics; and (ii) thinking in terms of **systems** and parts. In the first category, electric fields are treated like a *doppelgänger* of gravitational fields, and then magnetic fields are introduced as a contrasting complement to electric fields. In the second category, the **microscopic** appreciation for **forces** and more of **energy** is applied to **macroscopic** components that are assembled into circuits.

The first topic on *Electric Fields* sequences the content in the same way as in *Gravitational Fields*, so the analogy should be quite transparent, providing further opportunities to revisit ideas about **fields**, **force** and (potential) **energy**. Nonetheless, because charge has a valence, complications will arise that require careful consideration of negative signs and directions when dealing with scalars and vectors. Learners should also gain some familiarity with the relevant constants (e.g. permittivity) and units (e.g. coulomb). Based on the topics in *Mechanics*, learners would also be expected to analyse the **motion** of a charge in uniform and radial electric field **patterns**. The concept of capacitance to store **energy** is introduced in analogy with the potential energy stored in a spring.

In the next topic on *Currents*, we take the perspective of **systems** where the collective **microscopic** behaviour of charges produces **macroscopic** currents and voltages that can be measured. Current and voltage characterise the flow of charge and **energy** respectively, which are **conserved** quantities. Sinusoidal alternating currents are introduced as electrical analogues of the simple harmonic oscillator, with the a.c. source providing an input power to compensate for resistive losses.

In the topic on *Circuits*, we then see how various electronic components can be put together for practical applications. By considering the **system** and its components, the principle of charge and energy **conservation** guides the analysis of circuits containing resistors, capacitors and e.m.f. sources (including a.c. sources[20]). In this topic, we interpret resistance graphically using I-V characteristics. We discuss how resistivity is affected by drift velocity and the number density of charges. Learners are also taught to analyse series and parallel combinations of resistors (including internal resistance) and of capacitors, including simple charging and discharging in RC circuits. Exploratory investigations and design tasks can be built around these.

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[20] For simplicity, we keep to d.c. sources if the circuit includes capacitors.

The topic on *Electromagnetic Forces* begins with describing examples of magnetic field **patterns**, before discussing the **forces** on moving charge and current. Electromagnetic forces have applications such as velocity selection and in a current balance (including versions of a Kibble balance). Learners should also gain some familiarity with the relevant constants (e.g. permeability) and units (e.g. tesla). A deeper discussion of electromagnetism is covered in H3 Physics.

The final topic on *Electromagnetic Induction* is based on Faraday's and Lenz's laws of electromagnetic induction. The concept of magnetic flux plays a key role in the theory, and learners should try to gain an intuition for flux and flux density by comparison with definitions of pressure and intensity. Learners should see from the previous topic that moving charges in a magnetic **field** can experience **forces**, and see from this topic that moving charges in a magnetic field can cause changes in magnetic flux and thus induce e.m.f. (and currents too, if the circuit is closed). Induction is of practical importance for power transformers used in the electrical grid with alternating current, as well as in induction cookers.

Contexts

The theme of "Electronics" can cover many technological applications that pervade modern society – from the tiny integrated circuits densely packed into our handheld smartphones to large-scale power transformers and particle accelerators. Our understanding of the science behind electricity and magnetism was an important enabler for the accelerated (and accelerating) technological evolution of human society.

Electronics is a relevant and hands-on context to introduce concepts associated with currents and circuits. Basic electronics using LEDs, resistors, diodes, capacitors, sensors, and actuators can be assembled with microcontrollers and programming to serve as simple *Internet of Things* (IoT) devices. Semiconductor devices in computers and smartphones are the engineered inventions based on our deep understanding of electricity and magnetism in solid-state materials. We live in exciting times with innovations in information technology also pushing on the quantum frontier (e.g. using superconducting circuits, ultracold atoms, and even diamonds) to harness quantum information by manipulating qubits in quantum computers.

Electric power generation and transmission is a great context at an industrial scale to introduce electromagnetic induction (and the historic "battle of the currents"), which can be extended to discuss the existential issue of harnessing clean and sustainable sources of energy for human society. Electromagnetic field concepts are central to particle accelerators like cyclotrons – circular accelerators use both magnetic and electric fields while linear accelerators use electric fields only. While accelerators (e.g. the Large Hadron Collider at CERN) are commonly associated with advanced particle physics research, cyclotrons are also used in medical physics – with important applications like cancer treatment.

Plenty of natural phenomena showcase the beauty and power of electricity and magnetism. Singapore experiences one of the highest incidences of lightning strikes in the world – the meteorological phenomenon of thunderstorms provides a natural context to introduce the concepts of charges, electric fields, electric potential, and capacitance. The rapid movement of clouds during the formation of a thunderstorm leads to frictional charging, which sets up an electric field between the cloud and the ground. The system of cloud and ground acts as a large capacitor that discharges through the air in the form of lightning.

Auroras at the Earth’s poles present another remarkable natural phenomenon due to electromagnetic interaction of the solar wind (highly energetic charged particles from the Sun) with gases in Earth’s atmosphere. The charged particles are constrained to move in helical paths through the Earth’s magnetic field (magnetosphere), colliding with gas particles in our atmosphere and creating colourful displays in the night sky.

In biology, electricity is also important in signalling and control, complementing neurochemical transmission and reception. The heart rhythms are maintained by waves of electrical excitation, from nerve impulses that spread through special tissue in the heart muscles. Heart rhythms can be electrically monitored, and even “rebooted” using a defibrillator in life-threatening situations.

[H2 Physics] Topic 14: Electric Fields

Charge is a fundamental property of **matter**. The valence of charge (positive versus negative) affects the directions of electric (and magnetic) **forces** experienced, as well as the sign of the potential **energy**. Charged particles set up electric **fields** in the region of space around them. These fields mediate long-range **interactions** with other charges.

This topic, designed with a clear parallel to *Gravitational Fields*, is an important opportunity to revisit representations such as **field** lines and equipotential surfaces, using 2D/3D visualisations as well as appropriate graphs. Key distinctions for electric fields relative to gravitational fields include the possibility of both attractive and repulsive interactions (represented in terms of **forces** as well as **energy**), as well as sign conventions for charge and definitions like field strength and potential.

Just like in *Mechanics* topics, we analyse the **motion** of a charge in uniform and radial electric field **patterns**. The concept of **energy** should as always be linked to work done, and used to analyse systems, including the storage of energy with capacitance.

Learning Outcomes Students should be able to:
14.1 Coulomb's law
14(a) recall and use Coulomb's law in the form $F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$ for the electric force between two point charges in free space or air
14.2 Electric field strength
14(b) recall and use $E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$ for the electric field strength due to a point charge, in free space or air, to solve problems
14.3 Electric potential and energy
14(c) define electric potential at a point as the work done per unit charge by an external force in bringing a small positive test charge from infinity to that point
14(d) use the equation $V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$ for the electric potential in the field due to a point charge, in free space or air
14(e) show an understanding that the electric potential energy of a system of two point charges is $U_E = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r}$
14(f) recall that electric field strength at a point is equal to the negative potential gradient at that point and use this to solve problems
14.4 Uniform electric fields
14(g) calculate the field strength of the uniform electric field between charged parallel plates in terms of the potential difference and plate separation
14(h) calculate the force on a charge in a uniform electric field
14(i) describe the effect of a uniform electric field on the motion of a charged particle
14.5 Capacitance
14(j) define capacitance as the ratio of the charge stored to the potential difference and use $C = \frac{Q}{V}$ to solve problems
14(k) recall that the electric potential energy stored in a capacitor is given by the area under the graph of potential difference against charge stored, and use this and the equations $U = \frac{1}{2}QV$, $U = \frac{1}{2}\frac{Q^2}{C}$ and $U = \frac{1}{2}CV^2$ to solve problems.

Electricity is an essential part of modern living. We rely heavily on electrical appliances and electronic gadgets daily – water heaters, refrigerators, air-conditioners, smartphones, laptops – which are all powered with electric current.

In this topic, we consider how the collective **motion** of **microscopic** charges produces **macroscopic** measurable currents and voltages. Current and voltage characterise the flow of charge and **energy** respectively, which are **conserved** quantities. While an applied **field** establishes a potential difference that in free space would cause charges to accelerate, the loss of **energy** through heating in a resistor is analogous to the "drag" experienced by a falling parachutist, resulting in a low average *drift velocity* for charge that is akin to "terminal velocity" (though the individual charges really move quickly and in essentially random directions).

Just like in *Thermal Physics*, the **energy** lens is used heavily since it is a reliable principle that we can apply even in complicated **systems**. Sinusoidal alternating currents are introduced as electrical analogues of the simple harmonic oscillator, with the root mean square current/voltage characterising the time-averaged resistive heating effect.

Learning Outcomes Students should be able to:
15.1 Current and drift velocity
15(a) show an understanding that electric current is the rate of flow of charge and solve problems using $I = \frac{Q}{t}$
15(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
15.2 Potential difference and power
15(c) recall and solve problems using the equation for potential difference in terms of electrical work done per unit charge, $V = \frac{W}{Q}$
15(d) recall and solve problems using the equations for electrical power $P = VI$, $P = I^2R$ and $P = \frac{V^2}{R}$
15.3 Power supplies: d.c. and a.c.
15(e) distinguish between electromotive force (e.m.f.) and potential difference (p.d.) using energy considerations
15(f) show an understanding of and use the terms period, frequency, peak value and root-mean-square (r.m.s.) value as applied to an alternating current or voltage
15(g) represent a sinusoidal alternating current or voltage by an equation of the form $x = x_0 \sin \omega t$
15(h) deduce that the mean power in a resistive load is half the maximum (peak) power for a sinusoidal alternating current
15(i) distinguish between r.m.s. and peak values, and recall and use $I_{\text{r.m.s.}} = \frac{I_0}{\sqrt{2}}$ and $V_{\text{r.m.s.}} = \frac{V_0}{\sqrt{2}}$ for the sinusoidal case
15(j) explain the use of a single diode for the half-wave rectification of an alternating current.

[H2 Physics] Topic 16: Circuits

In this topic, we dive deeper into electrical **systems** created out of various circuit components. Circuits are everywhere, from the large-scale power grid supplying **energy** to our cities and homes, to the tiny integrated circuit chips in our electronic gadgets and smart devices. We can expect to see increased use of the *Internet of Things* (IoT), integrated sensors and circuits in automation, optimisation, monitoring and much more, bringing greater efficiency and convenience to our lives.

In analysing circuits, the **conservation** principles for charge and **energy** (also known as Kirchoff’s circuit laws) allow us to **model** and predict **system** behaviour, e.g. for series and parallel combinations of resistors (including internal resistance) and of capacitors. By understanding resistance graphically using I-V characteristics and after analysing simple charging and discharging in RC circuits, learners would be better able to design circuits for practical applications, incorporating other common circuit components such as light-dependent resistors and thermistors.

Learning Outcomes Students should be able to:
16.1 Circuit symbols and diagrams
16(a) recall and use appropriate circuit symbols
16(b) draw and interpret circuit diagrams containing sources, switches, resistors (fixed and variable), ammeters, voltmeters, lamps, thermistors, light-dependent resistors, diodes, capacitors and any other type of component referred to in the syllabus
16.2 Resistance, resistivity, and internal resistance
16(c) define the resistance of a circuit component as the ratio of the potential difference across the component to the current in it, and solve problems using the equation $V = IR$
16(d) recall and solve problems using the equation relating resistance to resistivity, length and cross-sectional area, $R = \frac{\rho l}{A}$
16(e) sketch and interpret the I-V characteristics of various electrical components in a d.c. circuit, such as an ohmic resistor, a semiconductor diode, a filament lamp and a negative temperature coefficient (NTC) thermistor
16(f) explain the temperature dependence of the resistivity of typical metals (e.g. in a filament lamp) and semiconductors (e.g. in an NTC thermistor) in terms of the drift velocity and number density of charge carriers respectively
16(g) show an understanding of the effects of the internal resistance of a source of e.m.f. on the terminal potential difference and output power
16.3 Resistors in series and in parallel
16(h) solve problems using the formula for the combined resistance of two or more resistors in series
16(i) solve problems using the formula for the combined resistance of two or more resistors in parallel
16(j) solve problems involving series and parallel arrangements of resistors for one source of e.m.f., including potential divider circuits which may involve NTC thermistors and light-dependent resistors
16.4 RC circuits with d.c. source
16(k) solve problems using the formulae for the combined capacitance of two or more capacitors in series and in parallel
16(l) describe and represent the variation with time, of quantities like current, charge and potential difference, for a capacitor that is charging or discharging through a resistor, using

Learning Outcomes Students should be able to:
equations of the form $x = x_0 \exp(-t/\tau)$ or $x = x_0[1 - \exp(-t/\tau)]$, where $\tau = RC$ is the time constant.

Earth's magnetic **field** forms a natural protective shield against the harmful high-energy solar wind and cosmic rays, giving rise to colourful auroras in the polar regions. What is the origin of this magnetic field, whose mystery was discovered in lodestones by the ancients and used in magnetic compasses for navigation?

One of the challenges in this topic is the spatial visualisation needed for the 3D nature of magnetic field **patterns** and the associated **forces** on moving charges and currents. Moving charges (e.g. in a current-carrying conductor) also produce a magnetic field, which can **interact** with another moving charge or current placed nearby.

We will also explore the use of electromagnetic forces in standard applications like a current balance. Everyday applications include motors, and more sophisticated applications can be found in mass spectrometers for identification of ions, in particle accelerators for cancer therapy or for research into elementary particles and the formation of the **universe**.

Learning Outcomes Students should be able to:
17.1 Magnetic fields and magnetic flux density due to currents
17(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
17(b) sketch magnetic field lines due to currents in a long straight wire, a flat circular coil, and a long solenoid
17(c) use $B = \frac{\mu_0}{2\pi}\frac{I}{d}$, $B = \frac{\mu_0}{2}\frac{NI}{r}$ and $B = \mu_0 n I$ for the magnetic flux densities of the fields due to currents in a long straight wire, a flat circular coil, and a long solenoid respectively
17(d) show an understanding that the magnetic field due to a solenoid may be influenced by the presence of a ferrous core
17.2 Force on a current-carrying conductor
17(e) show an understanding that a current-carrying conductor placed in a magnetic field might experience a force
17(f) recall and solve problems using the equation $F = BIl\sin\theta$, with directions as interpreted by Fleming's left-hand rule
17(g) define magnetic flux density as the force acting per unit current per unit length on a conductor placed perpendicular to the magnetic field
17(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
17(i) explain the forces between current-carrying conductors and predict the direction of the forces
17.3 Force on a moving charge
17(j) predict the direction of the force on a charge moving in a uniform magnetic field
17(k) recall and solve problems using the equation $F = BQv\sin\theta$
17(l) describe and analyse deflections of beams of charged particles by uniform electric fields and uniform magnetic fields
17(m) explain how perpendicular electric and magnetic fields can be used in velocity selection for charged particles.

[H2 Physics] Topic 18: Electromagnetic Induction

Electromagnetic induction allowed for electricity in the form of alternating current to be generated and transmitted on a massive scale during the second industrial revolution – a major milestone in the technological history of human society. Applications of electromagnetic induction in our everyday lives include induction cookers, wireless charging, electromagnetic braking, maglev trains, power transformers, and many more.

The key ideas in this topic are understanding and applying Faraday's law and Lenz's law of electromagnetic induction, which relate induced e.m.f. (and currents too, if the circuit is closed) to the rate of change of a quantity known as magnetic flux and involve the **conservation** of **energy.** This topic also connects back to alternating currents and electrical oscillations, in the analysis of power transformers used to generate high voltages for transmitting electricity over long distances with minimal resistive losses.

Learning Outcomes Students should be able to:
18.1 Magnetic flux
18(a) define magnetic flux as the product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density
18(b) show an understanding of and use the concept of magnetic flux linkage
18(c) recall and use $\phi = BA$ and $N\phi = NBA$ to solve problems, where N is the number of turns
18.2 Faraday's and Lenz's laws of electromagnetic induction
18(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.
18(e) recall and solve problems using Faraday's law of electromagnetic induction and Lenz's law
18(f) explain simple applications of electromagnetic induction
18.3 Power transformers
18(g) show an understanding of the principle of operation of a simple iron-core transformer and recall and solve problems using $\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$ for an ideal transformer.

More than 100 years ago, at the turn of the 20th century, landmark discoveries in physics brought into question well-established concepts from classical physics (such as in mechanics and electrodynamics). Inspired by these experimental results, new paradigms of the physical world emerged, forming the foundation of what we know today as quantum physics and relativity. Despite these advancements in our **model** of the physical world, classical physics continues to provide very accurate descriptions on the length scales and speeds we typically encounter in daily life.

The quantum revolution is an excellent example of the joint role of experiments and theory to push the boundaries of understanding. Well-grounded evidence can establish gaps in accepted wisdom, as well as provide support for alternative theoretical **models** which address such gaps while *still* being able to explain the weight of accumulated evidence that was previously explained.

Some knowledge of quantum physics is critical for understanding present-day technologies that pervade daily life. Nuclear physics is also important for scientific literacy – while the quantum theory of the strong and weak nuclear forces extends well beyond the syllabus, we should have some basic understanding of phenomena like thermonuclear fusion that powers the sun and other stars, spontaneous radioactive decay that contributes to background radiation, nuclear fission that can be harnessed to meet some of our energy needs but also to destroy the world many times over, radioactive medicine, therapy and diagnostics, and other industrial applications of radiation including in food safety.

Concepts

While it is often emphasised that the development of *Modern Physics* involved revolutionary paradigm shifts in thinking, these developments were still anchored to concepts in classical physics (mechanics, waves, thermodynamics, electromagnetism, etc.). In this section, we attempt to highlight the continuity with *Foundations* while giving learners a rich taste and appreciation of some important ideas that go beyond classical physics.

In the *Quantum Physics* topic, the big idea is that quantum mechanics is a unification of “particles” and “waves” at a fundamental level. The *Waves* section used the narrative of (particle) oscillations forming **waves** in space. Taking a step back, waves can be seen as disturbances in **fields** (e.g. electric and magnetic fields, gravitational fields, “matter fields” in which sound propagates). At more advanced levels of study, quantum field theory conceptualises particles as excitations of quantum fields. For the H2 syllabus, we develop the drama of the quantum world in three acts. Act One, the particulate nature of light (photoelectric effect, photon energy and momentum); Act Two, the wave nature of particles (de Broglie wavelength, wavefunction, Heisenberg uncertainty principle, particle in a box); Act Three, the quantisation of **energy** in matter (electronic energy levels and transitions in atoms, emission and absorption line spectra). Each piece of this narrative is anchored on some key ideas from early quantum physics for learners to focus on – these ideas are usually highly simplified rather than technically precise and accurate – and certainly not the last word on the topic.

Nuclear Physics begins with a discussion of experimental evidence for the small, massive[21], charged atomic nucleus. Next, the phenomenon of radioactive decay is explored, with a focus on modelling the decay rate using concepts like half-life. The randomness in nuclear processes is an indication that quantum mechanics is at play. We also place emphasis on understanding the characteristics of

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[21] Here, “massive” should be taken literally as having a (relatively) large mass.

nuclear radiation and appreciating the applications and hazards of radioactivity. This topic concludes with the study of nuclear reactions such as fusion and fission, which have major technological applications. We are reminded of the utility of the **conservation** laws, with a focus on nuclear binding **energy** and mass defect that are related as a consequence of mass-energy equivalence (predicted by special relativity).

Contexts

The theme of "Modern Technology" provides a wide scope for discussing applications. The explosion of computing power witnessed in the 20th century can be traced back to the invention of transistors, which are based on the quantum physics of semiconductors – how charge carriers move in a covalently bonded crystal lattice. This freed the intensification of computational power from the physical limitations of punch cards and vacuum tubes. The next great leap in computing power is expected to again be related to quantum technology as scientists and companies race to build quantum computers. Another key application of quantum physics is in the use of quantum tunnelling in flash memory devices such as SD cards and solid-state hard disks.

Beyond computing, there are many other important areas that can be highlighted, including connections with chemistry, where an understanding of quantum physics can provide critical insights into atomic properties, molecular bonding, and chemical dynamics. Another good everyday example is related to Singapore's location near the equator, which makes solar an important source of clean energy for us. Photovoltaic (PV) cells are typically based on semiconductors, though organic, dye-sensitised and quantum-dot PV technologies exist too. Focusing on quantum dots (QDs) might be particularly relevant because these are essentially a realisation of the particle-in-a-box (sometimes referred to as *artificial atoms*). QDs have potential applications not just in solar cells but also in consumer electronics (e.g. TVs and mobile devices using QD-technology for display screens) and tracers in medical applications.

For nuclear physics, relevant applications range from food safety (irradiation of food to destroy viruses and bacteria) to medical uses (positron emission tomography "PET" and radioactive tracers for diagnostics, gamma knife and proton therapy for treatments) to energy production (nuclear fission, thermonuclear fusion). Learners should also be aware of the many low-level radiation sources in their daily lives, and to contextualise the health hazards of radiation appropriately.

A powerful way to conclude the last topic of the syllabus is to circle back to the *interconnectedness* of all physics. Cosmic radiation, detectable here on Earth's surface, is a serious problem for exploration and applications that take place beyond Earth's protective electromagnetic shield, with profound implications for random software glitches. Radiation hardening of space hardware and building in redundancy and resilience into mission-critical components can provoke rich discussions on considerations in technological design. The Sun is essentially a giant fusion reactor held together by gravity. On Earth, we do not have such an abundance of mass, and are instead trying to figure out how to sustain controlled nuclear fusion by electromagnetic confinement. Inherently, nuclear fusion has great potential as an abundant, clean, and safe source of energy.

In this topic, we explore three main ideas: the particulate nature of light, the **wave** nature of matter, and the quantisation of **energy** levels. In keeping with the general level of technical and mathematical sophistication in the syllabus, these selected key ideas from early quantum theory are formulated simply without worrying too much about technical precision.[22]

We complicate the **model** of light (electromagnetic radiation) by first recalling the classical **wave** model from the section on *Waves* and the phenomenon of interference, then highlighting other experimental evidence (e.g. the photoelectric effect) that does not fit with the wave model. In these situations, the evidence counters an assumption that light delivers **energy** and momentum in a *continuous* stream of progressive waves. Instead, the evidence is more consistent with a photon model that accounts for the *discrete* particle-like properties of light in the way it **interacts** with matter. At this level of sophistication, while learners might want a *definitive* answer[23] to the question of whether light is a wave or a particle, it might be wise to maintain that this really depends on the context of its **interactions**.

The **model** of light as photons then suggests a complementary view of classical particles as having wave-like properties too, which is supported by interference experiments with single particles. Inverting the formula for photon momentum gives the de Broglie wavelength that is applied to "particles" like electrons and protons. Learners are introduced to the idea of a (complex-valued) wavefunction to **model** a *probability* distribution for quantum particles, which mathematically behaves like a classical **wave** displacement that obeys the principle of linear superposition. This wavefunction representation is then used to provide an intuition for the Heisenberg uncertainty principle.[24] We keep to a minimal level of technical sophistication[25] and focus on using the analogy of standing **waves** on a string to discuss the particle-in-a-box, which is a concrete example that has real-world applications and showcases features like **energy** quantisation.

This idea of **energy** quantisation is explored further in the rest of the topic. As we saw for the particle-in-a-box, there are only *discrete* allowed values for its (kinetic) energy. These are referred to as **energy** levels (with a very thin linewidth) corresponding to wavefunctions with certain allowed wavelengths (harmonics). Electronic *orbitals*[26] in atoms are a more complicated 3D version of the "standing waves" in the box. In this quantum picture of the atom, each bound electron inhabits a fuzzy "probability cloud" within which the electron has a certain likelihood of being found. Nonetheless, the **energy** levels are sharply defined, and the electrons in atomic gases can only emit

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[22] For example, the meaning of "uncertainty" when applying Heisenberg's uncertainty principle is not always obvious in physical situations; we simply make an order-of-magnitude estimate.

[23] Telling learners that photons are spin-1 vector gauge bosons in the Standard Model would require several layers of unpacking before it can be meaningfully understood.

[24] There is a limit to our simultaneous knowledge of the position of the particle (related to the width of the wavefunction) and the momentum of the particle (related to the wavelength composition of the wavefunction). In more detail, a particle in 1D space that is associated with a single definite wavelength (which physically corresponds to a fixed value of momentum) has its wavefunction extended indefinitely towards infinity in both directions. On the other hand, a wavefunction taking the form of a short (spatially localised) wave pulse is associated with a particle made up of "superposed component waves" with a range of wavelengths (corresponding to a range of momenta). In the former example, we know its wavelength and thus momentum, but not its position; in the latter example we have a better idea of its position, but its momentum could take many possible values.

[25] In the *Waves* section, we described waveforms without emphasising that these were solutions to the wave equation. Similarly, here we do not need to emphasise that the wavefunction obeys the Schrödinger equation.

[26] While this term is suggestive of classical gravitational orbits, the electrons do not move deterministically like planets tracing precise paths around the sun.

and absorb quanta of electromagnetic radiation (photons) at very *specific* energies to transition between *discrete* energy levels. The **patterns** of resonance can be used to "fingerprint" atomic species.

Learning Outcomes Students should be able to:
19.1 The particulate nature of light
19(a) show an understanding that the existence of a threshold frequency in the photoelectric effect provides evidence that supports the particulate nature of electromagnetic radiation while phenomena such as interference and diffraction provide evidence that supports its wave nature
19(b) state that a photon is a quantum of electromagnetic radiation, and recall and use the equation $E = hf$ for the energy of a photon to solve problems, where h is the Planck constant
19(c) show an understanding that while a photon is massless, it has a momentum given by $p = \frac{E}{c}$ and $p = \frac{h}{\lambda}$, where c is the speed of light in free space
19.2 The wave nature of particles
19(d) show an understanding that electron diffraction and double-slit interference of single particles provide evidence that supports the wave nature of particles
19(e) recall and use the equation $\lambda = \frac{h}{p}$ for the de Broglie wavelength to solve problems
19(f) show an understanding that the state of a particle can be represented as a wavefunction ψ, e.g. for an electron cloud in an atom, and that the square of the wavefunction amplitude $\lvert\psi\rvert^2$ is the probability density function (including calculation of normalisation factors for square and sinusoidal wavefunctions)
19(g) show an understanding that the principle of superposition applies to the wavefunctions describing a particle's position, leading to standing wave solutions for a particle in a box and phenomena such as single-particle interference in double-slit experiments
19(h) show an understanding that the Heisenberg position-momentum uncertainty principle $\Delta x \Delta p \gtrsim h$ relates to the necessity of a spread of momenta for localised particles, and apply this to solve problems
19(i) show an understanding of standing wave solutions ψ_n for the wavefunction of a particle in a one-dimensional infinite square well potential
19(j) solve problems using $E_n = \frac{h^2}{8mL^2} n^2$ for the allowed energy levels of a particle of mass m in a one-dimensional infinite square well of width L
19.3 Quantisation of energy in matter
19(k) show an understanding of the existence of discrete electronic energy levels for the electron's wavefunction in isolated atoms (e.g. atomic hydrogen) and deduce how this leads to the observation of spectral lines
19(l) distinguish between emission and absorption line spectra
19(m) solve problems involving photon absorption or emission during atomic energy level transitions.

[H2 Physics] Topic 20: Nuclear Physics

It is important to learn about nuclear physics as part of scientific literacy. While the fallout from nuclear disaster can be extremely hazardous, life on Earth has coped with an environmental level of background radiation. There are many creative applications that we have found to use nuclear radiation productively. Discussing such socio-scientific issues provides opportunities to situate scientific and technological understanding in the context of humanistic and economic concerns.

In terms of the physics concepts, this topic builds from *Electric Fields* when discussing Rutherford scattering of alpha particles from the atomic nucleus, as well as for understanding the characteristics of nuclear radiation. The rest of the topic is otherwise descriptive or involves data handling and simple mathematical modelling, such as the exponential curve in simple examples of radioactive decay, as well as applying **conservation** laws (including the famous mass-energy equivalence) in nuclear reactions and processes.

Learning Outcomes Students should be able to:
20.1 The nuclear atom
20(a) infer from the results of the Rutherford α-particle scattering experiment the existence and small size of the atomic nucleus
20(b) distinguish between nucleon number (mass number) and proton number (atomic number)
20(c) show an understanding that an element can exist in various isotopic forms, each with a different number of neutrons in the nucleus, and use the notation $^{A}_{Z}X$ for the representation of nuclides
20.2 Radioactive decay
20(d) show an understanding of the spontaneous and random nature of nuclear decay
20(e) infer the random nature of radioactive decay from the fluctuations in count rate
20(f) show an understanding of the origin and significance of background radiation
20(g) show an understanding of the nature and properties of α, β and γ radiations (knowledge of positron emission is not required).
20(h) define the terms activity and decay constant, and recall and solve problems using the equation $A = \lambda N$
20(i) 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
20(j) define and use half-life as the time taken for a quantity x to reduce to half its initial value.
20(k) solve problems using the relation $\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$
20(l) discuss qualitatively the applications (e.g. medical and industrial uses) and hazards of radioactivity based on: iii. half-life of radioactive materials iv. penetrating abilities and ionising effects of radioactive emissions
20.3 Nuclear processes and conservation laws
20(m) represent simple nuclear reactions by nuclear equations of the form $^{14}_{7}\text{N} + ^{4}_{2}\text{He} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{H}$
20(n) state and apply to problem solving the concept that nucleon number, charge and mass-energy are all conserved in nuclear processes

Learning Outcomes Students should be able to:
20(o) show an understanding of how the conservation laws for energy and momentum in β decay were used to predict the existence of the (anti)neutrino (knowledge of the antineutrino and the zoo of particles is not required]
20.4 Mass defect and nuclear binding energy
20(p) show an understanding of the concept of mass defect
20(q) recall and apply the equivalence between energy and mass as represented by $E = mc^2$ to solve problems
20(r) show an understanding of the concept of nuclear binding energy and its relation to mass defect
20(s) sketch the variation of binding energy per nucleon with nucleon number
20(t) explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.

H3 ADDITIONAL CONTENT

2.4 SECTIONS AND TOPICS IN H3 PHYSICS

The syllabus for H3 Physics builds on that for H2 Physics and includes the whole of the H2 Physics syllabus. Only content that is not already part of the H2 Physics syllabus is specifically set out below.

Candidates who offer H3 Physics should have a strong foundation in H2 Physics. They would be expected to tackle more sophisticated problems than candidates who only offer H2 Physics, partly because of the expanded scope. Furthermore, the mathematical requirements for H3 Physics are higher than those for H2 Physics, from the introduction of calculus to the use of column vector notation, as well as the language of scalar and vector products.

The five additional topics in H3 Physics are layered into four of the six main sections in H2 Physics, as listed in **Table 2.5**. For each section, a section narrative outlines the conceptual development and the contextual relevance. For each topic, we provide a topic narrative, followed by examinable learning outcomes.

Table 2.5: Additional topics in H3 Physics added to sections in H2 Physics

Sections	Topics
A. Foundations of Physics	1. Frames of Reference
B. Mechanics	2. Rotational Motion
C. Electricity & Magnetism	3. Electric & Magnetic Fields 4. RLC Circuits
D. Modern Physics	5. Special Relativity

The additional content has been selected to highlight basic principles in physics (e.g. inertial frames of reference, rigid body analysis, angular momentum, dipole moments, special relativity) and to strengthen the focus on applications (e.g. rotational motion, circuits with inductive and capacitive elements). The topics chosen as extensions to the H2 syllabus expand the scope for students to engage in solving challenging problems, while allowing a deeper appreciation of the unity and beauty of the discipline of physics.

For instance, in the topic of Frames of Reference, learners explore and wonder about the role of the observer in physical descriptions. In the topic of Rotational Motion, learners unlock possibilities for modelling rigid bodies by realising the analogy between translational and rotational **motion**. In the additional Electricity & Magnetism topics, the laws of electromagnetism are recast in integral form, which emphasises their geometrical nature, and allows characterisation of more complex field **patterns**. Learners explore the rotational **motion** of electric and magnetic dipoles, as well as the modification of electromagnetic fields in dielectric and ferromagnetic media, which is crucial for technological applications. In electrical circuits, the analogy with mechanical oscillations is established when inductive components are added to resistive and capacitive components. Through Special Relativity, learners are challenged with yet another paradigm shift – the theory of relativity that questioned accepted wisdom about the absolute nature of space and time. Space and time do not exist independently of each other, and the relative **motion** of observers distorts their assignments of space and time coordinates. Simultaneity is not as obvious as we naïvely expect because of the universal limiting speed of light.

The additional content in this section discusses the theoretical underpinning of *perspective* in physics, which opens the door to novel approaches to problem solving in classical physics (including the extension of mechanics to deal with rigid body rotational **motion**), as well as paves the way for the topic of *Special Relativity*.

Concepts

The topic on *Frames of Reference* raises the metacognitive awareness that quantities like velocity and kinetic **energy** are dependent on the reference frame chosen, yet there is a universality in the laws of physics when expressed appropriately. Newton's laws of **motion** are revisited with an appreciation for inertial frames and Galilean transformations. The centre of mass frame (zero-momentum frame) is also highlighted in the context of collision problems. Understanding frames of reference helps in almost any physical situation where one object is moving relative to another. Choosing an appropriate reference frame allows us to simplify problems, or to gain insight from considering new perspectives.[27]

Contexts

Standard kinematics and dynamics examples (e.g. collisions) are natural contexts for discussing inertial frames and appreciating their usefulness. Learners could be tasked to suggest and analyse some such examples in student-led presentations and discussions. As an extension, it would be interesting to also consider qualitatively how observers in *accelerating* reference frames would interpret forces and motion.

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[27] A uniformly accelerating frame, for example, can be thought of as producing an "effective gravity" as a fictitious force.

[H3 Physics] Topic 1: Frames of Reference

In Newton's *Principia*, the "fixed stars" were imagined to establish an absolute frame of reference, where the laws of **motion** held without requiring fictitious **forces**.[28] Since Newton's second law of motion for bodies of constant mass relates forces with *acceleration* not velocity, the (infinite) set of inertial frames, travelling at *constant velocity* relative to the fixed stars, would be suitable for applying Newton's laws of motion.

Learning Outcomes Students should be able to:
1.1 Reference frames
1(a) state that a frame of reference is a set of coordinates that can be used to determine positions and times of events in that frame
1.2 Inertial frames
1(b) show an understanding that Newton's laws of motion are obeyed in all inertial frames of reference.
1(c) recall and apply the Galilean transformation equations to solve problems relating observations in different inertial frames of reference
1.3 Centre of mass frame
1(d) show an understanding that the centre of mass frame (or zero-momentum frame) is the inertial frame in which the total linear momentum of the system is zero
1(e) solve one-dimensional collision problems by considering velocities relative to the centre of mass of the system (i.e. in the zero-momentum frame).

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[28] Newton also discussed examples like a rotating bucket of water, whose motion was revealed by the paraboloid curvature of the water surface.

The extension of H2 Physics to cover rotational **motion** is conceptually neat but technically challenging as the **model** of the mechanical **system** becomes more sophisticated. Regardless, such motion is exceedingly common in real-life, providing many interesting opportunities for learners to conduct investigations and experiments to test theory against observations. In H3 Physics, learners focus on simple examples of rigid body rotation about an axis whose orientation is fixed in space.[29]

Concepts

Just like with translational **motion**, we analyse the mechanics of rotational motion through kinematics and dynamics. Building on H2 topics (including those on the turning effect of forces and angular velocity in circular motion), analogous concepts and formulae are introduced, e.g. for displacement, velocity, acceleration, as well as for inertia, momentum, **force**, and kinetic **energy**. Learners should have opportunities to investigate and **model** illustrative examples of **motion** that combine both translational and rotational aspects, to build their practical competencies (including the ability to handle data from sensors and/or video tracking) and sharpen their analytical skills.

Contexts

A useful strategy to effectively engage learners might be to pair demonstrations with calculations. These could include rolling various objects down a slope, or the hinged stick and falling ball setup. Open-ended activities are also very useful, for learners to work in small groups to perform video analysis and modelling of some form of motion or mechanism. Such modelling could get quite difficult quite quickly without any simplifications or approximations made – so an important learning outcome is to identify ways to come up with effective models.

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[29] This exposure would prepare learners well to handle more general rotations at higher levels of study, e.g. to consider the moment of inertia as a tensor rather than a scalar, and to recast classical mechanics in the form of Euler-Lagrange equations and Hamilton's equations.

In the H2 topic on *Forces & Moments*, learners explore the *static* equilibrium of rigid bodies in terms of torque (i.e. resultant moment of **forces**). Extending this to *dynamics* requires use of the language of rotational kinematics, as well as introducing the analogous concepts of rotational inertia and angular momentum to apply the rotational equivalent of Newton's second law of **motion**. As with H2 Physics, the **energy** lens is often very useful – for rigid bodies, the rotational kinetic energy is (directly) proportional to the moment of inertia and (directly) proportional to the square of the angular speed.

In terms of kinematics, learners should be familiar with the angular analogues of position, displacement, velocity, and acceleration. Angular momentum can be considered as a vector quantity, which is **conserved** if there is no resultant torque. For simple examples of rigid body motion considered in the syllabus, the total kinetic **energy** can usually be neatly apportioned into two parts – corresponding to the translational motion of the body as a whole ("translational KE") and the rotational motion around its centre of mass ("rotational KE").

Learning Outcomes Students should be able to:
2.1 Kinematics of angular motion
2(a) show an understanding of and use the terms angular displacement, angular velocity, and angular acceleration of a rigid body[30] with respect to a fixed axis
2(b) solve problems using the equations of motion for uniform angular acceleration that are analogous to the equations of motion for uniform linear acceleration
2.2 Dynamics of angular motion
2(c) show an understanding of and use the terms angular momentum and moment of inertia of a rotating rigid body
2(d) calculate the moment of inertia about an axis for simple bodies by using calculus, the parallel-axis theorem or otherwise (knowledge of the perpendicular-axis theorem and mathematical derivation of the moment of inertia for spheres are not required)
2(e) show an understanding of torque produced by a force relative to a reference point, and apply the principle that torque is related to the rate of change of angular momentum to solve problems, such as those involving point masses, rigid bodies, or bodies with variable moment of inertia e.g. an ice-skater
2(f) derive, from the equations of motion, and apply the formula $E_{K,rot} = \frac{1}{2}I\omega^2$ for the rotational kinetic energy of a rigid body
2.3 Rigid body rotation about an axis of fixed orientation
2(g) recall and apply the result that the motion of a rigid body can be regarded as translational motion of its centre of mass with rotational motion about an axis through the centre of mass to solve problems, including the use of $F \leq \mu N$ for solid surfaces in no-slip contact (no distinction is made between the coefficient of static and kinetic friction).

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[30] The term "bodies" (or "objects") is used to refer to collections of matter that can be treated as having no internal structure, or an internal structure that can be ignored in typical contexts.

In the late 19th century, Maxwell set about to compile and synthesise the findings of Ampère, Faraday, Gauss, and others[31]. In piecing together these disparate fragments, he built on Faraday's "lines of force" concept to create a unified framework centered around **fields** as its foundation, which we now[32] refer to as Maxwell's equations. The physical theory and mathematical structure of electromagnetism provided important inspiration and motivation for Einstein's theory of relativity.

Understanding circuits also unlocks many applications. The inclusion of inductors and capacitors in circuits realises electrical analogues of mechanical oscillations, which is another illustration of the underlying **patterns**, laws, and principles for physical contexts.

Concepts

The topic on *Electric & Magnetic Fields* includes additional content that deepens the treatment at H2 level, building on **fields**, **forces**, and **energy**. We look at charge distributions on conductors and insulators, introducing Gauss's law and Ampère's law for characterising fields in integral form. These provide a more *global* perspective[33] in terms of flows and flux, sources and sinks – complementing what could be described as a more *local* perspective provided by Newton's law of gravitation and Coulomb's law of electrostatics. In addition, we go beyond charges (monopoles) to include the study of dipoles and the associated torque and potential **energy** in a field. Electric dipoles are common in nature since opposite charges attract to form dipoles, and infinitesimal current loops behave like magnetic dipoles.

In the topic on *RLC Circuits*, additional content beyond H2 enriches learners' understanding of circuits. The concept of inductance builds on electromagnetic induction, in a parallel of how capacitance builds on electric fields. The response of matter to electromagnetic **fields**, which is important for applications, is also discussed qualitatively here. To **model** the behaviour of circuits, the **conservation** principles for charge and **energy** continue to guide our understanding. H3 learners are expected to deal with simple classes of differential equations and their solutions.

Contexts

The impact of Maxwell's equations on science and technology cannot be overstated, as we are much more able to move charge to effectively manipulate electromagnetic fields than to move mass to effectively manipulate gravitational fields. Maxwell's equations also form the basis for understanding classical electromagnetic radiation – the speed of light in free space is related to the product of the permittivity and permeability of free space. Combined with the dipolar properties of matter, we can even explain laws for reflection and refraction.

Understanding inductors and capacitors is critical for analog signal processing, e.g. phase inversion, smoothing and noise reduction. With a greater level of mathematical sophistication (e.g. using phasors or complex numbers), we can model driven circuits involving an a.c. source, including further considerations such as attenuation, boosting, frequency response and resonance. As RLC circuits can mimic the physical mechanisms for sound in musical instruments, applications include

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[31] As well as Lenz and Neumann, who are not named in the four equations comprising Maxwell's equations.

[32] In its original form, Maxwell did not use vector calculus, and thus had to write out each component separately. The original set of over 20 equations was streamlined to 4 subsequently.

[33] One could argue that this is just a *different* perspective and not really a distinction between global versus local; after all, Gauss's law and Ampère's law can also be expressed in the differential form (using the language of vector calculus).

synthesised electronic pop and overdriven guitars. The interaction of electromagnetic waves with circuit components has also allowed us to develop radio technology, which we continue to depend on for WiFi, NFC, and other wireless communication protocols. The use of RLC circuits is vital in creating, receiving, and filtering such electrical signals.

[H3 Physics] Topic 3: Electric & Magnetic Fields

There is much beauty for learners to appreciate in this topic, as the perspective of **fields** is enriched through the geometrical ideas embedded in the formulation of Gauss's law and Ampère's law. Simple examples of using these laws showcase the elegance of symmetry arguments. The study of dipoles in terms of **forces** and **energy** also provides a natural context that builds on rotational **motion**.

Learning Outcomes Students should be able to:
3.1 Electric fields in a conductor
3(a) show an understanding that ideal conductors form an equipotential volume, and that the electric field within an ideal conductor is zero
3(b) show an understanding that electric charge accumulates on the surfaces of a conductor, and that the electric field at the surface of a conductor is normal to the surface
3.2 Gauss's law for electric and magnetic fields
3(c) recall and apply Gauss's law[34] for electric and magnetic fields (knowledge of the differential form of Gauss's law is not required), and i. solve problems involving symmetric charge distributions by relating the electric flux (in a vacuum) through a closed surface with the charge enclosed by that surface ii. show an understanding that the magnetic flux through a closed surface is always zero, suggesting the non-existence of magnetic monopoles
3.3 Ampère's law for magnetic fields
3(d) recall and apply Ampère's law[35] relating the line integral of the magnetic field (in a vacuum) around a closed loop with the electric current enclosed by the loop to solve problems involving symmetric field configurations (knowledge of the differential form of Ampère's law is not required) [Note further that students are not required to know Maxwell's generalisation of Ampère's law including the term related to the rate of change of electric flux, nor the Biot-Savart law.]
3.4 Electric and magnetic dipoles
3(e) define the magnitude of the electric dipole moment as the product of the charge and the separation
3(f) show an understanding of and use the torque on an electric dipole and the potential energy of an electric dipole to solve related problems
3(g) define the magnitude of the magnetic dipole moment for a current loop as the product of the current and the area of the loop
3(h) show an understanding of and use the torque on a magnetic dipole and the potential energy of a magnetic dipole to solve related problems
3(i) appreciate that while electric and magnetic dipoles behave analogously, the theoretical framework at this level of study does not admit the possibility of magnetic monopoles.

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[34] Note that the mathematical concepts and notation for integrating over a surface should be introduced as necessary in the context of Gauss's law, and are not general mathematical requirements in other contexts.

[35] Note that the mathematical concepts and notation for integrating along a contour should be introduced as necessary in the context of Ampère's law, and are not general mathematical requirements in other contexts.

[H3 Physics] Topic 4: RLC Circuits

The inclusion of inductors in H3 Physics broadens the scope for circuits and deepens the understanding of principles of charge and energy **conservation**. While capacitors store **energy** in the form of an electric field, we can think of inductors as storing energy in the form of a (changing) magnetic **field**. Learners will have opportunities to **model** RLC circuits by applying what they learn in mathematics about differential equations. Circuits with capacitors and inductors behave analogously to mechanical oscillators – **energy** sloshes between the electric and magnetic fields instead of between kinetic and potential stores – and including resistors in a circuit is like introducing damping.

Learning Outcomes Students should be able to:
4.1 Inductance
4(a) define self-inductance as the ratio of the e.m.f. induced in an electrical circuit/component to the rate of change of current causing it and use $V = L\frac{dI}{dt}$ to solve problems
4(b) show an understanding that mutual inductance is the tendency of an electrical circuit / component to oppose a change in the current in a nearby electrical circuit / component.
4.2 Dielectrics and ferromagnetic materials
4(c) show a qualitative understanding that dielectric materials enhance capacitance, and that dielectric breakdown can occur when the electric field is sufficiently strong (knowledge of the quantitative modification of electric fields in matter through the permittivity is not required)
4(d) show a qualitative understanding that ferromagnetic materials enhance inductance and that this enhancement is non-linear especially near saturation (knowledge of the quantitative modification of magnetic fields in matter through the permeability is not required)
4.3 Energy in an inductor
4(e) derive, by considering work done on charges, the expression for potential energy stored in an inductor, $U = \frac{1}{2}LI^2$, and use this to solve problems.
4.4 Circuits with capacitors and inductors
4(f) solve problems using the formulae for the combined inductance of two or more inductors in series and in parallel
4(g) solve problems involving circuits with resistors, inductors, and sources of constant e.m.f. (includes solving first-order differential equations). *[RL series circuits with constant e.m.f. source]*
4(h) solve problems involving circuits with inductors and capacitors only (includes solving second-order differential equations) *[LC series circuits without e.m.f. source]*
4(i) solve problems involving circuits with resistors, inductors and capacitors only (students are not expected to solve the general second-order differential equations, though they can be asked to verify and use particular solutions). *[RLC series circuits without e.m.f. source]*

The development of modern physics is a showcase of how scientific knowledge continually undergoes refinement. In the late 19th century, classical electrodynamics and classical mechanics seemed to be operating under different fundamental assumptions. The Galilean transformations between inertial frames in mechanics contradicted with an implied invariant speed of light from electromagnetism. Furthermore, from the perspective of Galilean transforms, there should be no conceptual difference between a magnet being moved towards a stationary coil versus a coil being moved towards a stationary magnet – yet the analysis of the resultant electromagnetic induction was couched in asymmetrical terms (where *only* the moving magnet induces an electric field).

Einstein considered how mechanics could be modified if electromagnetic theory was taken to hold true in all inertial frames. How could the speed of light (electromagnetic radiation) in free space be always the same *no matter how fast the observer was moving*? Paraphrasing Minkowski, space and time do not exist independently of each other – the relative **motion** of observers can warp their assignments of space and time coordinates, and conspire to give the same universal limiting speed of light!

Such thinking was simple yet profound.[36] The essence of special relativity is anchored on two principles: the equivalence of reference frames and the invariance of a physical speed limit. Despite how unintuitive and brain-bending this framework may seem, the accumulated evidence has convinced us that special relativity is a more accurate **model** for physical reality, and a better approximation than Newtonian mechanics. To truly appreciate physical reality, we need the humility to question even our most basic assumptions, the imagination to build alternative theories[37], and the courage to let go of "common sense" when it ceases to be useful.

Concepts

In the topic on *Special Relativity*, we first consider the historic Michelson-Morley experiment, while revisiting the idea of inertial frames and coordinate transformations in the context of a universal speed of light. Within this framework, we then discuss what it really means for events to be *simultaneous* and how to reconcile measurements made in different frames of reference. Learners explore how special relativity requires a significant upheaval of kinematics. This topic culminates in the energy-momentum relation, which encapsulates how concepts of momentum, **energy** and mass must change to accommodate our new understandings of space and time.

Contexts

Time dilation or length contraction is what allows a major component of background radiation (muons arising from cosmic rays) to reach Earth instead of attenuating in the atmosphere. Relativistic corrections are also necessary to maintain the accuracy of the Global Positioning System (GPS). Without these corrections, satellite clocks would accumulate a delay on the order of 0.1 ms

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[36] While it is often claimed that relativity (and quantum mechanics) have "overthrown" classical mechanics, there is still a lot of practical relevance for Newtonian mechanics as an accurate theory in many contexts, and is foundational in the study of physical science.

[37] In fact, Einstein's theory of relativity was not the only viable theory proposed. For example, in 1867, Ludwig Lorenz (not to be confused with Edward Lorenz or Hendrik Lorentz) used a framework in which changes to a field do not take effect immediately, but propagate outwards at the speed of light; this allowed measurements of time and position to be universal while adequately accounting for some of the discrepancies between classical and modern physics. In the end, however, Einstein, who was a more prominent public figure, turned out to have the more widely-accepted theory, which we continue to use to this day to explain such phenomena.

per day, which may sound small, but would correspond to an unacceptable drift of more than 10 km when used for navigating on the Earth’s surface.

At more advanced levels, the relativistic transformation of electromagnetic fields is necessary for consistent explanations of electromagnetic forces on moving magnets or charges. Relativistic considerations are also necessary for correctly calculating the properties of atoms, especially for larger atoms whose electrons “travel” at relativistic speeds. Some examples include the low melting point of mercury, the yellow colour of gold and the white colour of silver, and why lead-acid batteries produce high voltages.

Ether theory was hotly contested in the past even though it is hardly mentioned these days. The Michelson-Morley experiment provides a valuable opportunity to discuss how the *negative* result that was obtained provided evidence *against* ether theory. While it is true that relativistic kinematics is quite different from the naïve kinematics in Newtonian mechanics, learners should appreciate that such modifications were necessary and principled (rather than ad-hoc).

Understanding special relativity requires an emphasis on key ideas and careful exploration of simple examples. Visualisations and mathematical representations serve as valuable aids. Solving problems from first principles can help to highlight the power of clear thinking in unfamiliar situations, without relying on preconceived notions.

Learning Outcomes Students should be able to:
5.1 Michelson-Morley experiment
5(a) discuss qualitatively the results of the Michelson-Morley interferometer experiment and its implications on the ether theory (knowledge of the details of the experiment is not required)
5.2 Inertial frames and universal light speed
5(b) state the postulates of the special theory of relativity, that in all inertial frames, the laws of physics are the same and the speed of light in free space is the same regardless of the motion of the light source or observer
5(c) appreciate the failure of Galilean transformation equations when applied to a moving source of light
5.3 Lorentz transformations
5(d) discuss the concept of simultaneity
5(e) show an understanding of the terms proper time and proper length
5(f) apply the Lorentz transformation equations to solve one-dimensional problems
5.4 Length contraction and time dilation
5(g) derive the time dilation formula and length contraction formula, making use of the Lorentz factor
5(h) apply the time dilation formula and the length contraction formula in related situations (e.g. the lifetime of fast-moving muons) or to solve problems
5.5 Velocity addition
5(i) use the one-dimensional relativistic velocity addition formula to calculate velocities in different inertial frames or to solve problems
5.6 Energy-momentum relation
5(j) use the relativistic energy-momentum relation $E^2 = (pc)^2 + (mc^2)^2$ to solve problems, and show that it reduces, in the appropriate limits, to: 1. $E = pc$ (for massless particles); or 2. $E = mc^2 + \frac{1}{2}mv^2$ (for particles moving at low speeds $v \ll c$).

SECTION 3: PEDAGOGY

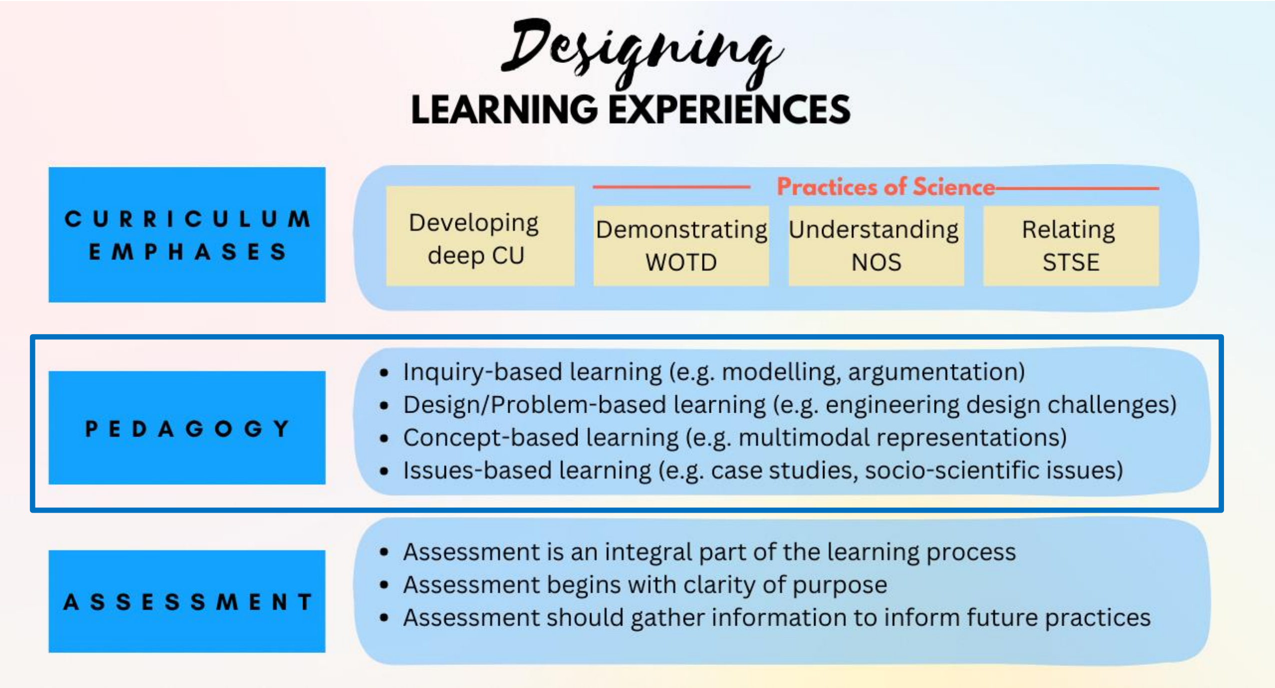
3. PEDAGOGY

3.1 INSPIRING STUDENTS THROUGH PEDAGOGICAL PRACTICES

Pedagogy is the intentional practice of teaching informed by educational theories, research and practice. They refer to classroom strategies, teaching actions and teacher-student interactions to help students learn and achieve the outcomes of the curriculum. It is guided by our core beliefs about teaching and learning as articulated in the Singapore Curriculum Philosophy.

Teachers are key in facilitating a variety of learning experiences, drawing on the *Knowledge Bases* and adopting the *Pedagogical Practices*, as described in the *Singapore Teaching Practice* (*STP*). Apt use of pedagogies considering student profile and the nature of the lesson can help our students develop 21CC and work towards the realisation of MOE's Desired Outcomes of Education (DOEs).

Through appropriate LEs and pedagogies, teachers can help students acquire an understanding of the scientific enterprise, its methods, limitations, benefits and pitfalls, and develop into scientifically literate citizens. Specific to science learning, four pedagogies are shown in **Figure 3.1** (see blue box).



- Inquiry-based learning (e.g. modelling, argumentation)
- Design/Problem-based learning (e.g. engineering design challenges)
- Concept-based learning (e.g. multimodal representations)
- Issues-based learning (e.g. case studies, socio-scientific issues)

- Assessment is an integral part of the learning process
- Assessment begins with clarity of purpose
- Assessment should gather information to inform future practices

Figure 3.1: Pedagogical Approaches when designing LEs

3.2 PRACTICAL WORK AS AN INTEGRAL PART OF SCIENCE LEARNING

The excitement of scientific investigation brings to life the theory and underpinning knowledge of many fundamental scientific concepts,[38] as they link the domain of observables and objects to the domain of scientific ideas (see **Table 3.1**).[39]

Table 3.1: Linking the domains of "observables" & "scientific ideas" through practical work

N	Type of Practical	A	P	Main Learning Objective
1	**Modelling** experiment (Model Development)	I	✓	Modelling a physical phenomenon
2	**Planning** (and doing) experiment	I	-	Planning (and conducting) an investigation
3	**Design Challenge** (Model Deployment)	D	-	Solving a problem or challenge given a physical setup
4	**Confirmatory** Experiment	D	✓	Practicing procedures & Confirming theory

A: Approach; P: Procedure; I: Inductive; D: Deductive

Depending on students' readiness and learning objectives, the level of inquiry in a science practical lesson can vary in terms of degree of complexity (see **Table 3.2**). An activity can be inquiry-based when students conduct the analysis and draw their own conclusions or design their own solutions. Scaffolding for students is instrumental in helping them advance their competencies in scientific inquiry, e.g. they could start from structured inquiry before progressing to higher levels of inquiry such as open-ended investigations. In such cases, students are required to design all or part of the experimental procedures, decide on what data to record, analyse and interpret the data on their own. This encourages greater autonomy and deeper practices of science in students.

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[38] Holman, J. (2009). Good Practical Science. Gatsby Foundation.

[39] Millar, R., & Abrahams, I. (2009). Practical work: making it more effective. *School Science Review, 91(334)*, 59

Table 3.2: Continuum of strategies in terms of amount of information given to the student[40]

Degree of complexity	**How much information is given to the student?**		
	Question?	**Methods?**	**Solution?**
Level 4 Open Inquiry *(Student formulates questions and designs experimental procedures)*	×	×	×
Level 3 Guided Inquiry *(Student designs or selects the experimental procedures)*	✓	×	×
Level 2 Structured Inquiry *(Teachers prescribed the experimental procedures)*	✓	✓	×
Level 1 Confirmation *(Results are known in advance)*	✓	✓	✓

In practical work, students learn to address challenges inherent in observing the physical world, including troubleshooting equipment used to make observations. The use of graphing software (e.g. Excel spreadsheets) allows convenient visualisation and analysis of data. Planning and conducting their mini-investigative projects individually or in small groups also provide many opportunities for students to harness digital tools in the process of recording data, analysing results, and presenting their findings.

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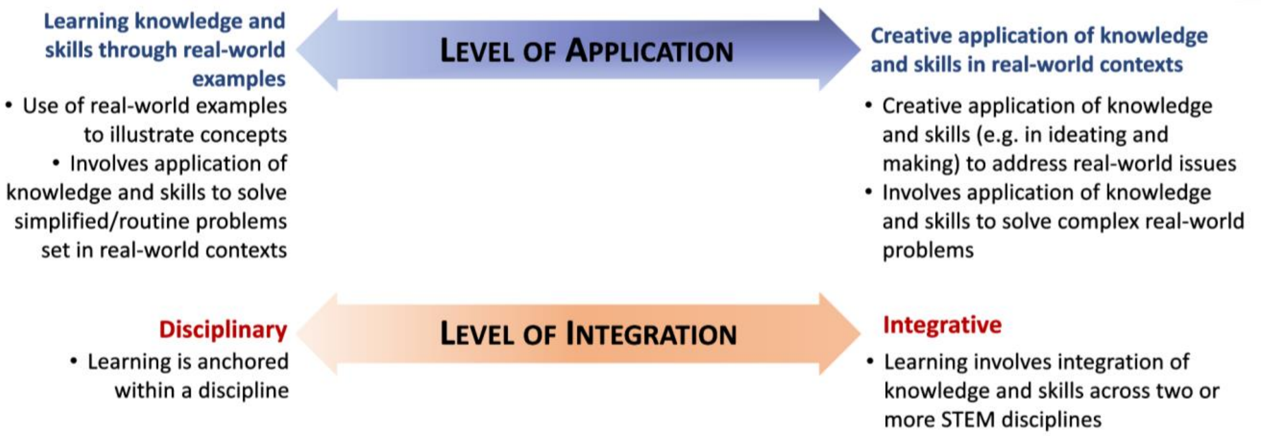
[40] Adapted from Bell, R. L., Smetana, L., & Binns, I. (2005). Simplifying inquiry instruction. *The Science Teacher*, 72(2), 30–33

3.3 SCIENCE LEARNING BEYOND THE BOUNDARIES THROUGH STEM LES

Given how scientists work in areas where subject boundaries are becoming more blurred and interdisciplinary work is increasing important, it would be helpful to teach and learn science that allow students to apply science in real-world contexts and to make connections to other subjects. The design of STEM LEs could be unpacked at two levels along a continuum: 1) level of application and 2) level of integration (see **Figure 3.2**). While the extent of curriculum integration could vary, an example of an interdisciplinary curriculum is one where there is a common theme, cross-cutting concept, project or unit across several subjects. Teachers could also make use of real-world contexts to illustrate concepts and applications, and expose students to problems that involve multiple solutions.



Learning knowledge and skills through real-world examples
- Use of real-world examples to illustrate concepts
- Involves application of knowledge and skills to solve simplified/routine problems set in real-world contexts

Creative application of knowledge and skills in real-world contexts
- Creative application of knowledge and skills (e.g. in ideating and making) to address real-world issues
- Involves application of knowledge and skills to solve complex real-world problems

Disciplinary
- Learning is anchored within a discipline

Integrative
- Learning involves integration of knowledge and skills across two or more STEM disciplines

Figure 3.2: Two design considerations for STEM LEs

To help students become future-ready, a range of STEM LEs can be adopted. These LEs should provide opportunities to:

a. **make learning relevant** for students by selecting suitable real-world contexts to illustrate knowledge, skills and practices within a discipline;
b. encourage **creative application** by allowing students to apply their knowledge skills and practices within a discipline to work collaboratively in solving problems set in real-world contexts;
c. **enhance students' understanding** to provide students a more coherent and complete understanding of what they are learning by making connections with what is learnt in other STEM disciplines; and/or
d. engage students in **managing complexity** through solving of real-world problems which require them to work collaboratively and apply their knowledge, skills and practices across the STEM disciplines.

SECTION 4: ASSESSMENT

4. ASSESSMENT

Assessment is the process of gathering and analysing evidence about student learning. This information is used to make decisions about students, curriculum and programmes. Assessments designed with a clarity of purpose and the provision of timely and targeted feedback can facilitate meaningful development of students' 21CC and scientific knowledge and skills.

Creating Learner-centred and balanced assessments that develops students' metacognition can improve engagement levels and inspire self-directed learning.

a. Assessment is an integral to the teaching and learning process. Assessment is a part of teaching and learning, and must be closely aligned with curriculum objectives, content and pedagogy. In a classroom where assessment is used to support learning, there is no divide between teaching and assessment. Everything that happens in the classroom, and everything that students do (e.g., questions they ask, responses to learning activities), become sources of information that help teachers assess what students know and can do. The teacher will analyse these sources of information to make teaching decisions which enhance the quality of learning and address learning gaps. Hence, assessment becomes an ongoing, cyclical process that is woven into the minute-to-minute and day-to-day life in the classroom.

b. Assessment begins with clarity of purpose. Assessment tasks should be fit for purpose and based on sound educational principles. Summative assessment serves to provide information on students' mastery of content knowledge and skills, while formative assessment is carried out for the purpose of enhancing teaching and learning. A balanced assessment system should comprise both summative assessment and formative assessment. Whether implemented as formal examinations or infused in classroom learning activities, assessment should support meaningful learning. Decisions on 'what' to assess and 'how' to assess should be based on a clear purpose, in relation to the learning outcomes.

c. Assessment provides feedback to move learning forward and improve teaching practices. Assessment information should allow both teachers and students to make continuous improvement to teaching and learning. In addition to interpreting assessment information and adapting instructional practices accordingly to address learning gaps, teachers also need to guide students to understand and use assessment information to improve their learning. This will help engender ownership of learning to students and boost their motivation to learn. As students learn to self-assess and self-regulate, they will be equipped to become self-directed learners who are able to learn for life. Assessment information should produce both quantitative and qualitative descriptions of learners' performance that are useful to teachers and students.

A-LEVEL EXAMINATION

The A-Level physics syllabuses at H1, H2, and H3 levels are 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.

ASSESSMENT OBJECTIVES

In the syllabus documents, the assessment objectives for the theory papers are grouped into two categories:

- Assessment Objective A (AOA) – Knowledge with understanding
- Assessment Objective B (AOB) – Handling, applying and evaluating information

For H2 Physics, an assessment objective is added for the practical paper:

- Assessment Objective C (AOC) – Experimental skills and investigations

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

A Knowledge with understanding

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

1. scientific phenomena, facts, laws, definitions, concepts, theories;
2. scientific vocabulary, terminology, conventions (including symbols, quantities and units);
3. scientific instruments and apparatus, including techniques of operation and aspects of safety;
4. scientific quantities and their determination; and
5. scientific and technological applications with their social, economic and environmental implications.

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

B Handling, applying and evaluating information

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

1. locate, select, organise and present information from a variety of sources;
2. handle information, distinguishing the relevant from the extraneous;
3. manipulate numerical and other data and translate information from one form to another;
4. use information to identify patterns, report trends, draw inferences and report conclusions;
5. present reasoned explanations for phenomena, patterns and relationships;
6. make predictions and put forward hypotheses;
7. apply knowledge, including principles, to novel situations;

8. bring together knowledge, principles and concepts from different areas of physics, and apply them in a particular context;
9. evaluate information and hypotheses; and
10. demonstrate an awareness of the limitations of physical theories and models.

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

C Experimental skills and investigations *(for H2 only)*

Candidates should be able to:

1. follow a detailed set or sequence of instructions and use techniques, apparatus and materials safely and effectively;
2. make, record and present observations and measurements with due regard for precision and accuracy;
3. interpret and evaluate observations and experimental data;
4. identify a problem, design and plan investigations; and
5. evaluate methods and techniques, and suggest possible improvements.

GLOSSARY OF TERMS USED IN PHYSICS PAPERS

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

1. **Define (the term(s) ...)** is intended literally. Only a formal statement or equivalent paraphrase, such as the defining equation with symbols identified, is required.
2. **What is meant by ...** normally implies that a definition should be given, together with some relevant comment on the significance or context of the term(s) concerned, especially where two or more terms are included in the question. The amount of supplementary comment intended should be interpreted in the light of the indicated mark value.
3. **Explain** may imply reasoning or some reference to theory, depending on the context.
4. **State** implies a concise answer with little or no supporting argument, e.g. a numerical answer that can be obtained ‘by inspection’.
5. **List** requires a number of points with no elaboration. Where a given number of points is specified, this should not be exceeded.
6. **Describe** requires candidates to state in words (using diagrams where appropriate) the main points of the topic. It is often used with reference either to particular phenomena or to particular experiments. In the former instance, the term usually implies that the answer should include reference to (visual) observations associated with the phenomena. The amount of description needed should be interpreted in light of the indicated mark value.
7. **Discuss** requires candidates to give a critical account of the points involved in the topic.
8. **Deduce/Predict** implies that candidates are not expected to produce the required answer by recall but by making a logical connection between other pieces of information. Such information may be wholly given in the question or may depend on answers extracted in an earlier part of the question.
9. **Suggest** is used in two main contexts. It may either imply that there is no unique answer or that candidates are expected to apply their general knowledge to a ‘novel’ situation, one that formally may not be ‘in the syllabus’.
10. **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.
11. **Calculate** is used when a numerical answer is required. In general, working should be shown.
12. **Determine** often implies that the quantity concerned cannot be measured directly but is obtained by calculation, substituting measured or known values of other quantities into a standard formula.
13. **Show** is used when an algebraic deduction has to be made to prove a given equation. It is important that the terms used by candidates are stated explicitly.
14. **Estimate** implies a reasoned order of magnitude statement or calculation of the quantity concerned. Candidates should make such simplifying assumptions as may be necessary about points of principle and about the values of quantities not otherwise included in the question.
15. **Sketch**, when applied to graph work, implies that the shape and/or position of the curve need only be qualitatively correct. However, candidates should be aware that, depending on the context, some quantitative aspects may be looked for, e.g. passing through the origin, having an intercept, asymptote or discontinuity at a particular value. On a sketch graph it is essential that candidates clearly indicate what is being plotted on each axis.

16. **Sketch**, when applied to diagrams, implies that a simple, freehand drawing is acceptable; nevertheless, care should be taken over proportions and the clear exposition of important details.
17. **Compare** requires candidates to provide both similarities and differences between things or concepts.

ASSESSMENT FOR H1 PHYSICS

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.

[H1 PHYSICS] SCHEME OF ASSESSMENT

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

Paper	Type of Paper	Duration	Weighting (%)	Marks
1	Multiple Choice	1 h	33	30
2	Structured Questions	2 h	67	80

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

Paper 2 (2 h, 80 marks)
This paper consists of 2 sections. All answers will be written in spaces provided on the Question Paper.

Section A (60 marks)
This section consists of a variable number of structured questions including one or two data-based questions, all compulsory. The data-based question(s) will constitute 15-20 marks.

Section B (20 marks)
This section consists of two 20-mark questions of which candidates will answer one. The questions will require candidates to integrate knowledge and understanding from different areas of the syllabus.

Weighting of Assessment Objectives
The assessment objectives are weighted as shown, for candidates taking H1 Physics.

Assessment Objectives		Weighting (%)	Assessment Components
A	Knowledge with understanding	45	Papers 1, 2
B	Handling, applying and evaluating information	55	Papers 1, 2

[H1 PHYSICS] ADDITIONAL INFORMATION

Mathematical Requirements

Candidates should familiarise themselves with the mathematical requirements.

Conventions, Symbols, Signs and Abbreviations

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

Data and Formulae

The list of data and formulae will appear as page 2 in Papers 1 and 2.

Disallowed Subject Combinations

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

[H1 PHYSICS] 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 $<, >, \ll, \gg, \approx, /, \propto, \langle x \rangle (= \bar{x}), \Sigma, \Delta x, \delta x, \surd$.

Geometry and trigonometry

Candidates should be able to:

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

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

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

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

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

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

Vectors

Candidates should be able to:

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

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

Graphs

Candidates should be able to:

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

(b) select appropriate variables and scales for graph plotting

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

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

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

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

(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.

ASSESSMENT FOR H2 PHYSICS

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.

[H2 PHYSICS] SCHEME OF ASSESSMENT

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

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

Paper 1 (1 h, 30 marks)

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

Paper 2 (2 h, 75 marks)

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

Paper 3 (2 h, 75 marks)

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

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

Paper 4 (2 h and 30 min, 50 marks)

This paper will consist of two sections and 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 4%. The assessment of skill areas MMO, PDO and ACE will have a weighting of 16%.

The assessment of PDO and ACE may also include questions on data analysis which do not require practical equipment and apparatus. Candidates will be required to process and analyse data using spreadsheet software.

All answers will be written in spaces provided on the Question Paper. Candidates will be allocated 1 h 15 min for access to apparatus and materials of each section (see details in Practical Assessment). Candidates will not be permitted to refer to books and laboratory notebooks during the assessment.

Weighting of Assessment Objectives

The assessment objectives are weighted as shown, for candidates taking H2 Physics.

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

[H2 PHYSICS] ADDITIONAL INFORMATION

Mathematical Requirements

Candidates should familiarise themselves with the mathematical requirements.

Conventions, Symbols, Signs and Abbreviations

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

Data and Formulae

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

Disallowed Subject Combinations

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

[H2 PHYSICS] 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 $<, >, \ll, \gg, \approx, /, \propto, \langle x \rangle (= \bar{x}), \Sigma, \Delta x, \delta x, \surd$.

Geometry and trigonometry

Candidates should be able to:

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

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

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

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

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

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

Vectors

Candidates should be able to:

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

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

Graphs

Candidates should be able to:

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

(b) select appropriate variables and scales for graph plotting

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

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

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

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

(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.

[H2 PHYSICS] PRACTICAL ASSESSMENT

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

H2 Physics Paper 4 (Practical)

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

Candidates will be assessed in the following skill areas:

(a) Planning (P)

Candidates should be able to:

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

(b) Manipulation, measurement and observation (MMO)

Candidates should be able to:

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

(c) Presentation of data and observations (PDO)

Candidates should be able to:

- present all information in an appropriate form;
- manipulate measurements effectively in order to identify trends/patterns; and
- present all quantitative data to an appropriate number of decimal places/significant figures.

(d) Analysis, conclusions and evaluation (ACE)

Candidates should be able to:

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

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

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

Within the Scheme of Assessment, Paper 4 constitutes 20% of the H2 examination. It is therefore recommended that the schemes of work include learning opportunities that apportion a commensurate amount of time for the development and acquisition of practical skills.

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

Apparatus List

The list in **Table 4.2** 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. 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.

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

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

Table 4.2: Apparatus List for H2 Physics

Electricity and Magnetism
ammeter (analogue): f.s.d. 500 mA and 1 A
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)
voltmeter (analogue): f.s.d. 3 V
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)
galvanometer (analogue): centre-zero, f.s.d. ±35 mA, reading to 1 mA or better
power supply: 12 V d.c. (low resistance)
dry cells: 2 × 1.5 V with holder, 2 V
lamp and holder: 6 V, 300 mA; 2.5 V, 0.3 A
rheostat: max resistance: 22 Ω, rating: at least 3.3 A
switch
jockey
leads and crocodile clips
wire: constantan 26, 28, 30, 32, 34, 36, 38 s.w.g. or metric equivalents
magnets and mounting: 2 × magnadur magnets plus small iron yoke for mounting, 2 × bar magnets
compasses: 2 × small
Thermal
long stem thermometer: –10 °C to 110 °C at 1 °C intervals
metal calorimeter
measuring cylinder: 50 cm^3, 100 cm^3
plastic or polystyrene cup 200 cm^3
means to heat water safely to boiling
heating mat
stirrer

Mechanics and General Items
pendulum bob
stand, boss and clamp: × 3 (rod length: 2 × 60 cm, 1 × 90 cm)
G-clamp × 2
pivot
pulley
tuning forks (set of 8 pc): (1 set per 4–6 candidates)
newton-meter: 1 N, 10 N
rule with millimeter scale (2 × 1 m, 1 × 0.5 m, 1 × 300 mm)
digital micrometer screw gauge (1 per 4–6 candidates)
digital vernier calipers (1 per 4–6 candidates)
stopwatch (reading to 0.1 s or better)
protractor
balance to 0.01 g (1 per 8–12 candidates)
beaker: 100 cm^3, 2 × 250 cm^3
Plasticine
Blu-Tack
wire cutters
bare copper wire: 18, 26 s.w.g.
springs
spirit level (1 per 4–6 candidates)
stout pin or round nail
optical pin
slotted masses: 1 each 5 g and 10 g, 2 × 20 g, 4 × 50 g; 1 × 50 g hanger
slotted masses: 4 × 100 g; 1 × 100 g hanger
cork
string/thread/twine
scissors
adhesive tape
card (assorted sizes)
sand and tray
wood (assorted sizes, for various uses, e.g. support)
bricks: 2 × (approx. 22 cm × 10 cm × 7 cm)

[H2 PHYSICS] REQUIREMENTS ON USE OF SPREADSHEET SOFTWARE FOR PRACTICAL ASSESSMENT

Candidates offering H2 Physics will be required to use spreadsheet software in Paper 4.

Candidates should be able to:

(a) import data files (in csv format) into the spreadsheet for subsequent processing
(b) input data obtained from an experiment for subsequent processing

Functions within the spreadsheet

Candidates should be able to:

(a) perform mathematical operations as stipulated in the Mathematical Requirements including sines, cosines, tangents (and the inverse functions) on angles in radians (converting from degrees as necessary), exponentials and logarithms (lg and ln), and use of scientific notation (e.g. 3.00E+14 for 3.00×10^{14})
(b) use features for numerical data manipulation
  i. use and input formulae and duplicate formulae across cells
  ii. adjust formatting (e.g. data type) and duplicate formatting across cells
(c) plot a labelled line graph using selected data from a table
  i. adjust the scale of both axes
  ii. use selected data points to give a line of best fit (using built-in functions to add a linear trendline)
  iii. display the equation of a trendline
  iv. determine the area under the line of best fit (e.g. summation of rectangular or trapezoidal areas)
  v. determine the gradient at a point on a curved line of best fit (e.g. calculating $\frac{\Delta y}{\Delta x}$ in a small interval near the point)

ASSESSMENT FOR H3 PHYSICS

The H3 Physics syllabus has been designed to build on and extend the knowledge, understanding and skills acquired from the H2 Physics (9478) syllabus. Candidates offering H3 Physics should simultaneously offer H2 Physics.

[H3 PHYSICS] SCHEME OF ASSESSMENT

There is one paper of 3 hours duration for this subject. This paper will consist of two sections and will include questions which require candidates to integrate knowledge and understanding from different areas of the syllabus.

Section A (60 marks).

This section will consist of a variable number of compulsory structured questions. The last of these will be a stimulus-based question which will constitute 15–20 marks.

Section B (40 marks).

This section will consist of a choice of two from three 20-mark longer structured questions. Questions will be set in which knowledge of differential and/or integral calculus will be necessary.

Weighting of Assessment Objectives

The assessment objectives are weighted as shown, for candidates taking H3 Physics.

Assessment Objectives		Weighting (%)
A	Knowledge with understanding	25
B	Handling, applying and evaluating information	75

[H3 PHYSICS] ADDITIONAL INFORMATION

Mathematical Requirements

Candidates should familiarise themselves with the mathematical requirements.

Conventions, Symbols, Signs and Abbreviations

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

Data and Formulae

The list of data and formulae will appear as pages 2 and 3 in the examination paper.

Required Subject Combinations

Candidates should simultaneously offer H2 Physics.

[H3 PHYSICS] MATHEMATICAL REQUIREMENTS

Additional requirements not found in the H2 Physics (9478) syllabus are marked with an asterisk (*).

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 $<$, $>$, $\ll$, $\gg$, $\approx$, $/$, $\propto$, $\langle x \rangle$ (= $\bar{x}$), Σ, Δx, δx, $\sqrt{}$.

Geometry and trigonometry

Candidates should be able to:

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

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

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

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

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

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

Vectors

Candidates should be able to:

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

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

*(c) use column vector notation for vectors, and unit vector notation (such as $\hat{\boldsymbol{x}}$).

*(d) use concepts and properties of scalar (dot) products and vector (cross) products, excluding triple products.

Graphs

Candidates should be able to:

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

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

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

(d) choose, by inspection, a straight line which will serve as the line of best fit 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.

Calculus

Candidates should be able to:

*(a) perform differentiation of simple functions, including trigonometric, exponential and logarithmic functions and the use of product rule and chain rule.

*(b) perform integration of simple functions, including trigonometric, exponential and logarithmic functions, and area integrals of circularly symmetric distributions and volume integrals of spherically and cylindrically symmetric distributions[41] (knowledge of integration by parts is not required).

*(c) evaluate definite integrals.

*(d) solve first-order differential equations of the form $\frac{dy}{dx} = f(x)$.

*(e) solve second-order differential equations of the form $\frac{d^2y}{dx^2} = f(x)$.

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

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[41] Candidates are only expected to be able to perform one-dimensional radial integrals that do not involve any non-trivial angular dependence.

ANNEX A: SUMMARY OF KEY QUANTITIES, SYMBOLS AND UNITS

[H1 PHYSICS] SUMMARY OF KEY QUANTITIES, SYMBOLS AND UNITS

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

Quantity	Usual symbols	Usual unit
Base Quantities		
mass	m	kg
length	l	m
time	t	s
electric current	I	A
thermodynamic temperature	T	K
amount of substance	n	mol
Other Quantities		
distance	d	m
displacement	s, x	m
area	A	$\mathrm{m^2}$
volume	V, v	$\mathrm{m^3}$
density	ρ	$\mathrm{kg\ m^{-3}}$
speed	u, v, w, c	$\mathrm{m\ s^{-1}}$
velocity	u, v, w, c	$\mathrm{m\ s^{-1}}$
acceleration	a	$\mathrm{m\ s^{-2}}$
acceleration of free fall	g	$\mathrm{m\ s^{-2}}$
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
power	P	W
pressure	p	Pa
torque	T, τ	N m
gravitational constant	G	$\mathrm{N\ kg^{-2}\ m^2}$
gravitational field strength	g	$\mathrm{N\ kg^{-1}}$
angle	θ	°, rad
angular displacement	θ	°, rad
angular speed	ω	$\mathrm{rad\ s^{-1}}$
angular velocity	ω	$\mathrm{rad\ s^{-1}}$
period	T	s
frequency	f	Hz
angular frequency	ω	$\mathrm{rad\ s^{-1}}$
speed of electromagnetic waves	c	$\mathrm{m\ s^{-1}}$
electric charge	Q	C
elementary charge	e	C
electric potential	V	V

Quantity	**Usual symbols**	**Usual unit**
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}
magnetic flux	ϕ	Wb
magnetic flux density	B	T
force constant	k	N m^{-1}
Celsius temperature	θ, T	°C
Avogadro constant	N_A	mol^{-1}
number	N, n, m	
activity of radioactive source	A	Bq
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 mol^{-1}
proton number	Z	
nucleon number	A	
neutron number	N	

[H2 PHYSICS] SUMMARY OF KEY QUANTITIES, SYMBOLS AND UNITS

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

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

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

[H3 PHYSICS] SUMMARY OF KEY QUANTITIES, SYMBOLS AND UNITS

The following list illustrates the symbols and units that will be used in question papers. Quantities **not** listed in H2 Physics are marked with an asterisk (*).

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

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

ANNEX B: DATA AND FORMULAE

[H1 PHYSICS] DATA AND FORMULAE

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

Data

speed of light in free space	$c = 3.00 \times 10^{8}\ \text{m s}^{-1}$
elementary charge	$e = 1.60 \times 10^{-19}\ \text{C}$
unified atomic mass constant	$u = 1.66 \times 10^{-27}\ \text{kg}$
rest mass of electron	$m_e = 9.11 \times 10^{-31}\ \text{kg}$
rest mass of proton	$m_p = 1.67 \times 10^{-27}\ \text{kg}$
the Avogadro constant	$N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$
gravitational constant	$G = 6.67 \times 10^{-11}\ \text{N m}^{2}\ \text{kg}^{-2}$
acceleration of free fall	$g = 9.81\ \text{m s}^{-2}$

Formulae

uniformly accelerated motion	$s = ut + \frac{1}{2}at^2$
	$v^2 = u^2 + 2as$
electric current	$I = nAvq$
resistors in series	$R = R_1 + R_2 + \cdots$
resistors in parallel	$\dfrac{1}{R} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \cdots$

[H2 PHYSICS] 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 $m_0 = 4\pi \times 10^{-7}$ H m^{-1}

permittivity of free space $e_0 = 8.85 \times 10^{-12}$ F m^{-1}

$(\frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^{9}$ m F$^{-1})$

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 $W = p\Delta V$

pressure $p = \frac{F}{A}$

gravitational potential $\phi = -\frac{Gm}{r}$

temperature $T/\mathrm{K} = T/^{\circ}\mathrm{C} + 273.15$

pressure of an ideal gas $p = \frac{1}{3}\frac{Nm}{V}\langle c^2 \rangle$

mean translational kinetic energy of an ideal gas particle $E = \frac{3}{2}kT$

displacement of particle in s.h.m. $x = x_0 \sin \omega t$

velocity of particle in s.h.m. $v = v_0 \cos \omega t$

$= \pm\omega\sqrt{(x_0^2 - x^2)}$

electric current $I = nAvq$

resistors in series $R = R_1 + R_2 + \cdots$

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

[H3 PHYSICS] DATA AND FORMULAE

Additional data and formulae **not** provided for H2 Physics are marked with an asterisk (*).

Data

speed of light in free space	c	=	3.00×10^{8} m s^{-1}
permeability of free space	μ_0	=	$4\pi \times 10^{-7}$ H m^{-1}
permittivity of free space	ε_0	=	8.85×10^{-12} F m^{-1}
	$\frac{1}{4\pi\varepsilon_0}$	=	8.99×10^{9} m F^{-1}
elementary charge	e	=	1.60×10^{-19} C
the Planck constant	h	=	6.63×10^{-34} Js
unified atomic mass constant	u	=	1.66×10^{-27} kg
rest mass of electron	m_e	=	9.11×10^{-31} kg
rest mass of proton	m_p	=	1.67×10^{-27} kg
molar gas constant	R	=	8.31 J K^{-1} mol^{-1}
the Avogadro constant	N_A	=	6.02×10^{23} mol^{-1}
the Boltzmann constant	k	=	1.38×10^{-23} J K^{-1}
gravitational constant	G	=	6.67×10^{-11} N m^{2} kg^{-2}
acceleration of free fall	g	=	9.81 m s^{-2}

Formulae

uniformly accelerated motion	s v^2	= =	$ut + \frac{1}{2}at^2$ $u^2 + 2as$
*moment of inertia of rod through one end	I	=	$\frac{1}{3}ML^2$
*moment of inertia of hollow cylinder through axis	I	=	$\frac{1}{2}M(r_1^2 + r_2^2)$
*moment of inertia of solid sphere through centre	I	=	$\frac{2}{5}MR^2$
*moment of inertia of hollow sphere through centre	I	=	$\frac{2}{3}MR^2$
work done on/by a gas	W	=	$p\Delta V$
pressure	p	=	$\frac{F}{A}$
gravitational potential	ϕ	=	$-\frac{Gm}{r}$
temperature	T/K	=	$T/^{\circ}\mathrm{C} + 273.15$
pressure of an ideal gas	p	=	$\frac{1}{3}\frac{Nm}{V}\langle c^2 \rangle$
mean translational kinetic energy of an ideal gas particle	E	=	$\frac{3}{2}kT$

displacement of particle in s.h.m.	$x = x_0 \sin \omega t$
velocity of particle in s.h.m.	$v = v_0 \cos \omega t$
	$= \pm\omega\sqrt{(x_0^2 - x^2)}$
electric current	$I = nAvq$
resistors in series	$R = R_1 + R_2 + \cdots$
resistors in parallel	$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$
capacitors in series	$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots$
capacitors in parallel	$C = C_1 + C_2 + \cdots$
energy in a capacitor	$U = \frac{1}{2}QV = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2$
charging a capacitor	$Q = Q_0[1 - e^{-\frac{t}{\tau}}]$
discharging a capacitor	$Q = Q_0 e^{-\frac{t}{\tau}}$
RC circuit time constant	$\tau = RC$
electric potential	$V = \frac{Q}{4\pi\varepsilon_0 r}$
*electric field strength due to long straight wire	$E = \frac{\lambda}{2\pi\varepsilon_0 r}$
*electric field strength due to large sheet	$E = \frac{\sigma}{2\varepsilon_0}$
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	$B = \frac{\mu_0 NI}{2r}$
magnetic flux density due to a long solenoid	$B = \mu_0 nI$
*energy in an inductor	$U = \frac{1}{2}LI^2$
*RL series circuit time constant	$\tau = \frac{L}{R}$
*RLC series circuits (underdamped)	$\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$
energy states for quantum particle in a box	$E_n = \frac{h^2}{8mL^2}n^2$
radioactive decay	$x = x_0 e^{-\lambda t}$
radioactive decay constant	$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$
*Lorentz factor	$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

*Length contraction	$L = \frac{L_0}{\gamma}$
*time dilation	$T = \gamma T_0$
*Lorentz transformation equations (1 dimension)	$x' = \gamma(x - vt)$ $t' = \gamma\left(t - \frac{vx}{c^2}\right)$
*velocity addition	$u' = \frac{u - v}{1 - \frac{uv}{c^2}}$
*energy-momentum relation	$E^2 = (pc)^2 + (mc^2)^2$

SECTION 5:

RESOURCES AND REFERENCES

5. RESOURCES AND REFERENCES

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

- Adams, S., & Allday, J. (2000). *Advanced physics*. Oxford, United Kingdom: Oxford University Press. (ISBN: 9780199146802)
- Akrill, T. B., Millar, C., & Bennet, G. A. G. (2011). *Practice in physics* (4th ed.). London: Hodder Education. (ISBN: 1444121251)
- Breithaupt, J. (2000). *New understanding physics for advanced level* (4th ed.). Cheltenham: Nelson Thornes. (ISBN: 0748743146)
- Boohan, R (2016). *The Language of Mathematics in Science: A Guide for Teachers of 11–16 Science. Association for Science Education*. (ISBN: 9780863574559) [https://www.ase.org.uk/mathsinscience]
- Duncan, T. (2000). *Advanced physics* (5th ed.). London: Hodder Education. (ISBN: 0719576695)
- Giancoli, D. C. (2013). *Physics: Principles with applications* (7th ed.). Boston, MA: Addison-Wesley. (ISBN: 0321625927)
- Mike, C. (2001). *AS/A-Level physics essential word dictionary*. Philip Allan Publishers. (ISBN: 0860033775)
- Sang, D., Jones, G., Chadha, G., Woodside, R., Stark, W., & Gill, A. (2014). *Cambridge international AS and A level physics coursebook* (2nd ed.). Cambridge, United Kingdom: Cambridge University Press. (ISBN: 9781107697690)
- Serway, R. A., Jewett, J. W., & Peroomian, V. (2014). *Physics for scientists and engineers with modern physics* (9th ed.). Boston, MA: Brooks/Cole. (ISBN: 1133953999)
- Urone, P. P. (2001). *College physics* (2nd ed.). Pacific Grove, CA: Brooks/Cole. (ISBN: 0534376886)
- Walker, J., Resnick, R., & Halliday, D. (2014). *Fundamentals of physics* (10th ed.). Hoboken, NJ: Wiley. (ISBN: 111823071X)

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