HANDBOOK FOR TEACHING SECONDARY PHYSICS
Dear colleagues,

The dominant public perception of Physics is that it is highly abstract and daunting. The challenge for Physics teachers is to debunk this perception and make Physics ‘accessible’ to all students. How would teachers illustrate that Physics is relevant, useful and interesting to the students? How would teachers make the abstract and invisible come ‘alive’ to be experienced and observed? These questions have motivated a group of Physics educators to come together to share their thoughts, strategies and experiences on the teaching of Physics. They have also taken the next step to pen down their thinking and professional practices so that these can be made available to all Physics teachers.

*The Handbook for Teaching Secondary Physics* is produced through the collective and collaborative efforts of curriculum officers from Curriculum Planning and Development Division, master teachers from the Physics Chapter of the Academy of Singapore Teachers, assessment officers from Singapore Examinations and Assessment Board and lecturers from National Institute of Education, Nanyang Technological University and National University of Singapore. People with different domain expertise have contributed to the *Handbook* to ensure it would be a useful and practical resource to inform and transform the teaching and learning of Physics.

Effective teaching and learning of Physics will help develop a technologically literate people and technologically competent workforce for Singapore. The deep dedication of all Physics teachers will drive them to always strive for excellence in Physics education and I believe the *Handbook* will be a part of this quest for better teaching and learning in Physics.

**Ms Low Khah Gek**  
*Director, Curriculum Planning and Development Division*  
*Ministry of Education*
This Handbook for Teaching Secondary Physics is a meaningful collaboration between the Curriculum Planning and Development Division Sciences Branch and the Physics Subject Chapter of the Academy of Singapore Teachers to build a professional learning community of confident and inspiring physics educators.

Written with a strong emphasis on pedagogical content knowledge, the wealth of knowledge presented in this Physics Handbook can be maximised through practice and reflection to increase teachers’ capacity. Building teachers’ capacity must be viewed not just as increasing the storehouse of facts and ideas but as a source and creator of knowledge and skills needed for instruction.

Research has shown that the building of teachers’ capacity for improved practice can be achieved through professional development that is job-embedded, instructionally focused, collaborative and ongoing. One such professional development tool is Lesson Study (LS) – a powerful teacher-driven, student-focused professional development process to deepen the various domains of teacher knowledge. The Lesson Study Cycle requires teachers to formulate their learning goals, design research lessons in their school context, teach and observe their peers teaching, and finally to analyse and document the lesson studied. Such experiences not only encourage Science teachers to fully utilise ideas and materials from the Handbook but also require teachers to collaborate with each other in developing impactful and innovative pedagogies that are underpinned by sound learning theories, experimentation and research. This is in line with the Academy’s mission of building a teacher-led culture of professional excellence where teachers lead and teach one another as a community of reflective practitioners.

I wish all teachers the very best in the effective use of the Handbook and their active participation in the transformative Lesson Study workshops that will be mounted by the Academy of Singapore Teachers from 2012 onwards to deliver the best education to their students.

Manogaran s/o Suppiah
Executive Director
Academy of Singapore Teachers
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Teaching in the knowledge society and economy is challenging due to the more complex 21st century world and context in which we live in. As informed and reflective practitioners, there is a need to ground our teaching practice on a wider range of evidence, reading and research. Besides being good at our craft of teaching, we need to also keep pace with the latest developments and understanding as to what constitutes effective pedagogy and best practice in education.

This book serves as a practical guide to the teaching of physics in secondary schools, drawn from research, theory and wisdom of practice. The ideas presented can help teachers make sense of what is going on in their classrooms and serve as lenses for understanding students’ growth, development, difficulties, and successes. We hope to be able to give you ideas and strategies to make physics more exciting and accessible for your students.

The contents of this book are presented in three sections:

- **Part I: Knowledge of Physics Teaching and Learning.** Chapter 1 gives an overview of the kinds of professional knowledge bases that a physics teacher needs to know and develop in order to be adaptable and effective at helping students learn better. Chapters 2-5 elaborate on these knowledge bases which include: goals of physics education and the physics curriculum for the 21st century, how students learn physics as well as instructional and assessment strategies that promote learning in physics.

- **Part II: Knowledge of Secondary Physics Curriculum.** Chapters 6-9 deal with each of the major sections in physics – Newtonian mechanics, thermal physics, electricity & magnetism and waves – and looks at the big ideas and their progression in the physics curriculum from the primary to pre-university levels. The historical development of our understanding in physics for each section and its relevance and value in society today are also discussed.

- **Part III: Reflective Practice in Physics Teaching.** Chapter 10 highlights the importance of continuing professional development of teachers through collaborative networked learning and teacher-research.

“The pessimist complains about the wind; the optimist expects it to change; the realist adjusts the sails”

William Arthur Ward

We trust that this book will spark off useful conversations and help reinforce your understanding of what constitutes good physics teaching and support you in your development as a teacher. Indeed, the way forward is a paradigm shift towards a student-focused, teacher-led excellence through professional and networked learning communities among teachers within and across schools. Let us work together to adjust our sails and raise the wonder of physics and the joy of learning physics in our students!

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In Part I, we examine the essential knowledge all physics teachers must have to bring about effective teaching and learning in their classrooms.

The first chapter “What makes an effective physics teacher?” introduces pedagogical content knowledge, an integrative understanding of both content and pedagogy that guides teachers in adapting the physics content for teaching and learning.

The second chapter “Making the physics curriculum relevant” highlights students’ progression in their understanding of physics ideas in the physics curriculum from primary to pre-university, and physics teachers’ role in preparing students for the 21st century.

The third chapter “How students learn physics” provides a brief introduction to learning theories and the use of conceptual change models in physics instruction.

The fourth chapter “Strategies for inquiry-based physics instruction” describes models of science teaching and specific instructional strategies that are consistent with teaching and learning physics as an inquiry.

The fifth chapter “Assessing student understanding in physics” distinguishes the different roles and purposes of assessment for learning, assessment of learning and assessment as learning, and the importance of assessment to the teaching and learning of physics.
“At the heart of PCK is the manner in which subject matter is transformed for teaching. This occurs when the teacher interprets the subject matter and finds different ways to represent it and make it accessible to learners.”

- Punya Mishra & Matthew Koehler, 2006

Chapter Overview

Teaching is a complex activity that involves many different aspects. Apart from understanding the subject content, good teaching also involves selecting the appropriate pedagogy to suit the particular context in which teaching and learning takes place. This chapter examines the kinds of professional knowledge that a successful physics teacher needs to acquire and develop. It unpacks the idea of pedagogical content knowledge (PCK) which can be understood as essential knowledge for teachers to transform their disciplinary knowledge into effective teaching. Shulman’s 6-stage model of pedagogical reasoning and action, which can be viewed as a set of processes of central importance to the development of PCK, is also introduced.

What every physics teacher needs to know

Good teaching is the skillful application of pedagogy for a specific subject matter in particular contexts. This special amalgam of content and pedagogy is a unique class of knowledge that is central to teachers’ work that would not be typically held by non-teaching subject matter experts or by teachers who know little of that subject. This blending of content and pedagogy into an understanding of how particular topics, problems or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction is known as pedagogical content knowledge (PCK), as first coined by Shulman (1986).
Conceptually, PCK, as represented in Figure 1.1, is an amalgamation of *subject matter knowledge* (**SMK**), *general pedagogical knowledge* (**GPK**) and *contextual knowledge* (**CtK**) which distinguishes the expert teacher in a subject area from the content expert. **PCK** is that special professional understanding that teachers have whereby they can integrate, transform and represent content knowledge in ways that are comprehensible to the learners. **SMK** is also commonly known as content knowledge. **GPK** includes classroom management and organization, instructional models and strategies, classroom communication and discourse while **CtK** includes knowledge of learners in a classroom or school and general educational goals and purposes.

**Teaching processes that help develop a teacher’s PCK**

Shulman (1987) also proposed a model of pedagogical reasoning and action. The model can be viewed as a set of processes of central importance to the development of PCK and included six stages: **Comprehension**, **Transformation**, **Instruction**, **Evaluation**, **Reflection**, and **New Comprehension**. Through the ‘wisdom of practice’, teachers continuously reconstruct and develop an understanding of teaching based on their teaching experiences through a reflective process.

*Figure 1.2 Model of Pedagogical Reasoning and Action.*

The 6-stage model of pedagogical reasoning and action (Figure 1.2) is summarized below:

**Stage 1: Comprehension**

This is the starting point and also the terminus for the entire pedagogical reasoning and action. According to Shulman, “pedagogical reasoning is as much a part of teaching as is the actual performance itself. Reasoning does not end when instruction begins. The activities of comprehension, transformation, evaluation, and reflection continue to occur during active teaching. Teaching itself becomes a stimulus for thoughtfulness as well as for action”.

The aspect of Comprehension means that the teacher understands critically what is to be taught and how ideas or concepts are inter-related both within and without the subject area. “To teach is first to understand”. This aspect
also encompasses the comprehension of general educational purposes such as developing the spirit of inquiry/innovation, skills and values among students needed to function in society.

Stage 2: Transformation

The second aspect, Transformation, is a process wherein “one moves from personal comprehension to preparing for the comprehension of others”. The teacher has to scrutinize the teaching materials based on his or her understanding of the subject matter and the educational purposes to decide what needs to be taught. The teacher then explores, selects and adapts the representations to suit the specific characteristics of the students.

Stage 3: Instruction

The third aspect, Instruction, involves the observable performance of various teaching acts such as classroom management, presentations and explanations, rapport and interactions with students, questioning and praising or criticizing students.

Stage 4: Evaluation

The next aspect, Evaluation, involves both the informal formative and the more formal summative feedback that the teacher obtains from the class. When evaluation is directed at one’s own teaching, it naturally leads to the next aspect of Reflection.

Stage 5: Reflection

“This is what a teacher does when he or she looks back at the teaching and learning that has occurred, and reconstructs, reenacts, and/or recaptures the events, the emotions, and the accomplishments”.

Stage 6: New Comprehension

Reflection can be done individually or in a large group and it is a set of processes through which the professional learns from experience. Through these reasoned acts of teaching, the teacher achieves “new comprehension, both of the purposes and of the subjects to be taught, and also of the students and of the processes of pedagogy themselves”.

Model for Science PCK

Building on Shulman’s notion of PCK, Friedrichsen et al., (2009) developed a useful model to represent the different components required for good science teaching (and indeed for physics teaching as well), as shown in Figure 1.3. The model elaborates on the components of science PCK that result from the unique blending of the three knowledge bases – namely SMK, GPK & CtK – as discussed earlier. The components for science PCK are the knowledge of curriculum, knowledge of students’ understanding, knowledge of instructional strategies and knowledge of assessment. The model also includes the additional component of Science Teaching Orientation which refers to the general way of viewing or conceptualizing science teaching in terms of the knowledge and beliefs about the purposes and goals for teaching science at a particular grade level.
The four major components of the science PCK model (Figure 1.3) are summarized as follows:

1. **Knowledge of Science Curriculum**

   This component consists of knowledge of learning goals, instructional materials, sequencing of instruction across particular topics (horizontal curricula), as well as knowledge of vertical curricula. In this book, the curricular knowledge is covered in Chapter 2 on “Making the Physics Curriculum Relevant” and Chapters 6 to 9 on “Newtonian Mechanics”, “Thermal Physics”, “Electricity and Magnetism” & “Waves”.

2. **Knowledge of Student Understanding of Science**

   This component consists of knowledge of what students know about a topic, including common misconceptions; requirements for learning the topic; how students learn that topic best; and areas of difficulty for student learning. In this book, Chapter 3 on “How Students Learn Physics” will address the learners and their learning.

3. **Knowledge of Science Instructional Strategies**

   This component consists of knowledge of science-specific approaches, and topic-specific activities and representations. In this book, Chapter 4 on “Strategies for Inquiry-based Physics Instruction” will provide a repertoire of instructional strategies for effective teaching and meaningful learning.
4. Knowledge of Assessment in Science

This component consists of knowledge of what and how to assess student learning in relation to stated goals. In this book, Chapter 5 on “Assessing Student Understanding in Physics” will discuss the big ideas on assessment for learning and assessment of learning.

Summary of Key Points

- **PCK** is the skillful blending of content and pedagogy in a particular teaching and learning context to achieve specific educational goals and purposes.
- **PCK** develops as teachers comprehend and transform their subject matter knowledge for the purpose of instruction, and then as they evaluate and reflect on their teaching.
- The different components of **PCK** in physics include the knowledge of the physics curriculum, knowledge of student understanding of physics, knowledge of instructional strategies in physics and knowledge of assessment in physics.
Physics and Physics Education

Kwek Leong Chuan

The Institute of Physics, Singapore (IPS) has for several years been organizing various Physics Education workshops to promote better Physics Teaching at the universities and the Schools. It therefore gives me, as the current President of IPS, great pleasure to congratulate the Sciences Branch, Curriculum Planning and Development Division (CPDD) and the Physics Subject Chapter of the Academy of Singapore Teachers for jointly coming together to compile a Physics Resource Book for teachers.

Ironically, even though I was trained in Physics (as well as Mathematics) and I am now teaching Physics at the University, I started my teaching career as a Mathematics teacher. As a trainee teacher, I was fortunate to be acquainted with an excellent Mathematics Educator at the former Institute of Education Singapore (IES), the late Dr Eric Latimer Plant. For many years, Eric taught Mathematics in various primary schools around the world and he accumulated a wealth of experience that no book could provide. At IES, he stood as a beacon of light for many of us who had recently forayed into teaching.

Eric introduced an excellent book on mathematics pedagogy by Richard Skemp [1] to us. Through Skemp's book, we learnt how to teach different topics in Mathematics with different strategies. And one of the famous phrases that we have gleaned from the book was the phrase: "from the concrete to the abstract and then from the abstract to the concrete!"

The principal emphasis of Skemp's argument was that we should always start playing around with mathematics before we proceed to various abstract concepts or schemata. Richard Skemp's hierarchical abstraction theory was partly built on an earlier work by Zoltan Dienes [2]. Many of these ideas predate the current emphasis on Lee Shulman's pedagogical content knowledge [3]. Unlike Mathematics, Physics is an observational and experimental science. So besides knowing how to teach a subject conceptually, all Physics students should learn to acquire the skill of observation and hands-on practices. A steady hand at turning knobs is just as useful as a good brain. Naturally, you do not need to be an expert in both aspects: Kepler for instance was a great physicist but he needed the data from Tycho Brahe, who was able to collect the data from his observatory.

But like many philosophical ideas and educational theories, there are very few new good ideas. More often than not ideas are often revived and rehashed. This does not mean that old rehashed ideas are not useful. Revived ideas often provide new insights under a new context or a new situation. In particular, I would like to point out a well-known phrase from Confucius (or his disciples):

学然后知不足， 敎然后知困。
知不足， 然后能自反也。
知困， 然后能自强也。 (学记)

This phrase came from the Book of Learning “Xueji” and it roughly translate as:

“When you start learning, you will realize your shortcomings; when you start teaching then you..."
will know the reasons for your shortcomings (and the difficulties); you can improve yourself by reflecting on your shortcomings; and you can hone your pedagogical skills by realizing the reasons (cause) for your shortcomings”.

Although this phrase was formulated thousands of years ago, it continues to embrace the modicum of understanding that enshrouds pedagogical content knowledge as we understand it today.

A good teacher must be a good learner. This is somewhat contrary to George Bernard Shaw’s somewhat sneaky remark: “Those who can, do, those who can’t, teach”. Placed in the wrong context, this quote has become the bane of the teaching profession and a popular line for cynical colleagues among us who are disappointed with teaching at times or cheeky colleagues who use this phrase as a tongue-in-cheek. I see this phrase from a different angle. It somehow seems to mirror the previous Confucian quote.

As a teacher, I often encourage my students to explain what they learn to each other. It is only when they can put across the basic ideas effectively to someone else that they have thoroughly understood the topic. In this sense, the teacher has the biggest advantage in the classroom. His job daily entails the need to reflect carefully on his teaching skills. By focusing on the difficulties of teaching, he gains invaluable insights into his content. So pedagogical content knowledge goes both ways. Through teaching, one learns and through learning one needs to teach.

Whether you are a good Physics teacher or a researcher, you must find the time to read. There are already plenty of excellent resource books in Physics and two books deserve special mention, both for their content and pedagogy: Arnold B. Aron’s book on Physics Teaching [4] and Clifford E. Swartz’s sourcebook on Teaching Introductory Physics [5]. The best teachers are often the best researchers.

Therefore, I would encourage you to dabble with instruments in your school laboratory every now and then, and see if you could discover something new (this really needs luck) or something pedagogically interesting. There is also a need for you to communicate your findings with everybody else, and this is the primary purpose of scientific publication.

Finally, I would like to say something about this book. No resource book, no matter how comprehensive or thorough, can replace the knowledge in Physics teaching that you can acquire on the job in your classroom. Within the covers of this book, the editors have carefully selected and assembled a number of eminent scholars in various fields and expertise to provide some insights that you might find it helpful in the classroom, and sometimes only if you reflect carefully on the ideas presented. I therefore hope that you will find this book useful in your teaching.

CHAPTER 2: MAKING THE PHYSICS CURRICULUM RELEVANT

“Look deep into nature, and then you will understand everything better.”

- Albert Einstein

Chapter Overview

The study of physics, from the time of Aristotle, to Newton and Einstein, and to contemporary physicists like Stephen Hawking, has served to revolutionise the way we think and interact with our environment. The school physics curriculum needs to serve the dual role of building students’ fundamental knowledge in ‘Classical’ physics, and extending their knowledge to current applications of ‘Modern’ physics so that students may better relate their physics study to their everyday life experiences and challenges. This chapter provides a brief description of the development of Classical (Newtonian) physics, the study of physics itself and its implications on our lives. The chapter then highlights the school physics curriculum, and how the topics in the physics curriculum at the primary and secondary levels focus on the Newtonian world view, while the study of physics at pre-university level goes beyond classical physics ideas to embrace a Quantum mechanical worldview of contemporary physics. The end of the chapter discusses the role of physics teachers in equipping students with new knowledge, skills and attitudes for the 21st century.

Development of physics

It is generally accepted that the science of physics originated from ancient Greece, with well-documented works of many Greek philosophers such as Pythagoras and Democritus who made the first attempts to understand the motion of planets and the constituents of matter. One of the giants of the ancient Greek world is Aristotle, whose philosophy influenced human thought for two millennia after his death. His most important contribution to the field is probably his invention of its name - physics - derived from a Greek word meaning ‘nature’ (Gamow, 1988).

The shortcomings of Aristotelian philosophy was the belief that mathematics was of little value in describing physical phenomena and great emphasis was placed on direct, qualitative observations and debate as the basis for forming theories. Real progress in physics began only when scientists recognised the value of mathematical prediction and careful measurement.

Galileo Galilei, one of the earliest experimental physicists, devised simple measuring devices, such as a water clock to measure time. He also expressed the results of his measurements of the motion of objects through mathematical form. This led Isaac Newton, who is widely accepted as the father of modern-day physics, to develop his laws of motion and universal gravitation. His treatment of mechanical phenomena was so clearly and precisely stated mathematically that the formulae can be used unchanged in contemporary books of classical mechanics.

Newton succeeded in extending his laws of mechanics, which are based on experimental observations and measurements on Earth, to explain the motion of celestial objects. This ignited scientists’ belief that universal laws do exist and that the universe is dominated by these laws, which may ultimately be discovered and understood by Man (Rutherford, Holton, & Watson, 1981).

Today, scientists recognise that Newtonian mechanics holds true only within a well-defined region of physical phenomena. For example, at the atomic and sub-atomic scale, entirely non-Newtonian concepts are required to explain the observed motions of these particles. A branch of physics, commonly referred to as Modern Physics,
employs the theory of quanta and the theory of relativity to extend our knowledge into the realms of the very small and the very fast.

**Nature of Physics**

**Study of Physics**

The main goal in the study of physics is to discover the physical forces, interactions, and properties of matter in our physical world, which encompasses both the terrestrial world (i.e. Earth) and the celestial world (i.e. planets, stars and the universe). Key concepts related to the study of physics include mass, energy, force, momentum, charge, field, light, entropy, quanta, and relativity. These topics are included in the school physics curriculum at various levels.

Two key questions that physicists strive to answer through observations, experiments, models and theories of physical phenomena are:

1. What are the physical properties of matter and energy?
2. How can these properties be measured, expressed through mathematical formulae and explained by physics theories?

In seeking answers to these key questions, physicists share the viewpoint that the universe and the physical world are ultimately explainable through theories and laws of physics. Physicists therefore seek to develop hypotheses or theories that they can test and perfect by extended study and experimentation. These theories will then provide physicists with the capacity for predicting how nature will behave in one situation on the basis of experimental data obtained in another situation. Physicists then conduct further observations or experiments to confirm or falsify them so as to build on the range of applicability of the existing theories (Paul & Elder, 2003).

**Implications of Physics for Society**

Physics is often considered to be the most fundamental of all sciences. In order to study biology, chemistry, or any other natural sciences, it is important to also have a firm understanding of the principles of physics. Advances in our knowledge of the physical world through the study of physics have important implications for mankind’s interactions with our terrestrial and celestial world.

Perhaps the greatest testimony of man’s achievement owing to scientific and technological advances is our exploration of space. Throughout history, mankind has exhibited a natural curiosity to explore and discover. Space exploration, driven by rapid advances in science and technology, has allowed Man to use space travel to discover the nature of the Universe beyond the Earth. In a short period of 12 years, from 1957 to 1969, Man advanced from launching the first artificial satellite Sputnik 1 to the Apollo 11 Moon mission, when for the first time in history, a human set foot on a celestial body (Worldbook@NASA, n.d.).

Current space projects such as the Hubble telescope and the International Space Station have also utilized our increasing knowledge in physics to extend our understanding of the Universe. The application of knowledge in Optics in each generation of space telescopes has allowed scientists to be able to gaze further into the Universe beyond the Earth, and further back in time, toward the beginning of the Universe. The International Space Station is a research facility placed in orbit around the Earth which enables scientists to conduct Microgravity clinical research on the human body in space. This research has the potential to help us endure long-term space travel and perhaps even build colonies in space in the future.
At the other extreme in scale in terms of space and time, Quantum Mechanics and Relativity theories have allowed us to explain new behaviours of matter at the nano-scale or subatomic scale. We now have the technology to manipulate inorganic and organic matter at the atomic level. Nano-science and nano-technology, although still in their infancy, promise to radically change almost all areas of society in the 21st Century, from materials to health care, transportation to energy sources, businesses, industries, and economies (Canton, 2001).

While our knowledge of physics has provided us with deep insights into the workings of the physical and natural world at the extremes in scale of space and time, it is the application of this knowledge through engineering that has led to the more visible dramatic changes in our lifestyles, in areas such as transportation, communication, machinery and tools.

However, applications of this knowledge have also been misused by Man in ways that have led to major implications on Mankind, notably in the building of weapons of mass destruction and the pollution of the environment from irresponsible use of resources in the production, distribution and use of energy. The challenge in teaching school physics therefore will be to educate our students on the discoveries and new knowledge in science and its innovative applications to improve our lives, and at the same time ensure that emphasis is given to recognise the need for ethical responsibility in the application of this knowledge for the benefit of Mankind.

**Current School Physics Curriculum**

*Physics topics*

The study of physics in primary and secondary schools may be grouped into four main themes: Mechanics, Thermal Physics, Electricity & Magnetism, and Waves. Topics include concepts and theories that were recognised and fairly well developed before the beginning of the 20th Century and serve as an important foundation for students in physics.

*Mechanics* is widely recognised as the oldest branch of physics. Using a careful process of observation and experimentation first developed by Galileo Galilei, physicists study an idealised system in which complicating factors (e.g., friction) are absent, and then transfer this understanding to describe and explain the motion of a real physical process with its complexities and subtleties. Newton's three laws of motion and his law of universal gravitation developed in the 17th Century form the basic concepts of mechanics which allow us to successfully explain and predict the motion of terrestrial as well as celestial objects. Important concepts in mechanics include speed, velocity, acceleration, force, gravitational field and energy transfer and conservation.

*Thermal Physics* or *Thermodynamics* is a branch of physics which studies and describes how systems respond to changes in their surroundings in terms of energy transfer, and the relationship between heat and mechanical work. Historically, thermodynamics sprang from a need to increase the efficiency of early steam engines used in transportation and industries. The concepts of thermodynamics are still widely applicable today in diverse fields such as engineering, electrical power generation, materials science and the study of biological organisms. Important concepts in thermal physics include temperature, heat (or thermal energy transfer), internal energy and the kinetic model of matter.

The study of *Electricity* and *Magnetism* focuses on the properties of particles at rest, and when they are in motion. For a long time, electricity and magnetism were seen as independent phenomena. The exact relationship between an electric current and the magnetic field it produced was deduced mainly through the work of Andre Marie Ampere. However, the final major discoveries in electromagnetism were made by two of the greatest names in physics, Michael Faraday and James Clerk Maxwell. Important concepts in electricity and magnetism include electric charge, current flow, resistance, potential difference, energy and power in electrical circuits, and electromagnetic induction.
The Waves section examines the nature of waves and its propagation, and the application of wave properties in everyday life such as in radio communication, home appliances, and medical and industrial use. Much of our understanding of wave phenomena today has been accumulated over the centuries through the study of light (optics) and sound (acoustics). The study of wave properties will provide an important foundation for the description of the behaviour and interactions of energy and matter at the atomic and subatomic scales. Important concepts in waves include frequency, wavelength, reflection, refraction and superposition.

In general, the physics theories and concepts introduced to students at the primary and secondary levels deal adequately with common observable physical phenomena and fall under a category of physics commonly known as Classical Physics. However, in the early 1900s, a number of revolutionary new concepts in physics were proposed to provide a more comprehensive theory (the quantum theory of matter) to explain nature at the atomic and subatomic level where the laws of classical physics generally do not hold true. Topics such as Quantum Physics, Semiconductors and Nuclear Physics form the section on Modern Physics at the pre-university level. The Modern Physics section introduces GCE A-level students to contemporary ideas in physics that move away from a completely deterministic worldview where nature is predictable, according to classical Newtonian mechanics, to a more uncertain and probabilistic worldview determined by Quantum mechanics, where we are restricted in our ability to know the state of a physical system and hence to predict its future.

Figure 2.1 shows the topics covered in the main sections of the Physics curriculum at the different levels. Shaded bullets indicate topic coverage at the Primary (Pri), Lower Secondary (LS), Upper Secondary (US), and Pre-University (JC) levels.
Physics Curriculum for the 21st Century

As we have moved a decade into the new millennium, governments around the world are acutely aware, more than ever, of the need to reform their education systems to prepare their citizens to meet the challenges of the 21st century. What new knowledge, skills and attitudes in physics do teachers need to imbue in their students in the 21st century? The answer can be culled from the quote below:

“Reading, math and science are the foundations of student achievement. But to compete and win in the global economy, today’s students and tomorrow’s leaders need another set of knowledge and skills. These 21st century skills include the development of global awareness and the ability to collaborate and communicate and analyse and address problems. And they need to rely on critical thinking and problem solving to create innovative solutions to the issues facing our world. Every child should have the opportunity to acquire and master these skills and our schools play a vital role in making this happen.”

- Michael Dell, CEO, Dell, Inc.
Partnership for 21st Century Skills, 2009, p. 4

21st Century Skills

Trilling and Fadel (2009) identified two skill sets that will be essential job requirements for 21st Century work: (1) the ability to quickly acquire and apply new knowledge and (2) the know-how to apply essential 21st Century skills such as problem solving, communication, teamwork, technology use, and innovation. The role of education in the knowledge age of the 21st Century will need to change to adapt to the increasingly powerful technologies we have for communicating, collaborating, and learning, as well as to the central role of life-long learning in our students’ lives.

How do we prepare our students for a globalised and technologically driven 21st Century world? In MOE’s Framework of 21st Century Competencies (MOE ‘Nurturing Our Young for the Future’) shared with schools in 2010, Values, Social and Emotional Competencies and 21st Century Skills were identified as key components (Figure 2.2) that are necessary to help our students thrive in the fast-changing world. In the Framework, the 21st Century Skills are depicted in the outer ring, with Values and Social and Emotional Competencies in the centre and second ring, respectively.

Figure 2.2 MOE’s Framework of 21st Century Competencies
The three essential 21st Century Skills in the Framework are:

- **Civic literacy, Global awareness and Cross-cultural Skills** – students need to have a broad worldview and be able to work with people from diverse cultures, with different ideas and perspectives. At the same time, they should be informed about national issues and contribute actively to the community.

- **Critical and Inventive Thinking** – students need to be able to think critically, assess options and make sound decisions. They should have a desire to learn and innovate, and not be afraid to face challenges.

- **Information and Communication Skills** – students need to be discerning in adopting ethical practices in cyberspace, and be able to sieve information and extract that which is relevant and useful. They should also be able to communicate their ideas clearly and effectively.

**Teaching and Learning Physics for the 21st Century**

In the 2003 report, Learning for the 21st Century (Partnership for 21st century skills, 2003), a few key elements for fostering 21st Century learning were identified. The key elements listed below provide a guide on what needs to be done to teach Physics for the 21st Century.

1. **Emphasis on core subjects**

   Knowledge and skills for the 21st Century must be built on core subjects such as Language, Math and Science, and must focus on understanding of the core content at a much higher level than basic competency.

   This implies that we will need to rebalance the coverage of content with the uncovering of ideas and concepts so that the nature of physics and the scientific processes can be made explicit to the students. The process of how knowledge is created, modified, discarded, and revised as part of a continual learning cycle needs to be emphasized so that students may emerge from their physics lessons with an appreciation of the body of knowledge in physics and of the dynamic inquiry processes involved in the generation of that knowledge.

2. **Emphasis on learning skills**

   To cope with the demands of the 21st Century, students need to know how to use their knowledge and skills such as thinking critically, applying knowledge to new situations, communicating, collaborating, solving problems and making decisions, as well as how to keep learning continually throughout their lives.

   With this emphasis, the challenge now is to incorporate learning skills into our classroom deliberately, strategically and broadly so that students will not only learn Physics, but will also acquire learning skills to enable them to acquire new knowledge and skills, connect new information to existing knowledge, develop habits of learning and working with others. This is to say that students need to have opportunities for self-directed experimentation as well as guided inquiry activities that will engage them in raising questions and designing and implementing investigations to verify their hypotheses and solve problems. Through the inquiry process, students learn important concepts, processes and habits of mind of science. They will also benefit from working and learning collaboratively with their peers, gain better confidence and motivation levels, and improved social interactions and feelings toward other students.
3. Use of 21st Century tools to develop learning skills

Students need to be proficient in ICT literacy. They should be able to use digital technology and communication tools to access, manage, integrate and evaluate information, construct new knowledge, and communicate with others in order to participate effectively in society.

For this, students need to have opportunities to use the Internet to access information and for communicating with others. ICT should also be used for students’ self-regulated and collaborative learning, and for collection, interpretation and presentation of their experimental results and theoretical conceptualization.

4. Teach and learn in a 21st Century context

Students need to learn academic content through real-world examples, applications and experiences both inside and outside of school. In a world where almost unlimited information is easily accessible, it is important to help students make meaningful connections between their school work and their lives outside the classroom so that they may be engaged and motivated about their learning.

The implication of this is that students need to develop coherent mental frameworks of their understanding in physics before they can apply their knowledge of physics to real-world contexts and to solve problems successfully. We will need to help students see the connections between ideas in Physics to support them in making links within the subject and with other disciplines in science. Students should also have opportunities to discuss the social, economic, technological, ethical and cultural influences and limitations that influence the applications of science in everyday contexts.

5. Use of assessments that measure and improve 21st Century skills:

A balance of summative assessments for accountability purposes and classroom (formative) assessments for improved teaching and learning is needed. Summative tests can measure only a few of the critical skills and knowledge that we want our students to learn, and alone do not provide the immediate diagnostic information that teachers and students need to improve learning.

This emphasis implies that we need a balance of summative and formative assessments that measure content knowledge, basic and higher-order thinking skills, deep understanding and application of knowledge, and 21st Century skills performance.

Due to the fundamental nature of physics, students often have difficulty understanding physics concepts and theories that are highly idealised and non-intuitive. Diagnostic assessments before or during instruction will provide teachers with information on students’ prior conceptions that may then be used to plan appropriate lessons and activities, and to address any misconceptions that the students may have. Besides, collaborative learning projects that deal with real-world problems, issues and questions may be used to provide opportunities for students to demonstrate their understanding and application of their knowledge in physics, and the 21st Century skills.
Physics Teachers’ Role in the 21st Century

Physics teachers face new demands to prepare students for the 21st Century. They need to re-examine and adapt their teaching practices to focus on developing students for a globalised, knowledge-based, digital, complex and rapidly changing world. Trilling and Fadel (2009) suggest that teachers should examine the range of teaching and learning practices on a balance (Figure 2.3), and decide how to rebalance their time between the left and right sides of the learning balance so as to provide students with learning experiences that can prepare them for the demands of the 21st Century.

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<tr>
<th>Teacher-directed</th>
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<td>Learning for school</td>
<td>Learning for life</td>
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Figure 2.3 21st Century Learning Balance (Trilling & Fadel, 2009, p. 38)

In Figure 2.3, the left side of the balance shows the traditional teaching practices hitherto. They do not adequately prepare our students for the demands of the 21st Century. However, swinging to the extreme right side of the balance will also not provide the best learning environment for students. Physics teachers therefore need to blend both the left and right sides in a good balance for the students. For example, to become competent in physics, students need to have learning experiences that develop their knowledge in the subject as well as the skills and processes involved in conducting investigations to explain and understand physical phenomena. Teachers will also need to balance their time between a teacher-directed approach (where they are the prime source of knowledge and motivation for student learning) and a learner-centred approach where students take a greater ownership of their learning, conducting guided and self-regulated inquiry and sharing of their ideas. Classroom teaching and learning practices need to focus not on content delivery by the teacher but on the student thinking and skills.

In addition to re-examining teaching practices, Trilling and Fadel (2009) strongly recommend that 21st Century teachers will also have to be expert in the same 21st Century skills that they are to develop in their students. To do this, physics teachers will need to systematically and formally advance their knowledge, skills and understanding in ways that will lead to changes in their thinking and classroom practices. This may be done through collaborating in learning teams to research and develop innovative student-centred teaching and learning practices, communicate and share resources and best practices on digital platforms, and continually upgrade their craft through professional development programmes and related opportunities.
Summary of Key Points

- Physicists hold a viewpoint that the universe and the physical world are ultimately explainable through theories and laws of physics.
- These theories are developed, tested and modified based on further observations or experiments to confirm or falsify them so as to build on the range of applicability of the existing theories.
- The advancement in our knowledge of the physical world through the study of physics has led to many important lifestyle changes in society, and in our interactions with the world.
- The topics in the primary and secondary physics curriculum introduce the fundamental concepts of Classical physics. Modern physics concepts, that move away from a completely deterministic worldview to a more uncertain and probabilistic worldview, are introduced at the pre-university level.
- Physics teachers will need to re-examine and adapt their teaching practices to better prepare students to face the new demands of a complex and rapidly changing 21st Century world.
“Teaching is more than imparting knowledge, it is inspiring change. Learning is more than absorbing facts, it is acquiring understanding.”

- William Arthur Ward

Chapter Overview

The goal of good teaching is ultimately to bring about successful learning. In order to do that, teachers must first have a better understanding of how students learn to be able to design effective instructional strategies to promote meaningful and deep learning. In this chapter, we begin by highlighting three theoretical perspectives with which we view learning. We then look at three principles of learning introduced in the How People Learn report that are particularly important for teachers to incorporate in their teaching. At the end of the chapter, we examine the use of conceptual change models in physics instruction to address students’ difficulties in learning physics.

Learning theories

There are broadly three theoretical perspectives with which people view learning: Behaviourism; Cognitivism; and Constructivism. Although the ideas from these three predominant views of learning appear to be different, teachers may gain valuable basic understanding from each of these perspectives about learning that will help to answer the question: “What should I do in my lessons to bring about successful learning?”

Behaviourism

Behaviourism is a view of learning that continues to be widely applied in schools, especially in the area of classroom management. Behaviourists explain learning in terms of observable behaviours and how they are influenced by stimuli from the environment. It defines learning as a relatively enduring change in observable behaviour that occurs as a result of experience (Schunk, 2004; Skinner, 1953 cited in Eggen & Kauchak, 2010). Three key concepts that are related to a behaviourist’s explanation of learning are:

1. Classical conditioning

Classical conditioning occurs when the learner learns (through the process of association) to produce an involuntary emotional or physiological response similar to an instinctive or reflexive response. In the classroom, a student may ‘learn’ to be nervous (an involuntary emotional response) when taking tests because of his experience (failure in a previous test). To elicit positive emotions in students, it is important for the teacher to create a safe and welcoming classroom environment, so that the classroom is associated with feelings of security.

2. Operant conditioning

Operant conditioning (mainly through the work of B.F. Skinner) describes learning in terms of observable voluntary responses that change in frequency or duration as a result of consequences, events that occur following behaviours. For example, a teacher’s praise after a student’s answer is a consequence that may increase the student’s motivation to try to answer other questions. Operant conditioning, in particular, is used as a classroom management tool.
3. Social cognitive theory

Social cognitive theory (mainly through the work of Albert Bandura) focuses on changes in behaviour that result from observing others. Social cognitive theorists view learning as a change in mental (cognitive) processes that creates the capacity to demonstrate different behaviours. So, learning may or may not result in immediate behavioural change. Classroom applications of the social cognitive theory include modeling desirable behaviours for students and cognitive modeling, which involves verbalizing our thinking as we demonstrate skills so as to share strategies with our students to promote learning.

Cognitivism

Cognitivism explains learning in terms of changes in the mental structures and processes involved in acquiring, organizing, and using knowledge (Royer, 2005; Sawyer, 2006 cited in Eggen & Kauchak, 2010). Unlike behaviourism that assumes a learner is essentially passive and merely responding to environmental stimuli, the cognitivist views the learner as an active participant, mentally processing in order to learn, and whose actions are a consequence of thinking. Knowledge is seen as schemas or symbolic mental constructions and learning takes place as change in a learner’s schema. According to Jean Piaget, this change may result from integrating new experiences or conceptual materials into an existing schema (termed assimilation) or, when this is not possible, a new schema is developed to adapt to the new experiences and conceptual materials (termed accommodation).

Two key ideas in a cognitivist’s explanation of learning are (1) information processing, and (2) meaningful learning.

1. Information processing

Information processing uses the metaphor of the mind as a computer, with input, processing and output stages occurring in the mind. While cognitive learning theorists do not totally agree on the structure of human memory, most use a model as in Figure 3.1 (initially proposed by Atkinson & Shiffrin (1968)). The model of human memory consists of three major components: memory stores (repositories that hold information), cognitive processes (processes that move information from one store to another) and metacognition.

![Figure 3.1 Model of human memory adapted from Eggen & Kauchak, 2010](image)
The three memory stores are:

1. **Sensory memory** - the store that briefly holds incoming stimuli from the environment until they can be processed. Though nearly unlimited in capacity, the memory trace in sensory memory quickly fades away if processing does not begin almost immediately.

2. **Working memory** - the store that holds information as the individual processes and tries to make sense of it. It is where “conscious” thinking occurs, and where knowledge is constructed. We are not aware of the contents of either sensory memory or long-term memory until they are pulled into working memory for processing. However, the working memory is limited in its mental activity capacity (can hold about seven items of information at a time for 10-20 sec).

3. **Long-term memory** - the permanent information store which can be retrieved for reference and use. Long-term memory capacity is vast (almost limitless) and enduring. We form schemas (mental constructs) which organise information into meaningful systems in long-term memory.

The cognitive processes involved in the memory model are:

- **Attention** - the process of consciously focusing on a stimulus. Our attention acts as a screen, allowing us to filter out unimportant information. Attention is limited, both in capacity and duration. Attention easily shifts from one stimulus to another (people are generally easily distracted).

- **Perception** - the process people use to find meaning in stimuli (the way we interpret objects and events). As people’s perception is constructed, it differs from one person to another, depending on a person’s disposition, belief and prior knowledge.

- **Encoding** - the process of representing information in long-term memory, either visually (images) or verbally.

- **Retrieval** - occurs when learners pull information from long-term memory back into working memory for further processing. Forgetting is the loss of, or inability to retrieve information from long-term memory.

- **Rehearsal** is the process we use to retain information in the working memory until it is used or forgotten. If rehearsed enough, this information can be transferred to long-term memory (rote learning). Rehearsal is an inefficient encoding strategy, however, because the information in long-term memory exists in isolation, not connected to other information and therefore lacks meaningfulness.

**Metacognition** is our awareness of and control over our cognitive processes. Metacognition helps a learner to:

- be aware of the importance of attention and the need to create effective personal learning environments;

- be aware of the possibility of misperceptions and the need to find corroborating information or check his understanding;

- regulate the flow of information through working memory. The ability to monitor the processing of information in the working memory is essential because of its limited capacity; and

- ensure meaningfulness of encoding. The learner who is metacognitive about his encoding consciously looks for relationships in the topics he studies.
2. Meaningful learning

It is well established that meaningful learning is more effective than rote learning (learning that involves acquiring isolated pieces of information, mostly through memorisation). By learning through making connections to existing schemas, the information acquired becomes interconnected ideas rather than isolated pieces, and is organised into meaningful systems in long-term memory. Strategies that support meaningful encoding of information include:

- **Imagery** - the process of forming mental pictures of an idea. According to the dual-coding theory, long-term memory consists of two memory systems: one for verbal information, and another for images. This implies that information is more meaningfully encoded when it can be represented both verbally as well as visually.

- **Organisation** - an encoding strategy that involves the clustering of related items of content into categories that illustrate relationships. Through well-organised content, cognitive load is decreased and encoding (and subsequent retrieval) is more effective. Research indicates that experts learn more efficiently than novices because their knowledge in long-term memory is better organised, allowing them to access it and connect it to new information.

- **Schema activation** - an encoding strategy that involves activating relevant prior knowledge so that new knowledge can be connected to it. This helps learners to form conceptual bridges between what they already know and what they are to learn.

- **Elaboration** - an encoding strategy that increases the meaningfulness of new information by connecting it to existing knowledge. Elaborative strategies include the use of examples, analogies and mnemonics.

**Constructivism**

Constructivism is a view of learning that sees the learner as a constructor, rather than a receiver of knowledge - learners create their own knowledge of the topics they study rather than record knowledge transmitted to them by another source, such as another person or something they read (Bransford, Brown, & Cocking, 2000 cited in Eggen & Kauchak, 2010). There are two primary perspectives of constructivism: (1) cognitive constructivism, and (2) social constructivism.

1. **Cognitive constructivism** (mainly through the work of Jean Piaget) focuses on individual, internal constructions of knowledge. It emphasises individuals’ search for meaning as they interact with the environment and test and modify existing schemas. Piaget described a person’s intrinsic need for understanding, order, and certainty as the drive for equilibrium - if we can explain new experiences, we remain at equilibrium; if we can’t, our equilibrium is disrupted, and we are motivated to re-establish it. When our understanding advances as a result of regaining equilibrium, development or learning occurs.

2. **Social constructivism** has become the view of learning most influential in guiding the thinking of educators today. This view, grounded in Vygotsky’s social development theory, suggests that learners first construct knowledge in a social context and then individually internalise it. Two key ideas in social constructivism are zone of proximal development and cognitive apprenticeship.

The Zone of Proximal Development (ZPD) described by Vygotsky, is the distance between a learner’s ability to perform a task with guidance by a more knowledgeable other (such as a teacher or a parent) and/or with peer collaboration and the learner’s ability to solve the problem independently. According to Vygotsky, learners must be in the zone to benefit from assistance provided by more knowledgeable others and for learning to take place.
Cognitive apprenticeship is a strategy where less-skilled learners work at the side of experts in developing cognitive skills. Processes involved in cognitive apprenticeship commonly include:

- **Modeling** – teachers demonstrate skills, such as problem solving, and simultaneously model their thinking aloud.

- **Scaffolding** – teachers ask questions and provide support, decreasing the amount of scaffolding as students’ proficiency increases.

- **Verbalisation** – teachers encourage students to express their developing understanding in words, so as to gain insights into their students’ thinking.

- **Increasing complexity** – teachers present students with more challenging problems or tasks as their students’ proficiency increases.

- **Exploration** – teachers ask students to identify and apply their skills to relevant problems and new situations.

How People Learn

The learning theories from research in the cognitive and developmental sciences in recent decades have provided invaluable insights into how the brain works and its immense capacity to learn and functionally reorganize, encode and retrieve information. Undoubtedly, learning about how students learn, how they remember, and also why they forget should be fundamental knowledge that all teachers should have and be able to use to design effective teaching strategies to promote deep learning.

In its report in 1995, published as *How People Learn: Brain, Mind, Experience, and School*, the National Research Council (NRC) attempted to synthesize developments in human learning research and to evaluate and make recommendations on the use of this research to enhance learning in schools. In the report, the authors established the scientific rationale for their recommendation of core educational principles which they organized around a central set of three principles about learning, and how these principles should be applied in education.

**Three principles of learning**

The *How People Learn* report highlighted three fundamental and well-established principles of learning that are particularly important for teachers to understand and be able to incorporate in their teaching (Bransford, Brown, & Cocking, 2000; Bransford & Donovan, 2005).

1. Students come to the classroom with preconceptions about how the world works which include beliefs and prior knowledge acquired through various experiences. If their initial understanding is not engaged, they may fail to grasp the new concepts and information, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom.

2. To develop competence in an area of inquiry, students must: (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application.

3. A “metacognitive” approach to instruction can help students learn to take control of their own learning by defining learning goals and monitoring their progress in achieving them.
Principle 1: Engaging prior understandings

New understandings are constructed on a foundation of existing understandings and experiences.

It is important as teachers to note that while students’ prior knowledge helps them in learning new concepts, they may also be hampered by them. For example in physics, students’ difficulties in understanding the law of inertia and the concept of force are largely due to their deep rooted preconceptions and experiences of the behaviour of objects in everyday life that appear to need a continual force acting on the objects to continue moving.

Preconceptions, such as the example given, are developed from everyday experiences from young and are often difficult for teachers to change because they generally work well enough in the students’ everyday context. If students’ preconceptions are not addressed directly, they often memorize content and formulae in physics, and revert to their untrained and often erroneous models of understanding when attempting to apply their knowledge to tasks presented to them. Doing well in classroom exams is also no guarantee that students have developed a functional understanding of the concepts.

Principle 2: Essential role of factual knowledge and conceptual frameworks in understanding

Learning with understanding affects our ability to apply what is learned.

To be able to achieve functional understanding in the subject (i.e. the ability to apply relevant concepts in situations and explain their reasoning), students need both a strong factual knowledge of the subject as well as a coherent framework of understanding of concepts. Neither factual nor conceptual understanding alone is sufficient. Concepts can only take on significant meaning when placed in related contexts in which they are applied. For example in physics, the abstract concept of density can be made more meaningful to students when it is related to the observable context of objects floating and sinking in fluids of different relative densities.

Studies of experts in their fields demonstrate that they know considerably more relevant detail than novices in tasks within their domain and have better memory for these details. But the reason they remember more is that what novices see as separate pieces of information, experts see as organized sets of ideas. This essential link between the factual knowledge base and a conceptual framework underscores the importance for students to understand the important organizing ideas or “big ideas” in physics together with a deep factual knowledge of the subject in order to facilitate retrieval and application.

Principle 3: Importance of self-monitoring

Self-monitoring is an important component of effective learning.

“Metacognition” refers to people’s knowledge about themselves as information processors - this includes knowledge about what we need to do in order to learn and remember information, and the ability to monitor our current understanding to make sure we understand. In the physics classroom, even the best instructional efforts can be successful only if the students are themselves active participants in learning. Teachers therefore need to help their students develop the ability to take control of their own learning, consciously define learning goals, and monitor their progress in achieving them. Students should be engaging in self-explanation as they solve problems, and in self-assessment where they are provided opportunities to test their ideas by performing experiments and to justify their conclusions to others.
Motivation to learn

In addition to the three principles of learning presented in the *How People Learn* report, research highlights learners’ motivation as a key factor influencing both successes in learning in school and in test performance. Motivation is often classified into *extrinsic motivation* and *intrinsic motivation*. *Extrinsic motivation* is motivation to engage with an activity as a means to an end (e.g. studying to achieve a good grade in a test), whereas *intrinsic motivation* is motivation to be involved in an activity for its own sake (e.g. studying to understand the content). Both categories of motivation need not be mutually exclusive.

While teachers may want students to be intrinsically motivated (all day and everyday), it is more realistic for teachers to seek to motivate student learning through providing meaningful and relevant learning experiences that will benefit them and sustain their motivation to learn. Eggen and Kauchak (2010) noted that research has found that learners are more motivated to learn when their experiences:

- Present a challenge – challenge occurs when the goals are moderately difficult to attain. Learners find meeting challenges emotionally satisfying.

- Evoke curiosity – learners are motivated by novel, surprising or unexpected events and experiences.

- Involve creativity and imagination – creative tasks allow learners to personalise their learning and use their imagination.

- Promote learners’ feelings of autonomy – learners are more motivated when they find they are in control of their own learning.

Student learning difficulties and misconceptions in Physics

*Conceptual change*

Physics is the domain of science in which most research studies on investigating students’ conceptions and on conceptual change have been carried out. One major reason for this dominance of physics in the research on teaching and learning science is students’ difficulties in learning physics due to the abstract and highly idealized nature of physics.

Often in physics, abstractions and idealizations are made in order that the complexities of real world phenomena may be greatly reduced to make quantitative predictions possible. Physics thinking therefore usually does not originate from the minute observations of the world around us but from the reconstruction of this world under the assumption of theories and principles. This shift in perspective is a major factor that makes it difficult for students to learn physics.

Research on students’ preconceptions that they bring to the classroom suggest that often, students’ ideas are incompatible with the physics concepts and principles to be achieved and these preconceptions, which students have relied on to understand and function in their world, are highly resistant to change. Thus, simply presenting new concepts or correcting students’ less scientifically useful ways of thinking simply by telling, often does not bring about conceptual change. As a result of this concern, researchers began to focus their attention on developing a theoretical model of learning to influence changes in students’ concepts.

In 1982, Posner, Strike, Hewson and Gertzog developed a conceptual change model which forms the foundation of many of the current conceptual change practices. Posner *et al* identifies the learner becoming *dissatisfied* with an
existing conception as a critical prerequisite condition to initiate a radical conceptual change. Thus, a key component for conceptual change is for learners to experience a cognitive conflict or disequilibrium, where they are presented with a problem that they come to realise cannot be solved using their existing conception, creating in them a feeling of dissatisfaction and a need for accommodation.

In addition, the model introduces three further conditions which may allow a learner to accommodate the new replacement conception. The replacement conception must be sensible and understandable by the learner (intelligible), believable (plausible), and useful in solving other problems (fruitful). This early model was later refined to take in other affective (e.g. motivation, values, interests) and social (e.g. learning from others) issues as factors that influence a learner’s conceptual change. Thus, it was recognised that conceptual change is not solely influenced by cognitive factors. Affective, social, and contextual factors also contribute to conceptual change, and must be taken into account when teaching for conceptual change.

Teaching and learning approaches to address students’ needs

Davis (2001) noted that although there are a number of models and strategies developed using cognitive conflict as the basis for teaching for conceptual change, they share a similar structure to the conceptual change teaching strategy proposed by Nussbaum and Novick (1982). That is:

1. Reveal student preconceptions

Students often are not conscious of their own preconceptions concerning physical phenomena (be it correct or incorrect). Thus, the first step to teaching for conceptual change is to make students aware of their own ideas about the topic or phenomenon under study. This may be achieved by eliciting students’ interpretations and explanations of relevant ‘exposing’ events that require them to use their existing conceptions. Students can represent their ideas in many ways such as writing descriptions, drawing illustrations, creating physical models or drawing concept maps to indicate their understanding of a particular concept. Regardless of the method, the goal is to help students recognize and begin to clarify their own ideas and understandings. Once students’ conceptions are made explicit, teachers can use them as the basis for further instruction.

2. Discuss and evaluate preconceptions

Students clarify and revise their original conceptions through group and whole-class discussions. Whole class discussions is preferred if students are new to conceptual change activity. Such discussions allow the teacher to model the evaluation process before students evaluate each other’s ideas in smaller groups. The teacher begins by leading the class in evaluating some students’ conceptions in terms of its intelligibility, plausibility, and fruitfulness in explaining the exposing event. Students then work in pairs or groups to evaluate each other’s ideas and present their rationale for selecting the conception which they think best explains the exposing event.

3. Create conceptual conflict with those preconceptions

As students become aware of the inadequacy of their own conceptions in comparison with alternative conceptions of their peers (or ‘planted’ conceptions by the teacher) in explaining the exposing event, they begin to become dissatisfied with their own ideas and are more open to changing them. To create greater conflict, the teacher may introduce a discrepant event. The discrepant event is a phenomenon or situation that cannot be explained by the students’ current conceptions but can be explained by the concept that is the topic of instruction.
4. Encourage and guide conceptual restructuring

A safe learning environment is necessary to support students in reflecting on their ideas and sharing of their viewpoints as they consider and evaluate other perspectives. This is especially important for low achieving students as they may experience a loss of self-confidence, viewing the conflict as another failure. Eventually, through the teachers’ careful managing of group discussions and facilitation of self-inquiry, students are guided to reconcile any differences between their conceptions and the target theory.

Physics instruction should build on the insights about learning and focus on issues of conceptual change as a major goal. Understanding scientific knowledge often requires a change in, not just an addition to, what people notice and understand about everyday phenomena. Traditional instruction that does not explicitly address students’ everyday conceptions typically fails to help them refine or replace these conceptions with others that are scientifically more accurate. Teachers need to explore new ways to engage students in learning physics and support them in their steps of personal meaning-making in order to come to terms with the scientific viewpoint.

### Summary of Key Points

- There are broadly three theoretical perspectives with which people view learning: *Behaviourism*; *Cognitivism*; and *Constructivism*. These views of learning provide teachers with valuable basic understanding about learning that will help in the design of instruction to bring about successful learning in physics.
- Three principles of learning are identified in the *How People Learn* report as: (1) *Engaging prior understandings* - new understandings are constructed on a foundation of existing understandings and experiences; (2) Essential role of *factual knowledge* and *conceptual frameworks* in understanding - learning with understanding affects our ability to apply what is learned; and (3) Importance of *self-monitoring* for effective learning.
- In addition to the three principles of learning, research highlights learners’ *motivation* as a key factor influencing both successes in learning in school and in test performance.
- Students often have very strongly held pre-instructional conceptions about physical phenomena that were developed from childhood from their everyday experiences. To correct their misconceptions, students will need to be given opportunities to make a *conceptual change* in the way they view the phenomena.
What does learning physics entail? From the perspective of social semiotics, learning science means “learning to communicate in the language of science” (Lemke, 1990, p. 1). Over the course of history, a particular system of language tools in the form of linguistics, gestures, graphics and mathematical symbols has been constructed to aid members of the physics community to communicate effectively and meaningfully with one another about the world’s objects and processes. Learning physics, thus, entails a meaning-making process whereby learners are involved in identifying things and processes which the abstract symbols or patterns of symbols represent in our everyday life. This process goes beyond mere repetition of words or other forms of representation (e.g. velocity is the rate of change of displacement or $\Delta s/\Delta t$) to say its equivalent. Rather, you can imagine the process involving movement along a ladder; let’s call it an abstraction ladder whereby the top of the ladder represents abstract scientific signs and symbols and the bottom represents worldly objects and processes. See Figure 3.2 for an illustration of this process.

According to Hayakawa & Hayakawa (1990), science meaning-making is like moving down the abstraction ladder to know what object or operations the symbols stand for in the physical world (Hayakawa & Hayakawa, 1990). Therefore, making sense of the scientific language must involve a downward movement towards concretizing the connections between symbols and the physical world. This perspective suggests that science learning should be a deductive process. Traditionally, this is how science has been taught. Abstract and generalized physics concepts and laws (e.g., force and Newton’s laws) are presented first followed by concrete examples shown to the students. Such didactic instruction, which is often confined within the four walls of a classroom, tends to neglect the need for first-hand experience with the phenomenon in meaning-making. Instead, students are passively taking in all the “knowledge” that is diligently and creatively delivered by the teacher. This mode of instruction is often criticized for its shallow construction of knowledge, which seldom goes beyond recall and application in well-structured problems typically found at the end of a book chapter.

Another perspective of science meaning-making follows a Piagetian tradition which draws on the belief that generality of a concept comes from abstracting from something concrete (Roth & Hwang, 2006). Hence, concrete manipulable materials (e.g., puck and air-track) were provided for students to explore in the belief that generalizations of the phenomenon could be abstracted. Learning physics is thought of as an upward movement from concrete to abstract as students’ experiences with the phenomenon help to develop an interpretation of the scientific language.

The tension between the deductive and inductive approaches to science meaning-making could perhaps be resolved by drawing upon Vygotsky’s idea of development of scientific conception. Vygotsky (1986) saw science meaning-making not as a one-way movement from abstract to concrete or vice versa; but a dialectical movement between concrete and abstract. Vygotsky (1986) claimed that the two processes are closely connected as “in working its slow way upward, an everyday concept clears a path for the scientific concept and its downward development. ... Scientific concepts, in turn, supply structures for the upward development of the child’s spontaneous concepts toward consciousness and deliberate use” (p. 194). In this sense, the abstract nature of scientific concepts and the contextual, empirical and practical nature of everyday processes can act as co-supports for
their eventual growth towards each end of the abstraction ladder. In other words, a science learning environment should provide for the dialectical downward movement from abstraction towards concretization and the upward movement from concretization to abstraction, rather than separate processes of shifting from one end to the other. Such a dialectical perspective takes into account the situated nature of knowledge and thus is consistent with contemporary learning theories such as situated learning (Lave & Wenger) and situated cognition (Brown, Collins & Duguid, 1989).

![Abstraction Ladder Diagram](image)

**Figure 3.2 The abstraction ladder (adapted from Yeo, Tan & Tang, 2006)**

“Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. Students need repeated practice in interpreting physics formalism and relating it to the real world”.

- Lillian McDermott, 2001

Chapter Overview

This chapter establishes the importance of teaching science as an inquiry. Teaching science as an inquiry is not only a means to learn the science content but also an end in itself to equip students with the science processes and thinking necessary to discover and evaluate new knowledge. Indeed, the way we understand how science works and the nature of science will impact how we plan and teach science in the classroom. The chapter goes on to describe some models of science teaching that are consistent with the view of teaching science as an inquiry. These models are usually based on a learning cycle that provides a framework to plan, teach and assess a unit of instruction. Lastly, specific instructional strategies, including the use of ICT, that help support inquiry-based science are outlined. The chapter ends with a list of references to physics curriculum materials with instructional models or strategies based on physics education research.

Science as Inquiry

Teaching science as inquiry taps on the learner’s innate curiosity and desire to answer a question or solve a problem relating to science. More specifically, scientific inquiry refers to the activities and processes scientists engage in to study the natural and physical world around us. It may be seen as essentially consisting of two critical aspects: the what (content) and the how (process) of understanding the world we live in.

The inquiry approach to science instruction is aligned with the activities and processes scientists engage in: focusing on scientific theories and models, asking researchable questions, generating hypotheses, gathering information, presenting evidence, and forming arguments. Hence a major feature of science instruction should include opportunities that allow students to think, investigate and argue about evidence and ideas in science. Teaching science as inquiry is also consistent with constructivist beliefs, where students are challenged to form deep understandings about natural phenomena by engaging in the construction of scientific knowledge through an active process of investigation.

Other than being an approach to science instruction to help students develop conceptual understanding, science as inquiry should also be seen as a goal in itself. Students learn the skills and processes of inquiry in the context of learning science and develop epistemological understandings about the role of scientific evidence and how science works. In this way, students are better equipped to make informed judgments about various scientific knowledge claims and their applications.
In short, engaging students in inquiry helps students to develop:

- An understanding of scientific concepts, principles, laws and theories
- An appreciation of how we know what we know in science
- An understanding of the nature of science
- Skills necessary to become independent inquirers about the natural world
- The dispositions to use skills, abilities and attitudes associated with science
- A grasp of applications of science knowledge to society and personal issues

At a philosophical level, inquiry-based instruction is more than just following a set of procedures but is an orientation (i.e. a set of knowledge and beliefs) that guides curriculum design and the way we teach science in school. Indeed all our national science syllabuses are underpinned by the Science Curriculum Framework, which encapsulates the thrust of science education in Singapore to prepare our students to be sufficiently adept as effective citizens, able to function in and contribute to an increasingly technologically-driven world. Central to the framework is science as an inquiry, where inquiry is seen as:

- A goal for the science learner
- An orientation to science teaching that drives the curriculum design whereby the practice of science as an inquiry is founded on three integral domains of (a) Knowledge, Understanding and Application, (b) Skills and Processes and (c) Ethics and Attitudes.
- An instructional approach where teachers play the role of leaders of inquiry, nurturing students as inquirers through activities and processes that are grounded in the knowledge, issues and questions that relate to the roles played by science in daily life, society and the environment.

![Figure 4.1 The Science Curriculum Framework.](image-url)
Essential Features of Inquiry

The National Science Education Standards has outlined five essential features of inquiry-based science, which informs good science teaching:

1. Learner engages in scientifically oriented questions
2. Learner gives priority to evidence in responding to questions
3. Learner formulates explanations from evidence
4. Learner connects explanations to scientific knowledge
5. Learner communicates and justifies explanations

It is important to realise that inquiry-based teaching in the classroom represents a continuum of strategies, as can be seen from Table 4.1. Understanding the different aspects of inquiry can help teachers vary the types of teaching and learning experiences to better meet the needs of their science students. Typically, teachers can start using a more structured, teacher-directed inquiry and work up to variations of inquiry that are more open and student-directed. In this way, both teachers and students become accustomed to doing inquiry in an incremental way and gradually build up their confidence and skills to conduct increasingly student-directed inquiry.

Table 4.1  Adapted from the National Research Council (2000).

<table>
<thead>
<tr>
<th>Essential Feature</th>
<th>Variations Of Inquiry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Key features of inquiry</strong></td>
<td><strong>More</strong></td>
</tr>
<tr>
<td>Learner engages in scientifically oriented questions</td>
<td>Learner poses a question</td>
</tr>
<tr>
<td>Learner gives priority to evidence in responding to questions</td>
<td>Learner determines what constitutes evidence and collects it</td>
</tr>
<tr>
<td>Learner formulates explanations from evidence</td>
<td>Learner formulates explanation after summarizing evidence</td>
</tr>
<tr>
<td>Learner connects explanations to scientific knowledge</td>
<td>Learner independently examines other resources and forms the links to explanations</td>
</tr>
<tr>
<td>Learner communicates and justifies explanations</td>
<td>Learner forms reasonable and logical argument to communicate explanations</td>
</tr>
</tbody>
</table>
Models of Science Teaching

Models of instruction involve some arrangement of phases, steps, actions, or decision points for teaching and learning. They provide a framework to guide planning, teaching and assessment. Different instructional models in science build on different points of view about the nature of inquiry, processes of science, scientific knowledge and understanding, and goals of science learning. They also incorporate different principles from research on learning and development.

Learning Cycle Model

The Learning Cycle Model (Atkin & Karplus, 1962), an earlier model that guided teachers in the implementation of inquiry-based instruction, consisted of three phases: exploration, invention and application. The exploration phase provides learners with firsthand experiences to investigate science phenomena, often through laboratory experiments. The conceptual invention phase then allows learners to build science ideas through interaction with peers, texts, and teachers, which involves mainly inductive thinking. Finally, in the application phase, the learner is given the opportunity to explore the usefulness of the ideas and apply them to a new context, which involves mainly deductive thinking.

![Learning Cycle Model Diagram](image)

The exploration-invention-application learning cycle was derived from Piaget’s model of mental functioning as seen from Table 4.2 (Marek & Cavallo, 1997). The first phase of the learning cycle, exploration, is designed to cause students to assimilate data and eventually reach a state of disequilibrium. In other words, students gather data, look for trends or relationships in the data, and, from this, they become disequilibrated. The next phase, concept invention or development, is structured to lead students through the interpretation of their data, construction of the concept, and accommodation to the concept, which results in reequilibration. The elaboration phase is designed to give students opportunities to organize their newly learned concept with other concepts they already know.

<table>
<thead>
<tr>
<th>Mental Functioning</th>
<th>Learning Cycle Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assimilation → Disequilibrium</td>
<td>Exploration</td>
</tr>
<tr>
<td>Accommodation (Reequilibration)</td>
<td>Concept Development (Explanation)</td>
</tr>
<tr>
<td>Organization</td>
<td>Elaboration</td>
</tr>
</tbody>
</table>
A popular version of the learning cycle is the BSCS 5E Model: engagement, exploration, explanation, elaboration, and evaluation (Bybee et al., 2006). It incorporates the three original learning cycle phases while adding two more. At the beginning of the cycle, the engagement phase is an opportunity for the teacher to capture student attention and uncover their prior knowledge. While listed as the fifth phase, the evaluation phase is typically embedded throughout the cycle, providing opportunities to assess students’ progress both formatively and summatively. Table 4.3 gives a brief description of the purpose of each phase of the cycle.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engage</td>
<td>Create interest and stimulate curiosity, raise questions, reveal student ideas and beliefs, compare students’ ideas</td>
</tr>
<tr>
<td>Explore</td>
<td>Experience the phenomenon or concept, explore questions and test students’ ideas, investigate and solve problems</td>
</tr>
<tr>
<td>Explain</td>
<td>Compare ideas, introduce definitions and concept names, construct explanations and justify them in terms of observations and data</td>
</tr>
<tr>
<td>Elaborate</td>
<td>Use and apply concepts and explanations to new contexts, reconstruct and extend explanations to new contexts</td>
</tr>
<tr>
<td>Evaluate</td>
<td>The teacher looks for evidence of changes in students’ ideas, beliefs and skills, students review and evaluate their own learning</td>
</tr>
</tbody>
</table>

The modeling method of physics instruction introduced by Wells, Hestenes, and Swackhammer (1995) is another extension of the learning cycle. A central feature of the modeling method (as described more fully at http://modeling.asu.edu/) is the construction and application of conceptual models or scientific representations that help describe, explain, and predict physical phenomena. Instruction is organized into modeling cycles and involves both model development (which encompasses the exploration and term introduction phases) and model deployment (which corresponds to the concept application phase).
Table 4.4 Modeling Cycle Example: The Constant Velocity Model (Jackson, et al., 2008)

I. Model Development (Paradigm Lab)

A Pre-lab discussion
Students observe battery-powered vehicles moving across the floor and describe their observations. The teacher guides them toward a laboratory investigation to determine whether the vehicle moves at constant speed, and to determine a mathematical model of the vehicle’s motion.

B Lab investigation
Students collect position and time data for the vehicles and analyze the data to develop a mathematical model. (In this case, the graph of position vs. time is linear, so they do a linear regression to determine the model.) Students then display their results on small whiteboards and prepare presentations.

C Post-lab discussion
Students present the results of their lab investigations to the rest of the class and interpret what their model means in terms of the motion of vehicle. After all lab groups have presented, the teacher leads a discussion of the models to develop a general mathematical model that describes constant-velocity motion.

II. Model Deployment

A Worksheets
Working in small groups, student complete worksheets that ask them to apply the constant-velocity model to various new situations. They are prepare whiteboard presentations of their problem solutions and present them to the class. The teacher’s role at this stage is continual questioning of the students to encourage them to articulate what they know and how they know it, thereby correcting any lingering misconceptions.

B Quizzes
In order to do mid-course progress checks for student understanding, the modeling materials include several short quizzes. Students are asked to complete these quizzes individually to demonstrate their understanding of the model and its application. Students are asked not only to solve problems, but also to provide brief explanations of their problem-solving strategies.

C Lab Practicum
To further check for understanding, students are asked to complete a lab practicum in which they need to use the constant-velocity model to solve a real-world problem. Working in groups, they come to agreement on a solution and then test their solution with the battery-powered vehicles.

D Unit Test
As a final check for understanding, students take a unit test. (The constant-velocity unit is the first unit of the curriculum. In later unit tests, students are required to incorporate models developed earlier in the course into their problem solving; this is an example of the spiral nature of the modeling curriculum.)

The first stage – model development – typically begins with a demonstration and class discussion. This establishes a common understanding of the question to be investigated. Students then collaborate in planning and conducting experiments, followed by presenting and justifying their conclusions, based on the formulation of a model for the phenomena in question and an evaluation of the model by comparison with data. Technical terms and representational tools are introduced by the teacher as they are needed to sharpen models, facilitate modeling activities, and improve the quality of discourse.

During the second stage – model deployment – students apply their newly-discovered model to new situations to refine and deepen their understanding. Students work on challenging worksheet problems in small groups, and then present and defend their results to the class. This stage also includes quizzes, tests, and lab practicums. An example of the entire modeling cycle is outlined in Table 4.4 (Jackson, et al., 2008).

Models and Multiple Representations

We can think of a model as a representation of an object, event or idea. This representation creates a vehicle through which the object, event or idea can be conceptualised and understood. Commonly accepted ideas regarding models include (Etkina et al., 2006):

- a model is a simplified version of an object or process under study; the scientist creating the model decides what features to neglect;
- a model can be descriptive or explanatory; explanatory models are based on analogies - relating the object or process to a more familiar object or process;
- a model needs to have *predictive* power;
- a model’s predictive power has *limitations*.

Examples of models of physical phenomena include (a) descriptive particle models in kinematics: one-dimensional translational motion of objects with constant velocity and objects with constant acceleration, (b) explanatory particle models in forces and dynamics: free particle model and constant force particle model, and (c) the various models of light: ray model, wave model and photon model.

External representations that range from concrete to abstract forms – pictures, diagrams, words, graphs and equations – are often used in understanding and modelling real world physical phenomena. The general consensus from research indicates that multiple representations play an important role in student learning by facilitating the acquisition of knowledge and guiding in problem solving. A learner equipped with thinking in more than one representation is able to reason more flexibly when learning new material or solving a problem.

However, learners need to be orientated to the format of the representation and understand how the representation relates to the specific topic it is representing (see Table 4.5 for typical visual representations that are associated with specific topics). Additionally, learners have to be able to interpret given representations, construct the representations themselves and be given opportunities to translate between different representations and the real world.

Table 4.5  Typical visual representations associated with specific physics topics.

<table>
<thead>
<tr>
<th>Physics Topics</th>
<th>Visual Representations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematics</td>
<td>Motion diagrams</td>
</tr>
<tr>
<td>Forces &amp; Dynamics</td>
<td>Free-body diagrams</td>
</tr>
<tr>
<td>Energy</td>
<td>Energy bar charts</td>
</tr>
<tr>
<td>Field</td>
<td>Field line diagrams</td>
</tr>
<tr>
<td>Electric circuits</td>
<td>Electrical circuit diagrams</td>
</tr>
<tr>
<td>Geometrical optics</td>
<td>Ray diagrams</td>
</tr>
<tr>
<td>Waves</td>
<td>Wavefront diagrams</td>
</tr>
<tr>
<td>Quantum Physics</td>
<td>Energy level diagrams</td>
</tr>
</tbody>
</table>

Effective science instruction therefore depends, in part, on the teacher’s expertise in representing scientific knowledge in ways appropriate to a particular group of learners. In particular, the modelling instruction method discussed previously stresses developing a sound conceptual understanding through graphical and diagrammatic representations before moving on to an algebraic treatment of problem solving. For example, the motion of a car can be described using various representations, as depicted in Figure 4.3 (Heuvelen & Zou, 2001).
Strategies that Support Inquiry-Based Instruction in Science

Questioning

Perhaps the single most powerful tool in a teacher’s repertoire is questioning. Effective teachers use their questions to elicit and probe student thinking, not just to get the right answers. In addition, classroom dialogue enables students to articulate their ideas and listen to other viewpoints. The default teacher-student conversation pattern known as IRE (initiate-respond-evaluate) consists of the teacher asking a question, the students answering it, and the teacher evaluating the student’s answer. The teacher typically asks a closed question that is information-seeking, requiring a predetermined short answer, and that is usually pitched at the recall or lower order cognitive level. The IRE style of questioning does not foster discussion and higher order thinking.

Instead, a more productive model of classroom interaction in science consists of IRF (initiate-respond-feedback) chains, as depicted in Figure 4.4 (Chin, 2006). Unlike teacher questioning in traditional lessons where the main purpose is to evaluate what students know, the nature of questioning in constructivist-based or inquiry-oriented lessons is different. Three related sets of purposes underlying teachers’ utterances during the initiation and feedback moves in facilitative IRF iterations have been identified: (a) Draw out, (b) Cue and Provoke (c) Reinforce. In the initiation moves, the set termed Draw out consists of teacher questions that aim to elicit, probe, and extend students’ thinking. These work in tandem with Cue and Provoke where questions are designed to clarify, prompt, and challenge students’ responses. As for the feedback move, teachers’ utterances that affirm, restate, and consolidate students’ correct ideas have the overarching purpose of reinforcing the key scientific concepts involved in the lesson. The solid arrows in the diagram depict the two-way interaction between the initiation and feedback moves which are often closely linked. As teacher evaluation is central to the teaching exchange and was observed to be typically neutral and covert in nature, it is placed in the middle of the diagram and linked to the other purposes by dotted lines.
Active Learning

Active learning is anything course-related that all students in a class session are called upon to do other than simply watching, listening and taking notes (Felder & Brent, 2009). The basic active learning structure is:

- Tell the students to organise themselves into groups of 2–4 and randomly appoint a recorder in each group if writing will be required.
- Pose a challenging question or problem and allow enough time for most groups to either finish or make reasonable progress toward finishing. The time you give them should normally be between 15 seconds and three minutes. If they will need much more time than that, break the problem into several steps and treat each step as a separate activity.
- Call on several individuals or groups to share their responses, and ask for volunteers if the complete response you are looking for is not forthcoming. Then discuss the responses or simply move on with your planned lesson.

Two common active learning strategies are:

- **Think-pair-share.** Pose the problem and have students work on it individually for a short time; then have them form pairs and reconcile and improve their solutions; and finally call on several individuals or pairs to share their responses. This structure takes a bit more time than a simple group activity, but it includes individual thinking and so leads to greater learning.
- **Concept tests.** Ask a multiple-choice question about a course-related concept, with distractors (incorrect responses) that reflect common student misconceptions. Have the students respond using personal response systems (“clickers”) and display a histogram of the responses. If clickers aren’t available and the class isn’t huge, have the students hold up cards with their chosen responses in large letters and scan the room to estimate the response distribution. Then have the students get into pairs and try to reconcile their responses and vote again. Finally, call on some of them to explain why they responded as they did and then discuss why the correct response is correct and the distractors are not.

![Diagram](image-url)
Concept tests were developed, and their effectiveness clearly demonstrated, by Erik Mazur (1997) to encourage active learning through in-class peer collaboration in physics courses. Chapter Two of Mazur’s (1997) text Peer Instruction is available in electronic form at http://mazur-www.harvard.edu.

**Demonstrations**

An interactive demonstration consists of a teacher manipulating an apparatus and then asking probing questions about what will happen. Typically, the predict-observe-explain (POE) sequence is used whereby the students first predict the outcome of the demonstration before proceeding to observe the actual results and to explain why the result turned out the way it did. Often, the demonstration serves to elicit student alternative conceptions, and is designed to place students in cognitive dissonance (especially when the event is discrepant or unexpected) so that they are forced to confront and resolve any discrepancies with their earlier prediction.

**Inquiry Labs**

Inquiry labs generally consist of students manipulating apparatus, collecting data, analysing and interpreting data and communicating the results. The level of inquiry can range from highly teacher directed to highly student centred, depending on the amount of information provided to the student. Depending on wording and presentation, lab activities can be designed and tailored to the particular readiness levels of the class. For example, a Level 1 activity can become a Level 2 by having students complete it prior to learning the targeted concept, and a Level 2 activity can be revised easily to Level 3 simply by removing the procedural instructions. At Level 4, students pose or define their own problem or question and independently develop and execute an experimental plan. They also decide what data is appropriate to collect and how to collect, present, and process this data and justify their evidence-based conclusions.

**Table 4.6  The four levels of inquiry**

<table>
<thead>
<tr>
<th>Level of inquiry</th>
<th>Question?</th>
<th>Methods?</th>
<th>Solution?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Confirmation)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2 (Structured)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (Guided)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 (Open)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Concept Cartoons**

Concept cartoons make use of cartoon characters engaged in dialogue. They integrate text in dialogue form with a visual stimulus for focused discussion. They present the scientifically acceptable viewpoint together with several alternatives that are common misconceptions held by students. An example of a concept cartoon is given in Figure 4.5, taken from the website: http://www.conceptcartoons.com/science/examples_bungee.html.
Students can be asked to reflect on the concept cartoons, discuss what they think about the ideas posed by the characters, and explain why they have those ideas. The cartoons can generate discussion, encourage investigation, and challenge learners’ understanding. Students can also be asked to fill in blank speech bubbles to indicate what they are thinking. Cartoons are motivating, visually appealing and are especially valuable for students with weak language skills as there is minimal text. The same cartoon can be used with a variety of age groups as each group interprets the concept cartoon at their own level.

Concept Mapping

Concept mapping is a useful technique for finding out a student’s conceptual structures and understanding of the interrelationships among individual concepts. Individual ideas or concepts are circled or boxed up. But the real power of concept mapping lies in the opportunity for students to label the linking lines (directional arrows) with verbs or *propositions to describe* the logical connection or relationship between the concepts. An example of a concept map for the topic on density is shown in Figure 4.6.

Teachers can use concept maps as diagnostic tools to identify misconceptions, assess prior ideas that students have before teaching a topic, and assess the changes and progress in students’ understanding of science concepts.
ICT-Integrated Physics Instruction

Current research indicates (Law et al. 2008) that it is not appropriate to assume simply that the introduction of ICT necessarily transforms science education. Rather, we need to acknowledge the critical role played by the teacher in creating the conditions for ICT-supported learning through selecting and evaluating appropriate technological resources, and designing, structuring and sequencing a set of learning activities that match the learning goals of the curriculum and the learning needs of the students. Indeed the impact of ICT use depends not on how often ICT is used but on how it is used. Technology itself is neutral; what is crucial is how it is used with appropriate pedagogies to teach specific content. There are generally three ways to integrate technology in physics instruction:

- **Teacher-directed lessons.** Examples are the use of animations to illustrate abstract concepts, video-recorded demonstrations and use of classroom response systems to monitor student understanding of concepts.
- **Student-centred in-class activities.** Examples are the use of data-logging for laboratory experiments or simulation software with guided worksheets.
- **Out-of-class activities.** Examples are simulation-based homework, introductory exploration of a topic or as a pre-lab assignment.

Teachers’ knowledge of technology, science, and pedagogy culminates in knowing where (in the curriculum) to use technology, what technology to use, and how to teach with it (McCrorry, 2008, p.194). Some principles that guide the effective use of ICT include (Osborne & Hennessy, 2003, p.6):

- Ensuring that use is appropriate and adds value to learning activities
- Building on teachers’ existing practice and on students’ prior conceptions
- Structuring the activity while offering students some responsibility, choice and opportunities for active participation
- Prompting students to think about underlying concepts and relationships; creating time for discussion, reasoning, analysis and reflection

![Figure 4.6 Concept map for the topic on density (Vanides et al., 2005).](image)
• Focusing research tasks on developing skills for finding and critically analyzing information
• Linking ICT use to ongoing teaching and learning activities
• Exploiting the potential of whole class interactive teaching and encouraging students to share ideas and findings

In deciding to use technology in physics instruction, it is fundamental to decide where technology can help students learn or help the teacher teach. Equally important is to decide when not to use technology. The affordances of technology may apply generally across all topics in physics or could be used to address specific content areas in physics (see Table 4.7). For the latter, a key consideration that guides decisions about technology use would be to identify parts of the physics curriculum that are hard to teach where technology might enhance understanding and help overcome cognitive difficulties.

Educational technologies such as multimedia, dataloggers and simulations offer great potential to make physics concepts more accessible through visualization, modeling and multiple representations. For example, animations help students to better visualise abstract concepts such as field lines and the superposition of waves, and also to better appreciate the microscopic perspective for understanding the kinetic theory of matter. Simulation and multimedia learning environments offer the unique advantage of combining different representations in one interface. In particular, dynamic presentations offer the possibility of connecting representations not only by integrating them, but also by linking them so that a change in one representation is concurrent with a change in another representation. This helps learners establish relationships between the representations. Besides supporting learning in the classroom, simulations can also help consolidate and extend student learning beyond the classroom and allow motivated students to test out models of the physical phenomena in different scenarios at their own time.

Table 4.7 Pedagogical Affordances of Technology in Physics Instruction

<table>
<thead>
<tr>
<th>Use of Technology (General)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedagogical Affordance (Why &amp; How)</td>
<td>Technology (What)</td>
</tr>
<tr>
<td>Formative Assessment</td>
<td>Classroom response system, online survey</td>
</tr>
<tr>
<td>Communication</td>
<td>Word processing, desktop publishing, presentation software, email</td>
</tr>
<tr>
<td>Collaboration</td>
<td>Web 2.0 tools</td>
</tr>
<tr>
<td>Access to real-world scientific data</td>
<td>Internet websites and databases</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Use of Technology (Specific)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedagogical Affordance (Why &amp; How)</td>
<td>Curriculum (Where)</td>
</tr>
<tr>
<td>Imagery and visualisation</td>
<td>Visualizing fields, superposition of waves, kinetic theory or model of matter</td>
</tr>
<tr>
<td>Multiple-linked representations</td>
<td>Constant velocity or constant acceleration 1D motion, simple harmonic motion</td>
</tr>
<tr>
<td>Dynamic modelling</td>
<td></td>
</tr>
<tr>
<td>Data collection, analysis and presentation</td>
<td>Electromagnetic induction IV characteristics</td>
</tr>
</tbody>
</table>
In addition, these ICT tools facilitate the scientific investigative process in that they allow students to easily gather, analyse, visualise, model and communicate data. In particular, dataloggers allow real-time data collection and recording data that would otherwise be hard to gather. Transient events such as capturing the voltage induced when a magnet falls through a coil of wire or the light intensity variation of a tungsten filament powered by an ac source. In fact, recent developments merge visualization with analysis, by synchronizing the collected data and resulting graph with a movie clip of the phenomenon. Students can scroll across the graph and view the movie simultaneously, while pausing at critical points on the graph that match with interesting aspects of the phenomenon.

**Physics Education Research (PER) - based Instructional Models/Strategies**

Over the past decade, a number of active engagement curricula based on the constructivist model of student thinking and learning have been developed. The common feature of these curricula is that they encourage active learning and peer cooperation and they address student alternative conceptions in a constructivist mode.

**Lecture-based models/strategies**
- Peer Instruction/ConcepTests - Eric Mazur, Harvard University
- Interactive Lecture Demonstrations (ILDs) - Ronald Thornton, Tufts; David Sokoloff, U. of Oregon; ILDs from UMD PERG
- Just-in Time Teaching (JiTT) - Gregor Novak et al., IUPUI and USAFA
- Active Learning Physics Sheets (ALPs) (Alan van Heuvelen, Ohio State University)
- Ranking Task Exercises in Physics (Thomas O’Kuma et al.)

**Tutorial-based models/strategies**
- Tutorials in Introductory Physics (Lillian McDermott, et al., University of Washington)
- Activity-based Physics (ABP) Tutorials (Edward Redish et al., University of Maryland)
- Cooperative Group Problem Solving (Ken and Pat Heller, University of Minnesota)
- Context Rich Problems (Ken and Pat Heller, University of Minnesota)

**Laboratory-based models/strategies**
- RealTime Physics (R. Thornton, Tufts; D. Sokoloff, U. of Oregon and P. Laws, Dickinson College)

**Studio/Workshop models/strategies**
- Physics by Inquiry (Lillian McDermott, et al., University of Washington)
- Workshop Physics (Priscilla Laws, Dickinson College)
- The Physics Studio (Jack Wilson, Rensselaer Polytechnic Institution)
- Modeling Instruction in High School Physics (David Hestenes, Arizona State University)
- SCALE-UP (Bob Beichner, North Carolina State University)
- Technology Enabled Active Learning (TEAL) - Massachusetts Institute of Technology

**ICT-enhanced models/strategies**
- Physlets (Wolfgang Christian, Davidson College)
- PhET (University of Colorado)
- Virtual Reality (Lei Bao et al., Ohio State University)
- Web-Delivered Interactive Lecture Demonstrations (WebILDs)- Ronald Thornton, Tufts; David Sokoloff, U. of Oregon
Summary of Key Points

- Teaching science as an inquiry is consistent with how scientists engage in scientific investigations. It not only facilitates conceptual development in our students but also gives an understanding of how we know what we know in science.

- The essential features of inquiry are: engaging in scientifically oriented questions, giving priority to evidence, formulating explanations from evidence, making connections with other sources of scientific knowledge and developing a reasonable and logical argument in the communication of the findings.

- The Learning Cycle Model consists of the exploration-invention-application phases which involve both inductive and deductive thinking. The BSCS 5E Instructional model and the Modelling Instruction approach are two examples which build on the learning cycle model to help guide instructional planning and implementation.

- External representations of a physical phenomenon such as pictures, diagrams, words, graphs and equations are useful in helping us to understand and model the actual real world phenomenon.

- Some strategies that support inquiry-based science include: questioning, active learning strategies, demonstrations, inquiry labs, concept cartoons and concept mapping.

- The use of ICT such as multimedia, dataloggers and simulations offer great potential to make physics concepts more accessible through visualisation, modelling and multiple representations.

- Over the past decade, a number of inquiry-based instructional materials based on physics education research have been developed and tested to be found effective in enhancing student conceptual development and problem solving abilities.
Nurturing Critical and Inventive Thinking through Physics

Sow Chorng Haur

Physics education provides a great opportunity for students to acquire basic knowledge about nature. Through the learning of physics, students develop the skills of critical thinking in their attempts to understand and explain the wide variety of physical phenomena encountered. In addition, physics education plays a critical role in fostering creative invention. Thus, it is crucial for teachers to find ways to nurture critical thinking and to foster the habits of creativity in our modes of teaching and our curricula. The following are some suggestions on teaching approaches that might be useful.

We can design hands-on activities in our classroom discussion. In this way, the students can learn via the observation of an interesting phenomenon that stimulates their curiosity. A teacher can guide and lead the students in a discussion aiming to construct a theoretical model to account for the observation. Do not prematurely end the discussion with the emergence of the one “right” answer; promote consideration of multiple working hypotheses and means of testing them. The students go through this journey of discovery before arriving at a model that can account for the observation. Notably this is a model constructed by the students hence the students take ownership of the theoretical model and this often translates to effective learning. Typically these hands-on activities provide useful and vivid visual-thinking experiences that leave a lasting impression. “Hands-on” activities are often equated with enhanced processing and learning. In addition, the hands-on activities can be designed to challenge the students to explain “how things work”. In doing so, the students may be further stimulated to come up with their own inventions.

In our physics course, we can infuse design-oriented activities. This can take the form of a science project where the students are required to design and carry out a research project. Alternatively they can be tasked to implement technical development of an experimental technique. If students experience design-oriented activities, they will be more likely to develop a deeper understanding of the creative process itself. We can also offer science projects with open-ended applications. In this way the students first learn about the theoretical knowledge and experimental skills required to carry out a science project in a general sense, through which they develop in depth knowledge of the scientific concepts and appreciate the capabilities and limitations of the instrumentation. Subsequently the students can be invited to propose and carry out their own specific science research experiments for their investigations. These projects shall be designed by the students and hence provide a great opportunity to nurture the creativity of the students. For example, we have students who decided to point a telescope towards the Sun and make use of the telescope as a tool to focus the Sun’s energy for nanofabrication. Thus our curricula must provide sufficient support for individual initiative and self-discovery. Sometimes we tend to specify overly narrow learning outcomes with pre-conceived answers. In striking a balance, it is worthwhile to discuss unsolved problems as well. In which case a teacher can encourage thoughtful questions from the students and illustrate to the students the process of scientific reasoning even though there is no clear-cut answer.

The pace of learning in Singapore is extremely rapid with endless problem sets. This can undermine the open-ended reflection and self-assessment which are important components required for invention. During the teaching of physics, a teacher needs to strike a balance between the importance of discipline...
in building a body of knowledge and the importance of the creative use of that knowledge (such as through the use of open-ended problems). Here is a suggestion: the curriculum for laboratory class often involves detailed procedures with pre-determined outcomes. It would be useful to further challenge the students to apply the experimental technique to the study of unknown samples with unexpected properties. They can give a scientific presentation after their experiments detailing the results of their analysis. This is good training for critical thinking. Another suggestion would be to implement an innovative laboratory class that nurtures the creativity of the students. Rather than giving the students the usual procedure spelt out in a step-by-step format, they are given just an objective; for example “To determine which travels further in air, gamma, beta or alpha emission”, “To determine the percentage of alcohol in a solution through rate of evaporation” or “To determine the wavelength of a laser source”. For such experiments, we can provide some materials, instruments and components on the benches in the laboratory and challenge the students to design and carry out experiments to meet the objective.

Sometimes the rigid separation between disciplines can be restrictive to creative ideas and design. Hence we must also provide the opportunity for the students to appreciate the need for multidisciplinary approaches to real-world problems. Currently there are a number of challenges we are facing that require knowledge of different disciplines in order to tackle the challenges. Examples of such challenges include global warming, green energy, environmental issues and etc. We can turn these topics into themes for students’ project work. The students are required to develop in-depth appreciation of the nature and extent of the challenges and subsequently propose viable solutions to the challenges. Through this process, the students will develop their skills in critical thinking and hone their creative ability in coming up with interesting solutions to the challenges.
“When the cook tastes the soup, that’s formative; when the guests taste the soup, that’s summative.”

- Robert Stake

Chapter Overview

Traditionally, test scores at the end of students’ learning process are usually used as the sole measure of how much the child has learned and achieved. While summative assessment has its value in our education system, we come to realize that standardized tests are not adequate to present a complete picture of student performance. In this chapter, we encourage the use of assessment as an intentional and systematic tool to support students’ learning and improve teachers’ instruction.

Assessment to support learning

What is assessment? Assessment is the process of gathering, recording, interpreting, using and reporting information about a child’s progress and achievement in developing knowledge, skills and aptitude.

The form of assessment that we are familiar with is the testing of a child’s learning at the end of a given period, such as the end of a unit of work, a school term, or an academic year. The emphasis of such assessment is on measuring the child’s cumulative progress towards curriculum objectives and the determination of their standard of achievement. A grade or a score is often the only feedback a child receives.

Instead of leaving assessment as an afterthought at the end of the learning process, assessment processes should play a major role in supporting learning. The types of assessment are integral to student learning during the instructional phases and should serve to inform both the teacher and the students about their progress in meeting instructional targets. In science education, assessment, and teaching and learning are both distinct and closely related. According to Liu (2010), without teaching and learning, science assessment is meaningless; without assessment, science teaching and learning is mindless. It is critical to consider science assessment and teaching and learning at the same time when planning for effective science instruction.

Liu (2010) proposed a schematic illustration (see Table 5.1) on how assessment for learning (diagnostic assessment, formative assessment) and assessment of learning (summative assessment) can be powerful tools to inform instruction based on the backward design approach by Wiggins and McTighe (2005). He noted that although this approach is described by three stages, curriculum planning does not have to follow the stages in sequence. He also noted that one unit of instruction can be a part of a larger program of study, and thus summative assessment of one unit may become a diagnostic assessment for the next one or a formative assessment for the entire program of study.
### Table 5.1 Backward Design Approach and its implication for Assessment (adapted from Liu, 2010)

<table>
<thead>
<tr>
<th>Planning for Science Teaching and Learning</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired learning outcomes: What will students know and be able to do?</td>
<td>How do you know if students have achieved the desired learning outcomes?</td>
</tr>
<tr>
<td>Diagnostic assessment: What do students bring to the classroom and how are students’ understandings different from the desired understanding?</td>
<td>Summative assessment: What are the best ways to obtain evidence for students’ mastery of the desired learning outcomes?</td>
</tr>
</tbody>
</table>

### Assessment to Support Teaching and Learning

### Assessment of Learning

Assessment of Learning (AoL) aims to summarize how much or how well students have achieved at the end of a course of study over an extended period of time. Prominent examples of AoL include the PSLE and the GCE examinations. The results of these examinations are interpreted to answer questions such as: Is the student ready for the next course of study? Which course of study is best suited to the achievement of the student? In selecting students for highly competitive schools or courses, who should be selected on the basis of meritocracy?

For teachers in schools, AoL may take the form of end-of-year examinations or preliminary examinations. Following the examinations, teachers may be called upon to make recommendations on students’ next steps in their education course such as deciding who should benefit from, say, lateral transfers from one course to another or who should take ‘double mathematics and triple sciences’? When meeting the students’ parents and guardians at the end of the school year, teachers would comment on the students’ progress in the year. How much of the current course curriculum has the student mastered? Has the student mastered the basics after one year of study? What are their strengths? What are the major areas that need improvement?

Would the AoL provide sufficiently reliable evidence to make sound decisions and recommendations? How can such assessment be planned and implemented to provide this evidence? To answer these questions, the content of the assessment must be a representative sample of the curriculum. The use of a Table of Specification is meant to guide test assembly so that: (1) the test content does not over-represent or under-represent the curriculum; (2) the test content does not contain anything irrelevant (e.g., out-of-syllabus knowledge and skills; test items that are too difficult or too easy); (3) all the important knowledge and skills are tested.
When a test for AoL has been assembled, teachers should ask themselves the following questions: Does the test cover all the assessment objectives that define achievement in the subject? With the resources available, is this the best test that could be used to assess students’ achievement? Is this test fit for gathering evidence to sum up students’ achievement in the subject area?

Esther Yee, Assessment Specialist
Singapore Examinations and Assessment Board

Teachers can refer to both the Assessment Objectives in the syllabus document and the Revised Bloom’s Taxonomy in the design of the Table of Specification.

In the syllabus document, the assessment objectives for the theory papers are grouped into 2 categories:

Assessment Objective A (AOA): Knowledge with Understanding and
Assessment Objective B (AOB): Handling Information and Solving Problems.

The table below summarizes the weighting of assessment objectives for ‘O’ Physics, ‘O’ Science (Physics) and ‘N(A)’ Science (Physics) syllabuses from year 2013 onwards.

Table 5.2 Weighting of assessment objectives for ‘O’ Physics, ‘O’ Science (Physics) & ‘N(A)’ Science (Physics)

<table>
<thead>
<tr>
<th></th>
<th>AOA Knowledge with Understanding (Recall)</th>
<th>AOB Handling Information &amp; Solving Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘O’ Physics</td>
<td>45%</td>
<td>55%</td>
</tr>
<tr>
<td>‘O’ Science (Physics)</td>
<td>50% (20%)</td>
<td>50%</td>
</tr>
<tr>
<td>‘N(A)’ Science (Physics)</td>
<td>50% (20%)</td>
<td>50%</td>
</tr>
</tbody>
</table>

Another reference that teachers can use is the Revised Bloom’s Taxonomy (Anderson & Krathwohl, 2001), which classifies thinking into six categories in increasing level of complexity. The taxonomy is hierarchical; each level is subsumed by higher levels. That is, a student functioning at a certain level (e.g. applying) is assumed to have mastered the preceding levels (e.g. remembering and understanding).

Figure 5.1 Revised Bloom’s Taxonomy
The terms are defined below according to Anderson & Krathwohl (2001):

- **Remembering**: Retrieving, recognizing, and recalling relevant knowledge from long-term memory.
- **Understanding**: Constructing meaning from oral, written, and graphic messages through interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining.
- **Applying**: Carrying out or using a procedure through executing, or implementing.
- **Analyzing**: Breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing.
- **Evaluating**: Making judgments based on criteria and standards through checking and critiquing.
- **Creating**: Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing.

Thus, we can map the assessment objectives with the cognitive categories of the Revised Bloom’s Taxonomy as shown below.

<table>
<thead>
<tr>
<th>Revised Bloom’s Taxonomy</th>
<th>Assessment Objectives</th>
<th>Command Words</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creating</td>
<td>Handling information and solving problems</td>
<td>Predict, suggest, calculate, determine, etc</td>
</tr>
<tr>
<td>Evaluating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analysing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applying</td>
<td>Knowledge with Understanding</td>
<td>Define, state, describe, explain, outline, etc</td>
</tr>
<tr>
<td>Understanding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remembering</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 5.2 Mapping of Assessment Objectives to the Revised Bloom’s Taxonomy*

The table below (Table 5.3) is a sample Table of Specification to guide test assembly. It allows teachers to keep track of the weighting of both assessment objectives and at the same time allowing a good distribution across the various cognitive categories.

**Table 5.3 Sample Table of Specifications**
Assessment for Learning

The aim of Assessment for Learning (AfL) is to use information derived from assessment as feedback to students, and to implement remedial actions to identify and close the learning gaps that students have. All students come to the classroom with learning gaps; some with few learning gaps, others with many learning gaps; some with deep learning gaps, others with shallow learning gaps. When we think of AfL, we think of three things: “learning gaps”, feedback, and most importantly, remedial actions.

Learning gaps can be identified by testing students at the start of a semester or before embarking on a new topic. Given that later topics often build on earlier ones as prerequisites, topical tests provide information on students’ readiness for new learning and weaknesses can be rectified before the gaps widen further. This information, given as feedback to students, will guide, challenge or redirect their learning progress. But merely giving the information to students will not be enough to motivate students to improve. Neither will vague praises for a “good job”. Instead, the feedback needs to focus on specific qualities of the students’ work at: (1) the task level (does he understand the requirement of the task?); (2) the cognitive processing level (does he have the knowledge, skills and understanding to carry out the task?); or (3) the student’s intrinsic level (does he have the values, attributes and mindset to carry out the task?). By focusing on the specific things that can be changed, students are shown the possibility of improvement through actionable steps. Thus, the remedial actions are not only clear to the teachers but also to the students in terms of the actions required of them.

Remediation is often associated with students who need to “catch up” in their learning. Mastery learning is an appropriate strategy for these students. The teacher has to scope each learning outcome into meaningful components and design tests to assess achievement of the components before culminating in a test of the final learning outcome. Through frequent testing of small units of instruction, each layer of learning is solidly entrenched and students gain mastery in the unit of study before progressing to the next unit.

For students who are not challenged by traditional teaching methods, tuning into situational interests can enrich their learning experience. Students’ interest is piqued by fun and novel activities. For example, illustrating a scientific principle through a real-world problem or an out-of-classroom field trip (even if to a virtual destination on the internet) can help concretize science concepts and infuse science into their daily life.

Esther Yee, Assessment Specialist
Singapore Examinations and Assessment Board

In contrast to AoL, Assessment for Learning (AfL) is part of the daily teaching and learning process. It involves a series of actions with the main objective being to monitor students’ learning, identify learning gaps, and at the same time to adjust teachers’ instructions. This can be done through diagnostic assessment, teacher assessment or peer assessment. While tests can be part of these processes, it only makes up some elements of it.

As mentioned in the AoL article above, one of the key roles of formative assessment is to identify learning gaps. This can be done through diagnostic assessment. Diagnostic assessment allows teachers to identify students’ preconceptions. According to Liu (2010), “Preconceptions are ideas students bring with them before they learn a new unit. Students’ preconceptions provide valuable insight for the teachers to understand what students’ current understandings are, how they may be developed, and what new understandings need to be further developed for students to meet the learning standards”
For example, in the teaching of kinematics, teachers can use Socratic Questioning to check students’ understanding on constant velocity. From their responses, the teacher would decide if the class is ready to proceed to the next concept i.e. constant acceleration model or if there is a need to adjust instruction to enhance the understanding of the current concept.

Another way to check students’ understanding is through the conduct of a pre-test before the start of a new topic. An example of a pre-test is given in Figure 5.3 taken from Tutorials in Introductory Physics (McDermott, 2002). In this pre-test, instead of expecting a quantitative answer often dependent on memorized formulas, the focus is on students’ ability to do reasoning through the application of concepts and physical principles.

The three circuits below contain identical bulbs and identical batteries. Assume the batteries are ideal (i.e., the batteries have no internal resistance)

![Circuit Diagram]

Rank the brightness of the five bulbs above. Explain how you determined your answer.

That said, AfL should not be a spontaneous adjustment to instruction through the administration of adhoc tests or unstructured questions. It is an intentional and systematic effort on the part of the teacher to collect information, analyse it, and then take actions according to results of the analysis (Gallagher, 2007). From the information collected, teachers can evaluate his/her own teaching and make changes to his/her planning, organizational strategies and teaching methodologies in order to make learning more successful for the students.

Formative assessment can only be formative when information (“feedback” in the diagram) is used to both adapt and modify teaching and learning (“informs instruction”) in order to benefit students (“supports student learning”) as shown in Figure 5.4 (Enger & Yager, 2009). Thus, summative assessment can also serve a formative role when the results are used to inform and guide future instruction.
Given the close relationship between instruction and formative assessment, there is no clear distinction between formative assessment methods and instructional strategies. Any instructional strategy, if its intent and purpose is to gather information so as to improve teaching and learning, can be effective formative assessment tools too.
In summary, Stiggins (2004) gives an overview of the key differences between Assessment for and of learning in the table below.

Table 5.4  An overview of the key differences between Assessment for and of Learning

<table>
<thead>
<tr>
<th></th>
<th>Assessment for Learning</th>
<th>Assessment of Learning</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Purpose</strong></td>
<td>Find out students’ prior knowledge, what students have learnt and what their difficulties are and thus adjusting teaching to support ongoing students’ learning.</td>
<td>Record students’ achievement standard Measure the effectiveness of instructional programme/ curriculum objectives</td>
</tr>
<tr>
<td></td>
<td>“Where are the students in the learning process?”</td>
<td>“What did students learn?”</td>
</tr>
<tr>
<td><strong>Primary users</strong></td>
<td>Students, teachers, parents</td>
<td>Curriculum planners, school key personnel, students, teachers, parents</td>
</tr>
<tr>
<td><strong>When?</strong></td>
<td>Integrated part of teaching and learning</td>
<td>After a certain learning period</td>
</tr>
<tr>
<td><strong>Teacher’s role</strong></td>
<td>Set targets according to curriculum objectives; Inform students of targets; Plan suitable assessments; Adjust teaching based on responses and results; Offer descriptive feedback if possible; Involve students in assessment</td>
<td>Plan and administer school-based examinations carefully to ensure validity and reliability; use results to give feedback about achievement standards to students and parents</td>
</tr>
<tr>
<td><strong>Student’s role</strong></td>
<td>Contribute to setting targets; self-assess; keep track of progress; improve based on assessment results and feedback</td>
<td>Take the examinations; consolidate learning and study to meet standards; strive for good grades</td>
</tr>
<tr>
<td><strong>Primary Belief</strong></td>
<td>Intrinsic motivation to learn especially if supported by suitable learning environment</td>
<td>Extrinsic rewards and punishment</td>
</tr>
<tr>
<td><strong>Examples</strong></td>
<td>Performance and written tasks, discussions, class tests, student self- and peer-assessment (refer to next section for suggested assessment techniques)</td>
<td>Term/ Final Examinations</td>
</tr>
</tbody>
</table>
Assessment as Learning (AaL) takes AfL a step further by transferring ownership and accountability of learning to the student. Students are actively engaged in the learning and assessment process. When they make the connection between learning strategies and assessment results, they see for themselves which strategy works for them to get the results they desire. This will further spur them on to work harder using a correct study habit or discard undesirable study habits. In other words, students are their own assessor and personally monitor their learning, using feedback from teachers or peers or from assessment results to adjust and change their understanding. The teacher’s role is in helping students set clear targets and explaining assessment criteria and standards, giving effective feedback and affirming the student.

The three key components of AaL are self-monitoring, self-evaluation and self-correction which occur in a short, recursive cycle in the natural learning environment. This means assessment is part and parcel of the students’ school day.

Self-monitoring requires students to collect “evidence” of their learning and keep track of their progress. These evidences are assessment tasks designed and assigned by teachers to probe learning. It could be in the form of a short quiz, observation notes from an outing or an experiment or a summary/concept map of a recently-taught topic. The outcome of these tasks could be self-reported, peer-graded or teacher-marked. Whichever the approach, students ought to be familiar with the assessment criteria used to grade their work. The teacher can augment their understanding of the requirement by providing specific exemplars and guiding students in the use of assessment rubrics to distinguish the quality of work or performance. Younger students would normally require more help in organizing and record-keeping.

From the collected evidences, students self-evaluate, that is they review their records and determine whether they have met their target. By reflecting on their learning strategies and their progress, they decide which strategies work for them and which do not. Some questions which can be used to prompt students in their reflection include:

- What have I learnt?
- What do I like / dislike about this assignment?
- Which part of the piece of work am I most proud of?
- What was difficult about this assignment?
- What would have made this piece of work better or easier to work on?
- What should I still need to work on?
- What else should I know or do before I can improve on this piece of work?

Students then move on to self-correction. Having seen the results, or lack of it, due to their learning strategies, they construct steps for improvement, modifying or discarding poor habits and reinforcing good ones. This is crucial both in establishing accountability for learning and in boosting awareness of personal study habits. This is the step that integrates the academic knowledge of the discipline with metacognitive skills, which puts the learning IN assessment. The best strategies to improve learning engage students in the task, such as:
Moving towards AaL, the role of the assessor is handed to the learners. Assessment as learning focuses on the fostering of students’ capacity over time to be their own best assessors. For this to happen, teachers must make a conscious effort to fade away as an external assessor, and concurrently “present and model external, structured opportunities for students to assess themselves”. Students’ involvement in the assessment process does not mean a diminished role for the teacher, instead, it is an extension of the teachers’ role to design instruction and assessment that allows students to “self monitor, self evaluate and self correct”. We, as teachers, “.. must constantly remind ourselves that the ultimate purpose of evaluation is to enable students to evaluate themselves” (Costa, 1989). It is only when we involve students and promote their independence through this process that we eventually equip them with the tools to undertake their own learning wisely.

**Summary of Key Points**

- This chapter highlights three purposes of assessment; assessment of learning (AoL), assessment for learning (AfL) and assessment as learning (AaL).
- Teachers need to re-examine the role of assessment in enhancing student learning (as illustrated in AfL and AaL), This is when the role of assessment is taken into consideration in the planning stage and not left as an afterthought in the instructional process.
- Assessment of learning should be reserved for circumstances when it is necessary to make summative decisions. Teachers are responsible for reporting student learning accurately and fairly, based on evidence from a variety of contexts and applications.
As science teachers, we are interested to know how we can best integrate curriculum, assessment, and instruction so that our students learn and achieve the most in the knowledge and skills in science and acquire the desirable dispositions in the learning of science. Such information is obtainable from research findings on science education and the best practices in science assessment.

Schroeder, Scott, Tolson, Huang, and Lee (2007) and Wise (1996) analysed more than a hundred studies over a forty-year period to identify the following science teaching strategies that are effective in raising science achievement:
- Enhanced context strategies (where teachers relate topics to previous learning and engage students’ interest);
- Inquiry strategies (where teachers use student-centred instruction that is less step-by-step and teacher directed than traditional instruction);
- Questioning strategies (where teachers use a range of timing, positioning, and cognitive levels of questions);
- Focusing strategies (where teachers do something to alert students to the intent of the instruction);
- Manipulating strategies (where teachers present opportunities to students to work with physical objects);
- Enhanced materials strategies (where teachers re-write, simplify or annotate instructional materials to meet the needs of the students);
- Testing strategies (where teachers vary the frequency, purpose, and cognitive levels of testing).

Treagust and Chandrasegaran (2007) reported the successful use of two-tier multiple-choice diagnostic tests in a large-scale study in Taiwan to identify and remediate students’ scientific conceptions. The following test item is an example of a two-tier multiple-choice item tried out on a small purposive sample (n=500) of 17-year old physics students in Singapore, the percentages in parentheses indicate the proportion of students who chose the options:

What usually happens to a cart when it is pulled by a horse?
- It remains unmoved (23%)
- It moves in the direction of the pull (77%)*

Reason:
- The pull of the horse on the cart (action) is equal to the pull of the cart on the horse (reaction) (42%)
- The pull of the horse is greater than the pull of the cart on the horse (23%)
- The pull of the horse is greater than the frictional force on the cart (7%)*
- The pull of the horse is less than the frictional force on the cart (5%)

The first tier is a normal multiple-choice item with two to four options. The second tier probes the reason or underlying principle tested in the first tier. It is obvious from the example that while 77% of the students correctly chose option B for the first tier, only 7% could identify the correct explanation in the second tier. We should use two-tier multiple-choice items in schools more often.
Teachers can use them to assess students’ understanding as they teach, in the way a chef tastes the food as he cooks.

One aim of science education, among others, is to develop students to be the scientists of the future or, at least, scientifically literate citizens. The ability and disposition to ask questions is usually considered to be a mark of scientific literacy. As teachers, we should encourage our students to ask questions. We can even assess our students on the basis of the questions they ask. France and Bay (2010) reported that encouraging students to ask questions helped students to develop an understanding of scientific practice as a journey, make identity links with scientists, use the personal as a knowledge bridge, and benefit from the transformative experience.


In Part II, we highlight the core ideas and concepts in the school physics curriculum through four chapters: “Newtonian mechanics”, “Thermal physics”, “Waves”, and “Electricity”, with a focus on guiding the teaching and learning of physics at the upper secondary level.

Each chapter begins with a brief description of the historical development of the physics ideas, highlighting the major contributions made by many outstanding scientists. ‘Big’ ideas that form the core of the physics section are presented to serve as ‘anchors’ to connect and organize the concepts and ideas in the section.

In addition, a content map of the physics curriculum is provided as a useful overview of the topics covered in each section. A colour code is used to indicate the levels - Primary, Lower Secondary, Upper Secondary, Junior College - at which each topic is covered.

Key inquiry questions have also been included to help focus the inquiry to ‘uncover’ the ideas in the content of each subsection.

At the end of each chapter, subsection content maps are provided that focus on the concepts and ideas relevant to the upper secondary physics curriculum. Students’ prior knowledge and common misconceptions are included to help teachers support their students in making meaningful connections between their current knowledge and preconceptions with the new knowledge and concepts in the subsection.
CHAPTER 6: NEWTONIAN MECHANICS

“If I have ever made any valuable discoveries, it has been owing more to patient attention, than to any other talent.”

- Isaac Newton

Historical development of Newtonian Mechanics
(adapted from Rutherford, Holton, & Watson (1981), Project Physics)

Early ideas of matter and motion

Medieval physical science made a sharp contrast between objects on the Earth and those in the sky. All terrestrial matter (i.e. matter on or near the Earth) was believed to contain a combination of four “elements”: Earth, Water, Air and Fire. Each of the four elements was thought to have a natural place in the terrestrial region. Fire occupied the highest place. Beneath Fire was Air, followed by Water, and finally in the lowest position, Earth. Each was also believed to seek its own place.

The movement of any real object depended on its particular concoction of these four elements and on where it was in relation to the natural places of these elements. For example, when water is boiled, the element Water would be combined with the element Fire, whose higher natural place would cause the mixture to rise as steam. A stone on the other hand, was composed mainly of the element Earth and would fall when released, passing through Fire, Air and Water until it came to rest on the ground, its natural place. Medieval thinkers also believed that stars, planets and other celestial bodies differed in composition and behaviour from terrestrial objects and required a different physics to describe its motion.

This medieval physical science, built on notions of cause, order, class, place and purpose, was stated clearly in the writings of the Greek philosopher Aristotle (384 – 322 B.C.). Although it seemed to fit well with many everyday observations, Aristotle’s theory of motion had serious limitations.

Scientific inquiry

Through a cautious process of observation and experimentation, Galileo Galilei (1564 – 1642) discovered the flaws in Aristotle’s ideas of the motion of objects that dominated physics for about 2,000 years.

Galileo’s work on motion heralded a new and significant method of doing scientific research. This method is as useful
today as when Galileo demonstrated it. The basis of this procedure is a cycle, repeated as often as necessary, in its entirety or in part, until a satisfactory theory is found. The cycle roughly follows this form:

General Observation ➔ Hypothesis ➔ Mathematical Analysis or Deduction from Hypothesis ➔ Experimental Test of Deduction ➔ Revision of Hypothesis in light of Test

Galileo’s strategy, which is now a standard modus operandi in physics, involved studying an ideal system in which fringe factors (like friction, air resistance) are omitted, and then transferring this understanding to a real physical process with its complexities and subtleties.

The general sequence of observation, hypothesis, deduction, test, revision etc, so masterfully demonstrated by Galileo in the 17th century, is commonly evident in the work of scientists today. Although there is no single defining scientific method, some manifestation of this process is always evident in scientific research.

The outcomes of Galileo’s work significantly influenced the progress of physics. But they would barely have brought about a revolution in science by themselves. No rational scholar in the 17th century would have given up a belief in Aristotelian physics only because some of its predictions had been discredited. Still, Galileo’s work on free-fall motion helped to pave the way for a new kind of physics by planting the seeds of doubt about the basic hypothesis of Aristotelian science. For example, when it was recognised that all bodies fall with equal acceleration if air resistance is negligible, the entire Aristotelian explanation of falling motion started to disintegrate.

Aristotle’s physics had influenced Europe since the 13th century. To many scientists of that era, it seemed to suggest the most rational method for explaining natural phenomena. To overthrow such a firmly recognised doctrine, Galileo needed to use his talent in writing and tireless campaigning to challenge Aristotle’s theories. In his publication Two New Sciences (1638), Galileo presented his ideas on the motion of freely falling bodies in the form of a conversation among three speakers: one representing the Aristotelian view; another the new views of Galileo; and the third a man of good will and open mind. Eventually, the conversations lead, of course, to Galileo’s views. This book signaled the end of medieval physical science and the beginning of the era of modern-day physics.

Kinematics is the study of how objects move, but not of why they move. Galileo’s most important work dealt with specific types of motion, such as free fall. He showed clearly how these motions may be described using mathematical representations of kinematics concepts such as position, time, speed and acceleration. However, the greatest contribution to the development of mechanics was from arguably the greatest physicist of all time, Isaac Newton.

Isaac Newton (1642 – 1727), building on Galileo’s successful description of motion, started his studies of motion by focusing his attention on dynamics (the study of why an object moves the way it does). As the study of kinematics revealed that an object may remain at rest, move with uniform motion, and speed up (or slow down), Newton set out to “explain” these physical phenomena, and eventually published his outstanding document, the *Principia* (1687), which formed the basis for the development of much of our physics and technology.

In his document, Newton defined the concepts of mass, momentum, inertia and force. Then he presented his three laws of motion. The first law describes the behaviour of objects when no net force acts on them. Newton introduced the idea of inertia as the basic tendency of all objects to maintain its state of rest or uniform motion. Thus, what required explanation is not motion itself, but the change of motion (i.e. why an object speeds up or slows down or changes direction). In his second law, Newton provided a simple quantitative relation between the change in motion
(i.e. change in velocity) and the net force. He established that the rate of change of velocity of an object is related to both the mass of the object and the net force applied to it. The third law provided the relationship between interacting objects and gave a deeper insight into the concept of force.

The mechanics based on Newton’s three laws was very successful. However, what truly made the Principia an extraordinary document was Newton’s law of universal gravitation. Using proofs and arguments, Newton presented the central idea of universal gravitation which stated that “every object in the universe attracts every other object”, with the amount of attraction following a simple relation between the masses of the objects and the distance between them. This was Newton’s bold synthesis, combining terrestrial laws of force and motion with astronomical laws of motion. He had demonstrated that nature has an amazing simplicity and is governed by a few special rules or laws that can be discovered through the strength of human reasoning, and expressed in mathematical formulae. Newton’s combination of logical experimentation and mathematical analysis framed the way science has been conducted ever since.

Conservation laws

Following Newton’s work, scientists began new lines of investigation to answer a never-ending series of questions with new confidence. Although Newton’s laws were successful in explaining the motions of planets and provided a mechanistic model of the universe, they could not explain interactions that involved other physical quantities such as heat, light, and electric and magnetic forces. Eventually, the studies after Newton produced statements that were as grand as the law of universal gravitation. Among them were the conservation laws (mass, momentum, energy, charge) on which much of modern science and technology is based. These powerful principles offered a new way of thinking and opened up new areas to the study of physics, for example thermodynamics, electromagnetism and wave motion.

Many of the concepts that Newton used came from earlier scientists and those of his peers. For example, Galileo and Descartes had contributed the first steps leading to a proper idea of inertia, which became Newton’s first law of motion. In addition to his own experiments, Newton also used data from a large number of sources when he was unable to complete his own measurements. In spite of his achievements, Newton remained modest of his own contributions and once said if he has seen further than others, “it was by standing upon the shoulders of Giants”. Newton thus epitomized the collaborative nature of the scientific enterprise.

Today, scientists frequently need to collaborate with other scientists around the world in order to make significant discoveries and advances in their field of study. For example, the Large Hadron Collider project (built to study high-energy collisions) is a global collaboration of scientists and engineers to advance our understanding of the physical universe.
Big ideas in this section

The big ideas that help to organize and connect the concepts and content in this section are:

1. The study of motion involves first studying an idealised system in which complicating factors (like friction) are absent, and then transferring this understanding to a real physical process. Analysis of the motion of an object is performed using free-body and vector diagrams, graphical analysis as well as mathematical formulae.

2. There are four fundamental forces in nature: gravitational and electromagnetic forces (which are responsible for our everyday experiences) and strong nuclear and weak forces (which operate only at the sub-atomic scale). Gravitational force (a very weak attractive force between two masses) is very long range and is responsible for the interaction between celestial objects in the Universe as well as the Earth’s gravitational pull on us. Electromagnetic force (a very strong force between two charged objects) is very short range and is responsible for all inter-atomic forces of attraction and repulsion e.g. electrostatic forces, contact forces (normal force, friction, fluid resistance) and magnetic forces.

3. When any two bodies in the Universe interact, they can exchange energy. The law of conservation of energy states that in any closed system (including the Universe), the total quantity of energy remains fixed - energy is transferred from one form to another but none is lost or gained. Many forms of energy can be considered to be either kinetic (motion) energy or potential (stored) energy.

4. Newton’s three laws of motion and his law of universal gravitation have been successfully applied to explain and predict motion of terrestrial and celestial objects. Newton’s laws further show that it is possible to express natural phenomena in terms of a few special rules or laws that can be expressed in mathematical formulae.

5. When any two bodies in the Universe interact, they can exchange momentum. The law of conservation of momentum states that in any closed system (including the Universe) the total quantity of momentum is invariant - momentum can be transferred from one body to another (by an impulse) but none is lost or gained.

6. Many kinds of motion in nature are periodic motions or oscillations. The ideas from a type of oscillation known as simple harmonic motion is applied to explain many physical situations such as waves, sound, alternating electric currents and light.
### 6.7 Oscillations

**Periodic motion**
- **Key Inquiry Question:** How can we explain the periodicity of motion of objects in nature?

**Content:**
1. Simple harmonic motion
2. Energy in simple harmonic motion
3. Damped and forced oscillations: resonance

### 6.6 Motion in a circle

**Uniform circular motion**
- **Key Inquiry Question:** How can we describe the motion of objects moving in a circular path?

**Content:**
1. Angular velocity
2. Centripetal acceleration
3. Centripetal force

### 6.5 Gravitational field

**Newton’s law of universal gravitation**
- **Key Inquiry Question:** How can we express the gravitational interaction between objects in the Universe?

**Content:**
1. Gravitational field
2. Force between point masses
3. Field of a point mass
4. Field near to the surface of the Earth
5. Gravitational potential

### 6.4 Dynamics

**Motion of objects**
- **Key Inquiry Question:** Why do objects on Earth and in the Universe move the way they do?

**Content:**
1. Mass, Weight & Density
2. Newton’s laws of motion
3. Free-body diagrams

**Linear momentum of objects in motion**
- **Key Inquiry Question:** How can we account for the linear momentum of objects before and after interaction?

**Content:**
4. Linear momentum and its conservation

### 6.3 Energy

**Energy transfers and transformations**
- **Key Inquiry Question:** How can we account for the ‘appearance’ and ‘disappearance’ of energy when objects interact with each other?

**Content:**
1. Work
2. Power
3. Potential energy and kinetic energy
4. Energy conversion and conservation

### 6.1 Kinematics

**Linear motion**
- **Key Inquiry Question:** How can we describe the motion of objects moving in a straight line?

**Content:**
1. Speed, velocity & acceleration
2. Graphical analysis of motion
3. Free-fall
4. Effect of air resistance

**Non-Linear motion**
- **Key Inquiry Question:** How can we describe the motion of objects moving in a curved path?

**Content:**
5. Projectile motion
6.1 Kinematics: Map of key concepts and ideas covered at upper secondary level

Linear Motion

Key inquiry question: How can we describe the motion of objects moving in a straight line?

1. Speed, velocity and acceleration
   - Physical quantities can be scalar (e.g. distance, speed) or vector (e.g. displacement, velocity, acceleration) quantities. Scalar quantities can be added algebraically. Vector quantities can be added using graphical methods (parallelogram method or ‘head-to-tail’ method).
   - Average speed of a body is given by total distance travelled / total time taken (v = d/t). Instantaneous speed is the speed at any instant.
   - Acceleration of a body is defined as its change in velocity / time taken (a = (v - u)/t). The direction of acceleration is the direction of the change in velocity.
   - Acceleration is: zero when velocity is constant (i.e. no change in velocity); positive (object is accelerating) when velocity is increasing; negative (object is decelerating) when velocity is decreasing.

2. Graphical analysis of motion
   - Displacement-time and velocity-time graphs of a body allow us to deduce when the body is: at rest; moving with uniform velocity and acceleration; moving with non-uniform velocity and acceleration.
   - Gradient of a displacement-time graph gives the velocity of the moving object; Gradient of a velocity-time graph gives the acceleration of the moving object; Area under a velocity-time graph gives the displacement travelled by a body.

3. Free fall
   - An object is in free fall if the only force acting on it is the force of gravity (it’s weight), i.e. no air resistance or contact forces act on the falling object.
   - Acceleration of free fall, g for a body near to the Earth is constant and is approximately 10 m/s² (regardless of the object’s mass or size).

4. Effect of air resistance
   - The motion of bodies with constant weight falling with or without air resistance are different (without air resistance, object will have constant acceleration and velocity increases continuously; with air resistance, velocity reaches maximum value or terminal velocity when the force due to air resistance = weight, and acceleration becomes zero). Terminal velocity occurs only when air resistance is considered.
Students’ Knowledge and Difficulties in Kinematics

Students’ prior knowledge of Kinematics

Primary level:

Students will not have been introduced to the concepts to describe motion. They would have knowledge of the effects of a force to stop or move an object; change its speed (move faster or slower) or direction of motion.

Lower secondary level:

Students learn that speed:

- is a measure of how fast an object is moving;
- depends on the distance (length) travelled and the time taken (unit: m/s).

Objects usually do not move at the same speed, hence, it is more useful to measure its average speed which is defined as total distance travelled / total time taken. Speed at any instant is the average speed over an extremely short time interval.

Students’ common misconceptions and learning difficulties in Kinematics

Displacement, velocity and acceleration:

Students’ concepts of displacement, velocity, and acceleration are not well differentiated. They often think that:

- same position means same velocity for two objects;
- same velocity means same acceleration for two objects;
- larger (or smaller) velocity means larger (or smaller) acceleration;
- zero velocity means zero acceleration;
- and acceleration and velocity are always in the same direction.

Displacement-time and velocity-time graphs:

Students often view the position and velocity graphs as the actual path of the object, rather than a graphical representation of an object’s motion.
6.2 Forces: Map of key concepts and ideas covered at upper secondary level

Forces and its effects

Key inquiry question: What are the characteristics and effects of forces in nature?

1. & 2. Types of force and its effects
   - *Friction always opposes* the motion between the two surfaces in contact. The frictional force between two surfaces on a horizontal plane depends on the material in contact; surfaces in contact; force pressing the two surfaces together; independent of area of contact.

3. Pressure
   - Pressure = *force per unit area* ($p = F/A$).
   - The transmission of pressure in hydraulic systems is used in machines e.g. the hydraulic press. Hydraulic systems work due to the incompressibility of liquid and if pressure is applied to one part of an enclosed liquid, the pressure is transmitted to all parts of the liquid.
   - Pressure due to a liquid column = *height of column x density of the liquid x gravitational field strength* ($p = h \rho g$).
   - Pressure at any one depth in a liquid acts equally in all directions. The height of a liquid column may be used in instruments such as a barometer and manometer to measure the atmospheric pressure and pressure differences.
   - The weight of air above the Earth exerts an *atmospheric pressure*. The pressure inside our bodies balances the atmospheric pressure, so we do not normally feel it.

4. & 6. Turning effects of forces and Equilibrium of forces
   - The moment of a force (or torque) = *force x perpendicular distance* from the pivot. The moment of a force is used in simple machines like the lever.
   - *Principle of moments* states that for a body to be in rotational equilibrium, the sum of its clockwise moments about any point is equal to the sum of anticlockwise moments about the same point.

5. Centre of gravity and Stability
   - The weight of a body may be taken as acting at a single point known as its *centre of gravity*; the position of which affects the stability of the body.
   - Stability is a measure of a body’s ability to maintain its original position. Objects may be made more stable by lowering its centre of gravity or increasing its base area.
Students’ Knowledge and Difficulties in Forces

Students’ prior knowledge of Forces

Primary level:

Students learn that a force:

• may be a push or a pull that acts on an object, e.g. magnetic force and gravitational force (forces that act at a distance), elastic spring force and frictional force (only when objects are in contact),
• can move a stationary object; speed up, slow down, change the direction or stop a moving object; and change the shape of objects.

Students conduct simple experiments to investigate the effects of friction on the motion of objects and forces on springs (mass on spring system), and learn how friction can be useful and can also be a problem.

Lower secondary level:

Students learn that:

• a force (push or pull) is exerted when one thing interacts with another, e.g. gravitational force, frictional force and magnetic force.
• forces affect the state of rest or motion and the size and shape of a body (unit: newton) and the type of force will have different effects on an object.

Students define:

• pressure as force/area, \( p = \frac{F}{A} \) and use the concept of pressure to explain relevant everyday events (e.g. cutting with a knife, use of skis on snow).
• the moment of a force or torque (turning effect of a force) about a point as force \( \times \) perpendicular distance from the pivot (or fulcrum) to the line of action of the force (principle of moments is not required)

Students relate the application of moment of a force in everyday life e.g. in levers (with knowledge of a lever as a device with an effort, a load and a fulcrum).

Students’ common misconceptions and learning difficulties in Forces

Forces between masses, charges and magnets:

Students often think that:

• only active agents (usually living things) exert forces and cause motion, whereas passive forces by inert objects (e.g. a table) do not exist;
• an object moves in the direction of the strongest force rather than the direction of the resultant force; and force is a property of an object and gets used up.
Students’ Knowledge and Difficulties in Forces

**Pressure in a fluid:**

Students have difficulty understanding that pressure at the same depth of a fluid is the same in all directions. They tend to think that the pressure acting downwards is greater.

**Equilibrium of forces:**

Students often think that:

- at equilibrium, forces cease to act on the object; and
- the tension in a string is the sum of the forces acting on each end.
6.3 Energy: Map of key concepts and ideas covered at upper secondary level

Energy transfers and transformations

**Key inquiry question:** How can we account for the ‘appearance’ and ‘disappearance’ of energy when objects interact with each other?

1. & 2. Work and power

- Work done is defined as the force x distance moved in the direction of the force.
- When we do work, energy is ‘used up’. The amount of work is equal to the energy transferred or used.
- Power is the rate of doing work and is given by: power = work done / time taken (P = W/t).

3. Potential energy and kinetic energy

- Kinetic energy is the energy a body possesses due to its motion.
- Kinetic energy $E_k = \frac{1}{2} mv^2$.
- Potential energy is the energy stored in a body due to its position, state or shape (e.g. elastic, gravitational, chemical). Gravitational potential energy is the energy which a body possesses due to its position relative to the ground.
  Gravitational potential energy $E_p = mgh$.
- The total mechanical energy ($E_k$ and $E_p$) is conserved if no frictional forces are present in a moving system.

4. Energy conversion and conservation

- Energy is defined as the capacity to do work. Energy is transferred when work is done.
- There are different forms of energy e.g. kinetic energy, elastic potential energy, gravitational potential energy, chemical potential energy and thermal energy.
- Energy can be transformed from one form to another but cannot be destroyed or created (principle of conservation of energy).


**Students’ Knowledge and Difficulties in Energy**

**Students’ prior knowledge of Energy**

*Primary level:*

Students learn that energy:

- is required to make things *work* or *move* and energy from most of our energy resources is derived in some ways from the Sun, our primary source of light and heat energy.
- exist in *different forms* e.g. kinetic energy (movement energy), gravitational potential energy (objects above the ground), elastic potential energy (spring, elastic band), light energy, electrical energy, sound energy, heat energy and chemical energy (as a form of stored energy: food, batteries, fuels).

Students do simple experiments to investigate *energy conversion* from one form to another e.g. in an electric circuit; learn about sources of energy such as wind, water and fuels, and the need to reduce energy usage in our everyday lives.

*Lower secondary level:*

Students learn that:

- *work* is the use of a force to move an object.
- work done by a force is defined as *force* x *distance moved in the direction of the force* and, based on this definition of work, there are situations involving forces where work is done and where work is not done (calculation only for force parallel to direction of motion) (unit: joule).
- *energy* is the ability (or capacity) to do work or to produce change (work done = energy used) and there are different forms of energy e.g. kinetic, potential, light and sound.
- *energy is conserved* and can only change from one form to another (the total amount of energy before and after the change is exactly the same).
- *sources of energy* include fossil fuels (coal, oil, gas), kinetic energy from water and wind, nuclear, solar, and biomass.

**Students’ common misconceptions and learning difficulties in Energy**

*Forces between masses, charges and magnets:*

Students often think of energy either as a physical substance that flows out of one thing to another or as a kind of force.

*Work done on a body:*

Students have difficulty understanding that the work done on a body represents the *energy transferred* during the interaction between the body and another system, and does not represent energy stored in a body.

*Energy is conserved:*

Students often think that energy is *used up* or *lost* (disappears) during interactions.
6.4 Dynamics: Map of key concepts and ideas covered at upper secondary level

Key inquiry question: Why do objects on Earth and in the Universe move the way they do?

1. Mass, weight and density
   - Mass is a measure of the amount of substance in a body. A body’s mass resists a change in the state of rest or motion of the body (inertia).
   - Density of a substance is the mass per unit volume of the substance i.e. density = mass / volume (ρ = m/V). Density can be measured as the mass of 1 cm³ of any substance.
   - Mass, a measure of the amount of substance in an object has a magnitude only (scalar), whereas weight, which is the force acting on a body in a gravitational field, has both magnitude and direction (vector).
   - Using Newton’s 2nd law, Force = mass x acceleration; Weight = mass x acceleration due to gravity (or gravitational field strength) (W = mg).

2. Newton’s laws of motion
   - Newton’s Laws of motion may be applied to: describe the effect of balanced and unbalanced forces on a body; describe the ways in which a force may change the motion of a body; and identify action-reaction pairs acting on two interacting bodies.
   - Newton’s 1st law states that an object remains at rest or continues with constant speed in a straight line when no resultant force acts on it (no resultant force means that all the forces acting on the object are balanced).
   - Newton’s 2nd law states that the resultant force on a body = the mass of the body x acceleration of the body (F = ma). The direction of the acceleration is the same as the direction of the resultant force acting on the body.
   - Newton’s 3rd law states that the forces of two bodies on each other (action-reaction pair) are always equal and act along the same line in opposite directions. The two forces (action-reaction pair) are of the same type. Force always appears in pair. The existence of a single force is impossible.

3. Free-body diagrams
   - Free-body diagrams and vector graphical diagrams may be used to represent and analyse the forces acting on a body.
   - A free-body diagram shows the forces acting on a body only, not the forces the body exerts on other bodies.
   - The resultant force acting on the body can be found using graphical methods (parallelogram method or ‘head-to-tail’ method).
6.5 Gravitational field: Map of key concepts and ideas covered at upper secondary level

Newton’s law of universal gravitation

**Key inquiry question:** How can we express the gravitational interaction between objects in the Universe?

1. Gravitational field
   - A *gravitational field* is a region in which a mass experiences a force due to gravitational attraction.
   - *Gravitational field strength*, \( g \) of a field is defined as the gravitational force per unit mass.

4. Field near to the surface of the Earth
   - The *acceleration of free fall* for a body near to the Earth is constant and is approximately 10 m/s\(^2\).
Students’ Knowledge and Difficulties in Dynamics and Gravitational field

Students’ prior knowledge of Dynamics and Gravitational field

Primary level:

Students learn about mass (a measure of the amount of matter in a body) and volume (the amount of space that a body occupies) and the use of appropriate apparatus to measure these quantities (e.g. use of a lever balance, an electronic balance, a measuring cylinder, a syringe, and a measuring jug). However, the concept of density is not introduced although students do simple experiments to investigate the ability of objects of different materials (plastics, wood, rubber and metals) to float/sink in water.

Students recognize that objects have weight because of the gravitational force between them and the Earth and that weight is different at different places, and can be measured using a spring balance or a weighing scale.

Lower secondary level:

Students learn that:

- the density of a substance is the mass of the substance per unit volume, and can be used to predict whether objects sink or float.
- gravity exists between any two objects (e.g. ball and Earth). The weight of an object depends on the force of gravity pulling on that object.

Students’ common misconceptions and learning difficulties in Dynamics and Gravitational field

Newton’s first law:

Students often think that:

- a force is required to maintain an object in its motion;
- if there is no motion, there is no force acting;
- constant speed results from a constant force;
- friction (instead of inertia) causes objects to resist a change in its state of rest or motion.

Newton’s second law:

Students often think that:

- a larger velocity means a larger resultant force;
- acceleration implies increasing force;
- greater mass implies greater force;
- a force cannot move an object unless it is greater than the object’s weight;
- heavier objects fall faster than light objects.
Newton’s third law:

Students often think that force is a single physical quantity associated with a single object rather than as an interaction between two objects which must therefore exist as an action reaction pair. They have difficulty in understanding that:

- two objects of greatly differing masses (e.g. Earth and us) exert forces of equal magnitude on each other;
- the normal force on an object and the weight of the object do not always have equal magnitudes;
- gravity acts on an object all the time (not just when it is falling).
"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."

- Lord Kelvin

**Historical Development of Thermal Physics**
(adapted from Rutherford, Holton, & Watson (1981), Project Physics)

*Heat as energy*

Until the middle of the 19th century, heat was thought to be a fluid called ‘caloric fluid’. Certain objects, like wood or coal that released heat upon combustion, were thought to be able to ‘store’ the fluid. However, this explanation failed to explain why friction was able to produce heat. Count Rumford, through his observations while boring cannons in the late 18th century, concluded that heat is generated when work is done and continues to appear without limit, thus opposing the idea that heat is a conserved fluid contained in an object (in this case, in the cannon). He went on to obtain a good estimation of the ratio of heat to work. However, his work was not widely accepted by the scientific community, as there was no clear explanation of what heat is in terms of the models for matter at that time.

In the 1840s, James Prescott Joule, through experiments using falling weights to heat up water, obtained values for the work done (decrease in gravitational potential energy of the falling weights) and the amount of heat produced (product of mass of water and its temperature rise). In 1849, he published his results which provided evidence that heat is a form of energy, contrary to the caloric theory, and provided a numeric ratio that related a unit of mechanical energy to a unit of heat. Joule’s experiments were a strong argument for thinking of heat as energy and eventually replaced the caloric theory of heat.

Joule repeated his experiments many times, constantly improving his apparatus and his techniques, taking care to insulate the container to reduce heat loss to the surroundings. The more careful he was, the more exact was the proportionality of the quantity of heat and the amount of work done. Scientists improve the reliability of their experimental results by doing repeated experiments and modifying their experimental setup and equipment so as to arrive at evidence-based conclusions on the physical quantities measured.
Kinetic model of matter

Following the recognition that heat is not a substance but a form of energy, and that mechanical energy can produce heat and vice versa, scientists went on to reason that the “heat energy” of a substance is simply the kinetic energy of its atoms and molecules. This new school of thought brought about the kinetic model of matter. This model assumes that matter consists of a large number of particles, behaving like elastic spheres, which are in random rapid motion. In this model, the “heat energy” or more accurately the internal energy of a substance really refers to the kinetic and potential energies associated with the particles of the substance.

As molecules could not be observed directly, scientists made predictions and calculations based on this model and checked their hypothesis through indirect observation of the macroscopic properties of matter (such as pressure, volume, density and temperature). Through this indirect approach, they were able to relate the observable properties of gases to the microscopic properties of the gases (such as the speed of the molecules) and proved that the kinetic model of matter was successful in explaining the currently known gas laws, such as Boyle’s law which relates pressure and volume of a gas. The use of models to explain physical phenomena is an important tool used in scientific discoveries.

Further evidence on the kinetic model of matter was observed through the discovery of Brownian motion in 1827. A botanist, Robert Brown in his study of pollen grains in water under a microscope observed jittery motion of the pollen particles. He repeated the experiment and found this motion was also present for non-organic substances. However, it was Albert Einstein (1905) who helped to resolve the skepticism around the kinetic model of matter by providing the statistical analysis of Brownian motion as an indirect confirmation of the existence of atoms and molecules.

Laws of thermodynamics

At this point, the concept of “heat energy” was referred to as internal energy – energy internal to a substance that does not show up. The First Law of Thermodynamics (written as \( \Delta U = Q + W \)) provided a relation which showed that the heat supplied to a system \( Q \), and the work done on a system \( W \), becomes an increase in the internal energy of the system \( \Delta U \). Thus, the first law is actually a statement of conservation of energy in nature.
By 1850, the laws of conservation of mass, momentum and energy were firmly established. Yet, these successful conservation laws could not explain why energy became less useful when ‘lost’ as heat to the surroundings, or why certain transformations were irreversible and unable to return to its original organized structure. The Second Law of Thermodynamics accounted for the observation that natural processes have a preferred direction of progress, which leads to an increase in the entropy (state of disorder) of the system. Thus, heat will always flow to regions of lower temperature, never to regions of higher temperature without external work being performed on the system.

The laws of thermodynamics and ideas of heat comprise the most fundamental laws of physics. Heat transfer occurs at the global scale as well as throughout the universe. Monsoon winds and ocean currents are due to convection currents created from the balance of heat loss and heat gained of the entire Earth as a system. Steam engines (devices to convert energy from fuels to heat energy) which drove the industrial revolution in the 18th century continue to play an important role as the turbines that drive electric generators in most electric power stations.

One interesting interpretation of the Second Law of Thermodynamics is that it defines a unique direction for the flow of time. If all irreversible transformations were allowed to be reversible, it would mean that we would not be able to tell between moving forward or backward in time as all events are reversible. Competing theories to explain the beginning of time exist to this day, and scientists continue to look for observational evidence that may help them revise their models and theories to gain insights to the beginning of our universe.
The big ideas that help to organize and connect the concepts and content in this section are:

1. When a substance gains or loses heat, the substance may change its temperature, change its state, change its volume or change to a different substance. The kinetic model allows us to understand the macroscopic properties of matter and changes in its state in terms of its microscopic molecular structure and behaviour.

2. Energy may be transferred through all materials and through free space (vacuum). Our understanding of the different mechanisms of heat transfer through different materials enables us to control and make use of heat transfer in many appliances and machines.

3. Internal energy of a body consists of the total kinetic energy and potential energy of the particles in the body. Changes in a body or a substance due to heat gain or heat loss may be explained by the change in its internal energy.

4. Thermodynamics is the study of the relationship involving heat, mechanical work and other aspects of energy and energy transfer. The first law of thermodynamics is a general statement of the law of conservation of energy that includes energy transfer through heat as well as mechanical work. The ideal gas equation gives the relationship of the pressure, volume, temperature and number of moles of a gas. This equation allows us to find the state of a gas in any situation.
Content map of Thermal Physics

7.3 Thermal Properties of Matter

**Key Inquiry Question:**
How do we describe the behaviour of different materials to heating?

**Content:**
1. Internal energy
2. Specific heat capacity
3. Specific latent heat
4. Melting, boiling and evaporation

7.2 Temperature and Heat

**Key Inquiry Question:**
How do we describe the processes of heat transfer through different materials?

**Content:**
1. Temperature
2. Heat
3. Conduction
4. Convection
5. Radiation

7.4 Thermodynamics

**First law of thermodynamics**

**Key Inquiry Question:**
How is heat transformed to mechanical energy?

**Content:**
1. First law of thermodynamics
2. The ideal gas equation
3. Kinetic energy of a molecule

7.1 Kinetic Model of Matter

**Key Inquiry Question:**
How can we explain the effects of heat gain or heat loss on matter?

**Content:**
1. States of matter
2. Brownian motion
3. Kinetic model of matter
4. Expansion and contraction of matter
7.1 Kinetic Model of Matter: Map of key concepts and ideas covered at upper secondary level

Effects of heat on matter

Key inquiry question: How can we explain the effects of heat gain or heat loss on matter?

1. States of matter
   - The physical properties of solids, liquids and gases and their molecular structures may be related to the forces and distances between molecules and to the motion of the molecules.

2. Brownian motion
   - Brownian motion provides evidence of the movement of molecules. Pollen grains in water and smoke particles in air are observed to be in constant random motion due to collisions by the unseen fast-moving molecules of water and air respectively.

3. & 4. Expansion and contraction, and Kinetic model of matter
   - When the temperature of matter (solid, liquid or gas) increases, thermal energy is transferred to the molecules and the molecules gain kinetic energy, causing them to move faster.
   - The pressure exerted by a gas may be related to the collisions of the gas molecules with the walls of the container, causing a force per unit area (i.e. pressure) acting on the container. Using the kinetic model, we can explain the relationships of the pressure, volume and temperature of a gas.
Students’ Knowledge and Difficulties in Kinetic Model of Matter

Students’ prior knowledge of Kinetic Model of Matter

Primary level:

Students will have learnt that:

- there are three states of matter - solid, liquid and gas. The states of matter may be defined by their physical properties.
- water can exist in the solid, liquid and gaseous states. A change of state can occur when water gains or loses heat.
- solids, liquids and gases can expand when they are heated (gain heat) and contract when they are cooled (lose heat).

Lower secondary level:

Students will have learnt that:

- matter is made up of small discrete particles which are in constant and random motion (kinetic theory of matter). The space between particles, their arrangement and movement determine the characteristics of the three states of matter (solid, liquid and gas).
- models (like particulate model) are constructed, justified and continuously revised as new evidence is gathered to explain a phenomena (e.g. properties of solids, liquids and gases, and changes of state such as melting and boiling).
- generally, solids, liquids and gases expand when heat is absorbed and contract when heat is given out. A notable exception is water.
- effects and applications of expansion and contraction occur in everyday life.

Students’ common misconceptions and learning difficulties in Kinetic Model of Matter

Heat gain/loss:

Students have difficulty understanding that heat is energy in transit. If heat transfers to or from a substance, the substance may change its temperature, its state, its volume or change to a different substance.

Students often think that:

- heat and cold are kinds of substances that flow into and out of materials;
- objects can have a certain quantity of heat in them.
Content map of Temperature and Heat

7.2 Temperature and Heat: Map of key concepts and ideas covered at upper secondary level

Transfer of thermal energy

Key inquiry question: How do we describe the processes of heat transfer through different materials?

1. & 2. Temperature and heat

• A physical property used to measure temperature must vary continuously with temperature. Examples are: volume of a fixed mass of liquid; resistance of a metal wire; emf produced by junctions formed with wires of two different metals.
• Two fixed points are chosen (ice point and steam point) so that a standard scale of temperature may be obtained for all thermometers that will all ‘mean’ the same temperature at each fixed point.
• Thermal energy (or heat) is transferred from a region of higher temperature to a region of lower temperature.

3., 4. & 5. Heat transfer processes

• Conduction is the process by which thermal energy is transferred through a solid (metals and non-metals) from one particle (atom or molecule) to another, without a net movement of particles. Metals conduct heat faster than non-metals as they have free electrons which are able to move through the metal, transferring the energy gained from the hotter end to other electrons and atoms through collisions. This process is much faster than the process of conduction by vibration of the atoms in the solid.
• Convection is the process by which thermal energy is transferred in a fluid (liquid or gas) through bulk movement of its particles due to density changes. Heated fluid expands and rises as it has a lower density than the cooler denser fluid which sinks to replace it, thus generating a convection current.
• Energy transfer of a body by radiation does not require a material medium and the rate of energy transfer is affected by colour and texture of the surface; surface temperature; and surface area.
Students’ Knowledge and Difficulties in Temperature and Heat

**Students’ prior knowledge of Temperature and Heat**

*Primary level:*

Students will have learnt that:

- temperature of an object is a measurement of its *degree of hotness*.
- temperature can be measured using a thermometer or a datalogger.
- things that produce heat are known as *sources of heat* (e.g. electric iron, oven, water heater). The Sun is our main source of heat.
- when something gains/loses heat, its temperature rises/falls. Heat always flows from a hotter to a colder place or object. Heat continues to flow until both places or objects have the same temperature.
- materials (e.g. metals) that allow heat to flow through them easily are called *good conductors of heat*. Materials (e.g. wood, plastics, rubber, air) that do not allow heat to flow through them easily are called poor conductors of heat.

*Lower secondary level:*

Students will have learnt that:

- *conduction* is the process of heat transfer in solids by atomic vibrations without obvious movement of the material itself.
- liquids and gases are poor conductors of heat. The main process of heat transfer is by *convection*. In the convection process, heat is moved around the material by convection currents - the hotter, less dense liquid or gas rises due to thermal expansion while the cooler, denser liquid or gas sinks.
- *radiation* is the process of heat transfer without a material medium. The *rate of heat flow* through radiation depends on the temperature of the hot object and the nature of the surface: black, dull or rough surfaces are good radiators of heat; shiny, white or smooth surfaces are poor radiators of heat.

**Students’ common misconceptions and learning difficulties in Temperature and Heat**

*Temperature and heat:*

Students have difficulty differentiating *temperature and heat* as distinct concepts: temperature depends on the physical state of a material and is a quantitative description of its hotness or coldness; heat refers to energy in transit from one body to another because of a temperature difference.

Students often think that:

- heat is contained in a body;
- the temperature of an object is related to its size or volume;
- objects at room temperature that feel different have different temperatures;
- things we use to keep warm transfer heat to our bodies;
- hot objects transfer heat, cold objects transfer cold;
- if two bodies are at the same temperature, they have the same energy or heat;
- heat and temperature are the same.
7.3 Thermal Properties of Matter: Map of key concepts and ideas covered at upper secondary level

**Internal energy of a body**

**Key inquiry question:** How do we describe the behaviour of different materials to heating?

1. Internal energy
   - The *internal energy* of a body is the sum of its total kinetic energy (due to motion of its particles) and total potential energy (due to interatomic forces between its particles) of the atoms or molecules in the body.
   - When temperature increases, the *average kinetic energy* of the particles in the body increases, hence its internal energy increases.
   - When thermal energy is *transferred* to a body, either temperature increases (an increase in total kinetic energy) or the material changes state (an increase in total potential energy).

2. & 3. Specific heat capacity and Specific latent heat
   - The *heat capacity* $C$ of a body is defined as the amount of thermal energy (or heat) required to raise the temperature of the body by one degree. $C = \frac{Q}{\theta}$. *Specific heat capacity* $c = \frac{C}{m} = \frac{(Q/\theta)m}{m}$.
   - Materials with smaller specific heat capacity will show a greater increase in temperature. Water has a high specific heat capacity (takes in greater thermal energy for a one degree rise in temperature) and is used as a cooling liquid in car engines and heating systems.
   - The energy $Q$ that is absorbed when a substance changes from solid to liquid (melting) at constant temperature is called the *latent heat of fusion* $L_f$. *Specific latent heat of fusion* $l_f = \frac{L_f}{m} = \frac{Q}{m}$.
   - The energy $Q$ that is absorbed when a substance changes from liquid to gas at constant temperature is called the *latent heat of vaporisation* $L_v$. *Specific latent heat of vaporisation* $l_v = \frac{L_v}{m} = \frac{Q}{m}$.
   - Latent heat provides the energy to increase the *internal energy* of a substance (total potential energy of particles increases) when it changes state at constant temperature (total kinetic energy of particles remains constant).

4. Melting, boiling and evaporation
   - *Melting* is a process whereby the thermal energy entering a substance changes it from a solid to a liquid, without a change in temperature. Pure substances have definite *melting point* temperatures. The melting point of a substance can be found by plotting a *cooling curve*. *Freezing* is the reverse process of melting.
   - *Boiling* is the process whereby the thermal energy entering a substance changes it from a liquid to a gas, without a change in temperature. Pure substances have definite *boiling point* temperatures. *Condensation* is the reverse process of boiling.
   - Unlike boiling, *evaporation* occurs at all temperatures, occurs only at the surface of the liquid and the energy required is absorbed from the surrounding. Factors affecting evaporation of a liquid are: its temperature; its exposed surface area; the humidity and movement of surrounding air; and external pressure.
Students’ Knowledge and Difficulties in Thermal Properties of Matter

Students’ prior knowledge of Thermal Properties of Matter

*Primary level:*

Students will have learnt that:

- water changes from one state to another: melting (solid to liquid), evaporation/boiling (liquid to gas), *condensation* (gas to liquid), freezing (liquid to solid).
- the *rate of evaporation* of a liquid can be increased by: increasing the temperature of the liquid; have wind blow over the surface of the liquid; increase the exposed surface area of the liquid.

*Lower secondary level:*

Students will have learnt that:

- changes of state such as *melting* and *boiling* may be explained using the kinetic model of matter.

Students’ common misconceptions and learning difficulties in Thermal Properties of Matter

*Heat capacity:*

Students often think that:

- heat capacity is the heat gain that is stored inside the body.
- temperature will change during melting or boiling.
CHAPTER 8: ELECTRICITY & MAGNETISM

“Nothing is too wonderful to be true if it be consistent with the laws of nature.”

- Michael Faraday

Historical development of Electricity and Magnetism
(adapted from Rutherford, Holton, & Watson (1981), Project Physics)

Concept of Field

The man who began the science of magnetism in earnest was William Gilbert (1544 – 1603), who published De Magnete in 1600. The book is a classic in scientific literature, for Gilbert detailed his largely successful attempt to test theories of magnetism by experiments. Gilbert was the first to propose that the Earth is a giant magnet and performed a clever experiment to show that his hypothesis was a likely one. Using a large piece of natural lodestone in the shape of a sphere (Gilbert called this lodestone the terrella or “little earth”), he showed that a small magnetized needle placed on the surface of the lodestone acts just as a compass needle does at different places on the earth’s surface. Discussion of the actions of magnets now generally involves the idea that magnets set up “fields” all around themselves. Gilbert’s description of the force exerted on the needle by his spherical lodestone was a step toward the modern field concept.

Prior to Gilbert’s experiments, magnetism was a complete mystery. For example, garlic was not allowed on ships due to beliefs that its pungent fumes could cause a compass to malfunction. There were also many other theories that claimed supernatural powers in lodestones and associate magnetic direction to stars and regions beyond the heavens. Even in our modern context, there are knowledge or practices that claim or are made to appear scientific but do not adhere to appropriate scientific methodology. Hence, scientific literacy is important to discern pseudoscience.

Concept of Electric Charges

Amber (fossilized tree resin) is another natural substance which ancient Greeks recognized having a strange property of attracting things when rubbed vigorously against cloth (the term “electron” comes from the Greek word for amber (translated as electrum), and was chosen because of the material’s electrostatic properties). Gilbert also studied the electrostatic behaviour of many materials and showed that electric and magnetic forces are different. However it was Benjamin Franklin who proposed a mechanical model for such behaviour. In his model, charging an object electrically involved the transfer of an “electric fluid” that was present in all matter. An excess of fluid produced one kind of electric charge, which Franklin called “positive”, while a lack of the same fluid produced the other kind of electric charge, which he called “negative”. Some other theorists proposed a “two-fluid” model involving both a “positive fluid” and a “negative fluid”. There was some dispute between advocates of the two models, but both sides agreed to speak
of the two kinds of electrical charges as “+” or “-”. It was not until the late 1890’s that experimental evidence gave convincing support to any model for “electrical charge”. In modern terms, most of the electric phenomena observed may be explained involving an excess or lack of electrons.

Gilbert strongly argued that the facts of electrostatics must be learned in the laboratory rather than by just reading about them. Similar experimentally observable facts can be summarized in a systematic way by adopting a very simple model. A model is not an experimental fact which you can observe separately. It is, rather, a set of invented ideas which help describe and summarize observations. Both experimentally observable facts and invented explanations are needed, but they are not the same thing!

Concept of Electric Force

About 1775, Benjamin Franklin noted that a small cork hanging near the outside of an electrically charged metal can was strongly attracted. But when he lowered the cork by a thread into the can, he found that no force was experienced by the cork no matter where it was positioned inside the can. Franklin did not understand what he observed and asked his friend Joseph Priestley to repeat the experiment. Priestley verified Franklin’s results and went on to reach a brilliant conclusion from them. He remembered from Newton’s book, Principia, that gravitational forces behave in a similar way. Inside a hollow planet, the net gravitational force on an object would be exactly zero. Priestley therefore proposed that electric forces exerted by charges vary inversely as the square of the distance, just as do gravitational forces exerted by massive bodies.

Priestley’s proposal was based on reasoning by analogy, which is reasoning from a parallel, well-demonstrated case. Such reasoning alone could not prove that electrical forces are inversely proportional to the square of the distance between charges, but it strongly encouraged other physicists to test Priestley’s hypothesis by experiment. It was French physicist Charles Coulomb who provided direct experimental evidence for the inverse-square law for electric charges (which is now called Coulomb’s Law) suggested by Priestley.

Coulomb’s law, which describes the interaction of electric charges, is similar to Newton’s law of universal gravitation. They both obey an inverse-square law mathematical relationship.

\[
F_{el} = \frac{k q_1 q_2}{r^2}
\]

\[
F_{grav} = \frac{G m_1 m_2}{r^2}
\]

Newton’s law of universal gravitation

Coulomb’s law

Although the mathematical formulae may look similar, they describe very different physical phenomena and have important differences. Electrostatic forces (interaction between electric charges) are much greater (by about \(10^{36}\) times) than gravitational forces (interaction between masses). Gravitational forces between masses are always attractive whereas electrostatic forces for like charges are repulsive, and unlike charges are attractive.
Electric potential difference and current

For many centuries, the only way to charge objects electrically was to rub them. Then, around 1750, a way of storing electrical charges in a properly constructed jar (called a Leyden jar) was discovered. Devices such as Leyden jars are what we now refer to as capacitors. Until late in the 18th century, a flow of charge (an electric current) could be produced only by discharging a Leyden jar. In 1800, Alessandro Volta discovered a better way of producing electric currents. He invented the first electric battery, the voltaic pile, which he produced by stacking up several thin sheets of metals (zinc and silver) separated by layers of paper soaked in a brine mixture of salt and water. Through his voltaic pile, Volta was able to produce a more or less steady electric current for a long period of time. Unlike the Leyden jar, it did not have to be charged from the outside after each use. This device led to a start of a series of inventions that have contributed to our modern technological world.

Benjamin Franklin performed a series of experiments with the Leyden jar and showed that the effects of positive and negative charges can cancel each other. Because of this cancellation, he concluded that positive and negative charges were not really different. This led him to come to a powerful and correct idea that electric charge is neither created nor destroyed. Objects become charged by rearrangement of electric charges already present in them. This principle of conservation of electric charge is taken as a basic law of nature and is widely used in applications ranging from designing circuits to analyzing subatomic reactions. It is through the systematic investigation by scientist like Franklin that the laws of nature are uncovered. Hence, it is important for students to be able to have hands-on experiences in conducting simple experiments and making conclusions based on evidence from their results to learn about the nature of science.

In order to understand electric currents, and how they can be used to transport energy, a new concept, electrical potential difference (or voltage) was needed. A simple relationship describing the proportionality between current and voltage was first found by Georg Simon Ohm. His result is now known as Ohm’s Law and his name has been given to the unit of electrical resistance.

Discovery of Electromagnetism

For a long time, no one found the connection between electricity and magnetism until Hans Christian Oersted’s discovery in 1820. He found that when he placed a compass needle directly beneath a long horizontal conducting wire, the compass needle deflected toward an east-west direction (away from the usual north-south orientation of a freely suspended magnet) when a current is passed through the wire.

Oersted’s findings generated much research into the new field of electromagnetism throughout Europe and America. Of these, the work of Andre Marie Ampere stands out as one of the great achievements in science. He laid the mathematical foundation which led to the construction of the complete theories of electromagnetism by another two great physicists, Michael Faraday and James Clerk Maxwell.
Oersted’s experiment was one of the rare occasions when a discovery suddenly opens up a whole new subject of research. The reason why it took so long before his discovery was largely due to the totally new kind of effect that was not known till then. His results were the first ever found in which a force did not act along a line connecting the sources of the force (gravitational, electrical and magnetic forces all act along such a line). In fact, the force exerted between the current-carrying wire and the magnetic poles of the compass was perpendicular to such a line. Through more intensive investigations, he concluded that an electric current produces a circular magnetic field as it flows through a wire. Oersted’s discovery was seen by many scientists as mostly due to chance. However, it is acknowledged that he was led to perform his experiment through logical reasoning. Thus, both logic and chance do go together in discovering new revolutionary ideas in science.

Practical uses of Electromagnetism

The first Industrial Revolution began in the 18th century with the development of steam engines. Following the first battery made by Volta and the first electromagnetic rotator (electric motor) constructed by Faraday, many speculated that these scientific discoveries will spark another wave of industrial revolution. However, a better way of generating steady current was needed as energy in batteries depletes quickly. Moving on from his earlier experiments on electromagnetism, Faraday believed that if electricity could produce magnetism, the reverse could also be true for magnetism to produce electricity (such reasoning from symmetry is common in physics). Although he and a few other scientists made similar findings of electromagnetic induction around the same period of time, the published results from his series of extensive investigations conducted earned him the credit for the discovery. The breakthrough led Faraday to construct the first electric generator (dynamo), which eventually evolved into modern power generators that convert mechanical energy into electrical energy.

The development of electrical generators shows an interaction of science and technology. The scientists, who understood electricity, were not particularly interested in commercial applications. On the other hand the inventors, who desired to profit from the practical usage of electricity, knew little scientific theory. Universities started providing courses such as electrical engineering and a group of specialists were equipped with both the physics as well as the application of electricity.

Thomas Edison was one of the most prolific inventors but many did not know that he was not the first to invent an incandescent light. He took the features of earlier designs and designed the first practical light bulb for widespread use in homes. Edison capitalized on his monopoly of lighting business and patented a system for electricity distribution using direct current (DC). However as the demand for electric power increased, some shortcomings of DC became evident. A more efficient system using alternating current (AC), invented by Nikola Tesla and promoted by George Westinghouse, was accepted for future power generation and distribution.
Big ideas in this section

The big ideas that help to organize and connect the concepts and content in this section are:

1. **Electrical charge** is a property of matter. **Electrons** can be transferred from one place to another, but cannot be created or destroyed.

2. Electricity is one of the most common means by which we transfer energy; the electrical current (moving charges) brings us energy from power plants when there is a complete (closed) circuit from the power plants to our homes or to industries.

3. In a closed circuit, **potential difference, current and resistance** are related; a change in any part of the circuit affects all other parts (almost) instantaneously. By using various electrical components in different arrangements, we are able to set up practical circuits to serve specific purposes.

4. Naturally occurring magnets as well as man-made magnets interact with other magnets or magnetic materials. A freely suspended magnet comes to rest pointing in the N-S direction due to its interaction with the Earth’s magnetic field.

5. Electricity and magnetism are related effects that have many applications in everyday life: moving charges (electric current) create magnetic fields; varying magnetic fields create electric fields (electromagnetic induction).
Content map of Electricity and Magnetism

8.3 D.C. circuits

Key Inquiry Question:
How do electrical components arranged in series and parallel affect the current, potential difference and resistance of the circuit?

Content:
1. Practical d.c. circuits
2. Series and parallel arrangements
3. Potential dividers
4. Balanced potentials
5. Force on a current-carrying conductor
6. Magnetic fields due to currents
7. Force between current-carrying conductors
8. Magnetic flux
9. Laws of electromagnetic induction
10. Characteristics of alternating currents
11. Transmission of electrical energy

8.2 Current of Electricity

Key Inquiry Question:
How do we describe the energy transfer by an electric current in an electric circuit?

Content:
1. Electric current
2. Potential difference
3. Electromotive force
4. Resistance & resistivity
5. Electrical power & energy
6. Safe use of electricity

8.4 Magnetism

Key Inquiry Question:
How can we describe the interaction between magnets and between magnets and magnetic materials?

Content:
1. Laws of magnetism
2. Magnetic properties of matter
3. Magnetic field

8.5 Electromagnetism & EM Induction

Key Inquiry Question:
How are electric currents and magnetic fields related and how do they interact?

Content:
1. Force on a current-carrying conductor
2. Force on a moving charge
3. Magnetic fields due to currents
4. Force between current-carrying conductors
5. Magnetic flux
6. Laws of electromagnetic induction
7. Characteristics of alternating currents
8. Transmission of electrical energy

8.1 Static Electricity

Key Inquiry Question:
How can we describe the interaction between charged bodies?

Content:
1. Electrostatic Charges
2. Concept of an electric field
3. Electric field of a point charge
4. Force between point charges
5. Uniform electric fields
6. Electric potential

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8.1 Static Electricity: Map of key concepts and ideas covered at upper secondary level

Interaction between Charges

**Key inquiry question:** How can we describe the interaction between charged bodies?

1. Electrostatic charges and electrostatic charging
   - There are positive and negative charges and unlike charges attract and like charges repel.
   - *Electrostatic charging* may be by rubbing (which involves a transfer of electrons) and by induction.
   - There are many examples and applications of electrostatic charging in everyday life.

2. Concept of an electric field
   - An *electric field* is a region in which an electric charge experiences a force and the direction of the field lines gives the direction of the force acting on a *positive test charge*.

3. Electric field of a point charge
   - The *electric field pattern* for an isolated point charge and between two isolated point charges have distinguishing features - the lines must start from a positive charge and end on a negative charge; lines closer together indicates a stronger field; number of lines is proportional to magnitude of charge; field lines cannot cross each other.
Students’ Knowledge and Difficulties in Static Electricity

Students’ prior knowledge of Static Electricity

Primary level:

- Students will not have been introduced to the concept of static charges. They would have knowledge of current flow through a closed circuit but do not relate current as a flow of charges.

Lower secondary level:

- Students learn about charges through the topics ‘particulate model of matter’ and ‘simple concepts of atoms and molecules’.

Students’ common misconceptions and learning difficulties in Static Electricity

Charges on a charged body:

- Students have difficulty understanding that the net charge of a charged body is due to an excess/shortage of electrons making it net negatively/positively charged, and the net charge is therefore a multiple of the elementary charge - charge of an electron.

- Students often think that:
  - charge is continuous and can occur in any amount;
  - a charged body has only one type of charge;
  - an electron is pure negative charge with no mass.
8.2 Current of Electricity: Map of key concepts and ideas covered at upper secondary level

Current and Energy Transfer

**Key inquiry question:** How do we describe the energy transfer by an electric current in an electric circuit?

1. Electric current
   - *Current* is a rate of flow of charge
   - \( I = \frac{Q}{t} \). Conventional current flow is used to describe the direction of the flow of current, and is opposite to the scientific model of electron flow.

2. Potential difference, p.d.
   - The p.d. across a component in a circuit is the work done to drive a unit charge through the component \( V = W/Q \). A voltmeter connected in parallel to the component measures the p.d. across it.

3. Electromotive force, Emf
   - *Emf* is the work done by a source in driving a unit charge around a complete circuit \( E = W/Q \).
   - In a cell or battery, chemical changes take place which provides the energy required to drive the electric charge (electrons) round the circuit.
   - Emf of a cell can be measured by connecting a voltmeter directly across its terminals.

4. Resistance and resistivity
   - *Resistance* is the ratio of the p.d. across the component to the current flowing through it \( R = V/I \). The value of an unknown resistor \( R \) can be found experimentally by taking the average \( R \) of corresponding \( V \) over \( I \) ratios.
   - The current and *effective resistance* in a circuit depends on the number of resistors and how they are connected in the circuit.
   - The resistance of a wire is proportional to its length and inversely proportional to its cross-sectional area. *Resistivity* \( \rho \) is a property of the material of a wire. Good conductors have low resistivity, poor conductors have high resistivity.
   - *Ohm’s Law* states that the graph of \( V \) against \( I \) for a metallic conductor at constant temperature passes through the origin, the gradient of the graph giving the constant resistance of the metal conductor. As temperature increases, resistance of a metal conductor increases.
   - *I-V graphs* for a filament lamp and semiconductor diode do not obey Ohm’s law.

5. Electrical power and energy
   - The *total emf* of several sources connected the same way in series is the sum of the individual emfs. For cells connected in parallel, the total emf is the same as the emf of each cell. However, the cells will last longer and can supply a higher current.
   - The rate of energy converted in an appliance is given by Power = \( p.d \times \text{current} \) (\( P = VI \)).
6. Safe use of electricity

- The heating effect of electricity is used in appliances. The energy converted by an appliance is given by \( E = p.d. \times \text{current} \times \text{time} \) (\( E = \text{Vlt} \)). The \( kW \ h \) is the energy unit used to calculate the cost of using electrical appliances.

- Non-renewable and renewable energy sources such as fossil fuels, nuclear energy, solar energy, wind energy and hydroelectric generation used to generate electricity have different energy conversion efficiencies, cost per \( kW \ h \) produced and environmental impact.

- The hazards of using electricity include the following situations: damaged insulation; overheating of cables; and damp conditions. There is a need for earthing metal cases and for double insulation for safety. Live, neutral and earth wires are wired into a mains plug. Switches, fuses, and circuit breakers are wired into the live conductor (rather than the neutral conductor) for safety.
Students’ Knowledge and Difficulties in Current of Electricity

Students’ prior knowledge of Current of Electricity

Primary level:

Students will have learnt that:

- an electric circuit consisting of an energy source (battery) and other circuit components (wire, bulb, switch) forms an electrical system.
- the flow of electricity in an electric circuit is called an electric current; a circuit through which electric current can/cannot flow is called a closed/open circuit.
- materials (e.g. metals) that allow electric current to flow through them easily are called electrical conductors. Materials (e.g. non-metals like glass, wood, plastic) that do not allow electricity to flow through them are called electrical insulators. Good conductors of electricity are generally good conductors of heat.
- it is important to conserve electricity and to use and handle it properly.

Lower secondary level:

Students will have learnt that:

- current is the rate of flow of electric charges (unit: ampere A). Electric current flows only when there is a source of electrical energy (e.g. electric cells and mains electricity) and a closed circuit. The cell provides the energy for electrons from the metal atoms to flow around the circuit, from the negative terminal of the cell and back to the positive terminal.
- potential difference or voltage is a measure of the difference in electrical potential energy of an electron between two points (unit: volt V).
- metals (e.g. copper, iron and aluminium) are electrical conductors. Non-metals are usually insulators (e.g. glass, plastic, wood, rubber). Our body is a conductor of electricity.
- electrical components have resistance which opposes the flow of electrons; the greater the resistance, the smaller the current flow (unit: ohm Ω). The current in a circuit is varied by varying the resistance in the circuit using fixed or variable resistors.
- power is the rate of energy converted in an appliance. Energy consumed = power (kW) x time (h) (unit: kilowatt-hour kW h). It is important to reduce electrical energy wastage.
- an electric current produces chemical, heating and magnetic effects that are used in some applications (e.g. electroplating, extraction of metals, water heaters, iron, electric motors and bells).
- precautionary measures are taken against electrical hazards (e.g. electric shock, electrical fires) to ensure the safe use of electricity in the home.
Students’ Knowledge and Difficulties in Current of Electricity

Students’ common misconceptions and learning difficulties in Current of Electricity

The battery as a source of energy:

Students often think that:

- electricity is a kind of material contained in a battery and it is “used up” by a bulb;
- the distance from a battery determines the brightness of a bulb (nearer brighter, further less bright);
- the battery is a constant current source;
- charges that flow in a circuit are from the battery;
- voltage flows through a circuit;
- voltage is energy.

Electric current:

Students often think that:

- resistors (and bulbs) “consume” charge;
- current is the same thing as or causes potential difference (voltage);
- current travels round a circuit from the battery, it gets “used up” as it goes along so that there is less current at the ‘end’ of the circuit.
8.3 D.C. circuits: Map of key concepts and ideas covered at upper secondary level

Electrical Circuits

Key inquiry question: How do electrical components arranged in series and parallel arrangements affect the current, potential difference and resistance of the circuit?

1. Practical d.c. circuits
   - An electric circuit is a complete or closed path through which charge can flow from one terminal of an electrical source to the other.
   - A circuit diagram is used to represent an actual circuit and uses symbols to denote electrical components in the circuit.

2. Series and parallel arrangements
   - The current at every point in a series circuit is the same. Current is measured using an ammeter connected in series to the circuit.
   - The sum of the p.d.’s in a series circuit is equal to the p.d. across the whole circuit.
   - Emf is a measure of the electrical potential energy which charges gain as they pass through the battery. As the charges flow round a circuit, they lose their potential energy, transforming it to other forms of energy. Total energy gained must equal total energy lost. Therefore, sum of emfs = sum of p.ds.
   - The current from the source is the sum of the currents in the separate branches of a parallel circuit. The p.d. across the separate branches of a parallel circuit is the same.
   - For resistors in series, the effective resistance is the sum of the individual resistances. For resistors in parallel, the reciprocal of the effective resistance is equal to the sum of the reciprocals of the individual resistances.

3. & 4. Potential divider
   - When a variable resistor is used to vary voltage, it is known as a potential divider or potentiometer. Fixed and variable resistors, thermistors and light-dependent resistors are used in variable potential divider circuits.
Students’ Knowledge and Difficulties in D.C. Circuits

Students’ prior knowledge of D.C. circuits

*Primary level:*

Students will have learnt that:

- *circuit diagrams* are used to represent actual electric circuits; electrical components (e.g. battery, wire, switch and bulb) are represented in circuit diagrams by different symbols.
- the current in a circuit is affected by the number of batteries, the number of bulbs and the arrangement of the bulbs *(series and parallel)*.

*Lower secondary level:*

Students will have learnt that:

- in a circuit diagram, symbols are used to represent the various components in a circuit (e.g. electric cell, battery, bulb, switch, connecting wires, ammeter (connected in series), voltmeter (connected in parallel), resistors (fixed and variable)).
- electric circuits can be classified into two main types: series and parallel. In a *series* arrangement, components are joined one after another to form a single path and the current flowing through each component is the same; a *parallel* arrangement has two or more branches, with electrical components in each of the branches. The current from the battery divides and flows through each branch.
- when more resistors are added in series, overall resistance in the circuit increases. When more resistors are added in parallel, overall resistance in the circuit decreases.

Students’ common misconceptions and learning difficulties in D.C. circuits

*Electric circuit:*

Students often think that:

- electrons move quickly (near the speed of light) through a circuit;
- current gets “used up” as it flows through the components of a circuit;
- current flows to each part of the circuit in turn and a change in the circuit affects only those parts which ‘come after’ the change;
- the resistance of a parallel combination is larger than the largest resistance;
- circuit diagrams are interpreted based on their diagrammatic layout and degree of symmetry rather than the electrical connections.
8.4 Magnetism: Map of key concepts and ideas covered at upper secondary level

Magnetic Interactions

**Key inquiry question:** How can we describe the interaction between magnets and between magnets and magnetic materials?

1. Laws of magnetism
   - Like poles of magnets *repel*, unlike poles *attract*.
   - Magnets attract magnetic materials through *magnetic induction*.
   - Repulsion is the only test to check if a specimen is a magnet. Attraction only tells us the specimen may be a magnet or a magnetic material.

2. Magnetic properties
   - Magnetic materials (e.g. iron and steel) may be *magnetised* and *demagnetised* through electrical methods. Magnetic materials may also be magnetised by the stroking method.
   - Magnets may be used as *temporary* magnets (e.g. iron) and permanent magnets (e.g. steel). Iron, which is easier to magnetise but loses its magnetism easily, is known as a soft magnetic material. Steel, which is harder to magnetise but does not lose its magnetism easily, is known as a hard magnetic material.

3. Magnetic fields
   - *Magnetic field lines* around a bar magnet and between the poles of two bar magnets may be plotted using plotting compasses. Magnetic field lines start from the north pole and end at the south pole; lines never cross each other; lines closer together represent a stronger magnetic field; a uniform field is represented by parallel lines.
   - The *magnetic field strength* of an electromagnet can be increased by passing a larger current through the coil; increasing the number of turns of the coil; inserting a soft iron core in the coil.
Students’ Knowledge and Difficulties in Magnetism

Students’ prior knowledge of Magnetism

Primary level:

Students will have learnt that:

- magnets have two poles (north pole and south pole) and can exert a push or a pull; unlike poles attract, like poles repel.
- magnets attract magnetic materials; the attraction of a magnet is the strongest at its poles (ends of the magnet).
- magnets can be made of iron or steel using the stroke method or the electrical method (electromagnet).
- not all metals are magnetic materials; all non-metals are non-magnetic materials.
- magnets are used in everyday objects.
- a freely suspended bar magnet comes to rest pointing in the North-South direction (the pole pointing to the North is called the north pole of the magnet; the pole pointing to the South is called the south pole).

Lower secondary level:

Students are expected to apply their knowledge of magnetism learnt at primary level in the topics ‘interaction of forces’ and ‘separation technique of a mixture’.

Students’ common misconceptions and learning difficulties in Magnetism

Magnetic poles:

Students often think that:

- the north and south magnetic poles are the same as positive and negative charges;
- magnetism is like a type of gravity.

Magnetic effect of a current:

Students often think that the wire, rather than the current, is the cause of magnetic effect, and only an uninsulated wire in a circuit would show a magnetic effect.
Current and Magnetic Field

**Key inquiry question:** How are electric currents and magnetic fields related and how do they interact?

1. & 2. Force on current-carrying conductors and moving charges

- The force acting on a current-carrying conductor, and on a beam of charged particles, in a magnetic field, is affected when the current or the direction of the field is reversed. The relative directions of force, field and current (moving charges) when any two of these quantities are at right angles to each other may be found using Fleming’s Left Hand rule.
- A current-carrying coil in a magnetic field experiences a turning effect which is increased by increasing the number of turns on the coil and/or the current. This turning effect is used in the action of an electric motor. The action of a split-ring commutator in a two-pole, single-coil motor and the effect of winding the coil on to a soft-iron cylinder play important roles in the motor.

3. & 4. Magnetic fields due to currents

- The magnetic fields due to currents in straight wires and in solenoids have specific features and are affected by changing the magnitude and/or direction of the current.
- The relationship between the direction of magnetic field lines around a wire and the direction of current in the wire can be deduced using the right-hand grip rule.
- The field patterns between currents in parallel conductors are related to the forces which exist between the conductors. The action of a circuit breaker uses the magnetic effect of a current.


- From Faraday’s experiments on E.M. induction, we can deduce that a changing magnetic field can induce an emf in a circuit and the direction of the induced emf opposes the change producing it.
- Faraday’s law of E.M. induction states that the magnitude of the induced emf is proportional to the rate of change of the magnetic flux linked with the circuit or the rate at which the magnetic flux are cut.
- Lenz’s law of E.M. induction states that the induced current is always in a direction to oppose the change producing it. Lenz’s law follows from the law of conservation of energy.

7. Characteristics of alternating currents

- The magnitude of the induced emf from an a.c. generator can be increased by: increasing the speed of rotation or number of turns of the coil; winding the coil on a soft iron core; and using stronger magnets. Slip rings are used in an a.c. generator to produce an alternating voltage output.
- A V-t graph is used to represent the variation of output voltage vs time for a simple a.c. generator. A cathode-ray oscilloscope (c.r.o.) is used to display waveforms and to measure p.d.’s and short intervals of time.
8. Transmission of electrical energy

- An *ideal transformer* may be used to transform the voltage from an a.c. generator (stepped-up or stepped-down). The values of the voltages and turns ratio are related using the equation $V_p / V_s = N_p / N_s$.
- From conservation of energy, for an ideal transformer, output power = input power, $V_s I_s = V_p I_p$.
- High voltage transmission reduces the energy loss in cables. To reduce heat loss through transmission cables ($I^2R$), $I$ is reduced by stepping up the transmission voltage $V$.
- Power loss = $I^2R = (P/V)^2R$
Students’ Knowledge and Difficulties in Electromagnetism and E.M. Induction

Students’ prior knowledge of Electromagnetism and E.M. Induction

Primary level:

Students will not have been introduced to the concept of Electromagnetism and E.M induction. They would have indirect knowledge through the use of electrical method to make a magnet.

Lower secondary level:

Students will not have been introduced to the concept of Electromagnetism and E.M induction formally. They would have indirect knowledge through the examples of applications of electricity in electric motors and bells.

Students’ common misconceptions and learning difficulties in Electromagnetism

Electromagnetism:

Students often think that:

- charges at rest can experience magnetic forces;
- magnetic flux, rather than change of magnetic flux, causes an induced emf;
- voltage can only be induced in a closed circuit;
- a step-up transformer gives you something more for less input;
- for alternating currents, charges move all the way around a circuit and all the way back.
CHAPTER 9: WAVES

“All the mathematical sciences are founded on relations between physical laws and laws of numbers, so that the aim of exact science is to reduce the problems of nature to the determination of quantities by operations with numbers.”

- James Clerk Maxwell

Historical development of Waves
(adapted from Rutherford, Holton, & Watson (1981), Project Physics)

Wave motion

17th century scientists were convinced that all physical phenomena could eventually be explained by considering matter and its motion. This mechanistic view point became known as the Newtonian world view. However, as scientists continued their study into the rich and complex processes in the real world, they found that the molecular model was not the only way to understand the behaviour of matter. Many phenomena (e.g. sound and light) could also be interpreted in terms of wave motions in continuous matter.

By the end of the 19th century, another means of description of physical phenomena, based on the idea of fields, became widely accepted to explain gravitational, electric and magnetic forces (the concept of a field is now generally believed to be the best way to discuss all physical forces). Scientists develop models that can best explain physical phenomena, modifying and even sometimes replacing existing models to accommodate new experimental results and observations.

A wave can be described as a disturbance that travels from one location to another location in a medium. In all cases involving waves, the effects produced depend on the flow of energy as the wave moves forward. Mechanical waves (e.g. water waves, seismic waves, sound waves) are waves where bodies or particles of the continuous medium in which the waves are travelling, physically move back and forth. There are also wave disturbances, electromagnetic waves (e.g. light, radio waves, microwaves), that can travel through a vacuum due to propagating electric and magnetic fields.
In the study of waves, we can describe the waves in terms of the behaviour of particles (fields in the case of Electromagnetic waves) or in terms of waveforms traveling from one point to another. Displacement-time and displacement-distance graphs are commonly used to represent waves.

Waves traveling through a medium change their behaviour when they encounter a barrier (reflection or diffraction), transfer to another medium (refraction), or interact with other waves (interference). Two important principles related to these observed properties of waves are:

1. Huygens’ principle - every point on a wavefront may be considered to behave as a point source for waves generated in the direction of the wave’s propagation; and
2. Superposition Principle of Waves - the resultant displacement of two or more waves meeting at a point is the sum of the individual displacements of each wave at that point.

Sound waves

The idea of sound as a wave grew out of thinking of water waves, and this reasoning by analogy was reinforced through observations of:

- the air motion generated by a vibrating body sounding a single musical note – this was observed to be also vibratory and of the same frequency as the body;
- the finite speed of sound traveling through air - French mathematician Marin Mersenne computed the speed of sound by timing echoes over a known distance; and
- the bending of sound around corners – water waves are also observed to exhibit diffraction, a wave phenomena.

In 1660, Robert Boyle described his experiment which demonstrated that the sound of a bell in a vacuum chamber faded as air was removed, proving that air was necessary for the transmission of sound. Today, we consider sound waves as waves that propagate through a medium, producing changes of density and pressure in the medium through which they travel. The medium can be solid, liquid or gas. Pitch and loudness are psychological responses of human hearing associated with the energy carried by the wave from the vibrating source of sound. The pitch of a sound goes up as the frequency of the wave increases and the loudness of sound is strongly related to the intensity (or amplitude) of the wave.

![Graphical representation of pitch and loudness](image-url)
The early studies of light were influenced by the need to understand natural phenomena such as lightning, sunlight, starlight and fire. The ancient Greek scientists and philosophers did not make any distinction between light and vision. Light to them, was not something that existed apart from seeing. But gradually, there arose a view that light actually “exists” regardless of whether or not someone is looking.

The early idea was that vision is initiated in the eyes, where light is believed to travel from, to the object and in return we are able to see. This is known as the Tactile theory. This model was found to be not sustainable as it was unable to explain why we cannot see in the dark. Aristotle then developed another theory called the Emission theory which states that the sense of sight is activated when a luminous object emits energy. Newton, however, through his observations of the rectilinear nature of light concluded that light consists of very small, light, fast particles that he called corpuscles. Despite being challenged by other scientists (e.g. Robert Hooke and Christian Huygen), Newton’s Corpuscular theory eventually prevailed due to his stature as a widely acknowledged iconic physicist.

In 1801, the situation changed dramatically when an English scientist, Thomas Young, announced that he had produced interference between two waves of light (an experiment that was difficult to perform with the technology of that era). His experimental results quickly settled the debate in favour of the Wave theory of light as interference is distinctly a wave-like phenomenon. In 1845, Michael Faraday made experimental observations which suggested that light is an electromagnetic wave, an oscillation of the electromagnetic field that does not require a material medium in which to travel.

Then, at the beginning of the 20th Century, physicists were faced with challenges in explaining the photoelectric effect, a phenomenon which could not be accounted for by classical theories of light. Albert Einstein eventually proposed a model to explain the phenomenon by treating light as a novel type of wave having certain particle like characteristic, known as photons (Einstein was awarded the Nobel Prize in 1922 for his work on photoelectric effect). Einstein’s introduction of the concept of photons (Photon theory of light) marked the end of classical physics and the beginning of a new era called quantum physics. However, although Einstein was able to develop his theory systematically, there were still some weaknesses. While some phenomena could be explained assuming light as electromagnetic waves, other phenomena could only be explained by assuming that it comprises of photons.

The development of the ideas of light leads us to a closer examination of the relationship between waves and particles. Classical physics made a clear distinction between waves and particles, whereby each of the objects in nature could be characterized as one or the other. However, as we enter the atomic realm, we realize that things may not be so clearly classified. Protons, electrons and even light are found to have characteristics of both particles and waves. In the subatomic world, rather than a wave-particle dichotomy of classical physics, we come to recognize a wave-particle duality in quantum physics.

The genesis in the evolution of ideas about the nature of light over the years is also a story of the toil of many physicists’ search for knowledge. This quest for an understanding of nature has guided many scientists in their relentless pursuit to uncover the workings of the world, overcoming the constraints and limitations of methodologies of their times through ingenuity and perseverance.
In 1800, British astronomer William Herschel was measuring the effect of various colors of light on a thermometer, using a prism to disperse light from the sun. Upon putting the thermometer past the red light, he noted an even larger increase in temperature than when the thermometer was bathed in visible light. It was obvious that there was “light” beyond the color red; this light was eventually termed “infrared” light. Around the same period, a German scientist Johann Ritter noted that the region of the colour spectrum just beyond the violet edge of visible light was more effective at turning silver halides dark. He reasoned that there was an invisible form of light beyond violet, which was later given the term “ultraviolet” light. These two discoveries led to the realization that the term “light” refers to a lot more than just visible light.

In the 1860s, Scottish physicist James Clerk Maxwell developed four fundamental mathematical equations (known as Maxwell’s Electromagnetic Equations) that gave the relations between the electric and magnetic fields. Maxwell was the first to see that his equations predict the existence of electromagnetic waves and his suggestion that ordinary visible light is an electromagnetic wave is one of the milestones in the history of science. This observation unified the fields of electromagnetism and optics, which were unrelated until then. Maxwell came to this suggestion by noticing that the speed of propagation of electromagnetic waves was very close to the speed of light.

Maxwell’s equations also implied that infrared light, visible light, and ultraviolet light are all the same phenomenon (with the same velocity), but with different values of wavelength and frequency and that there exist an entire range of possible wavelengths and frequencies for electromagnetic radiation making up the electromagnetic spectrum.

Following the development of Maxwell’s equations, many scientists set about deliberately creating electromagnetic radiation in a different region of the spectrum. This led to the generation of radio waves and microwaves (Heinrich Hertz), and the discovery of X-rays (Wilhelm Röntgen) and Gamma rays (Paul Villard). Today, we are able to enjoy the benefits of these scientists’ important discoveries, especially in the area of information and communication technology and in medical applications.
Big ideas in this section

The big ideas that help to organize and connect the concepts and content in this section are:

1. Waves are *disturbances* that propagate from one region of space to another. Waves are inherent in our everyday lives; how we hear, see and communicate is due to the way waves travel and transfer energy from a source (or disturbance) to places around it.

2. Sound waves are *vibrations* that propagate through a material medium. The speed of sound depends on the *medium* through which it travels; sound travels fastest through a solid, and slowest through a gas.

3. Light belongs to a family of waves known as *Electromagnetic waves*. Electromagnetic waves can propagate even in empty space where there is no material medium. Light and all other electromagnetic waves travel at the same speed ($3.0 \times 10^8$ m/s) through a vacuum. Electromagnetic waves have many important applications in communication, home appliances, medical and industrial use.

4. When two waves overlap, their total displacement is the sum of the individual displacements of the individual waves. This is the *principle of superposition of waves* which is applied to explain the formation of *stationary waves* and *interference patterns*. 
### 9.1 Wave motion

**General properties of waves**

**Key Inquiry Question:**
How can we describe wave motion?

**Content:**
1. Wave description
2. Longitudinal and transverse waves

### 9.2 Sound

**Sound propagation**

**Key Inquiry Question:**
How do we describe the characteristics and propagation of sound?

**Content:**
1. Speed of sound
2. Pitch and loudness
3. Echo
4. Ultrasound

### 9.3 Light

**Light propagation**

**Key Inquiry Question:**
How do we describe the interaction of light with different media?

**Content:**
1. Reflection of light
2. Transmission of light
3. Refraction of light
4. Action of thin lenses

### 9.4 Electromagnetic spectrum

**Electromagnetic waves**

**Key Inquiry Question:**
How do EM waves affect our lives?

**Content:**
1. Properties of EM waves
2. Applications of EM waves
3. Effects of EM waves

### 9.5 Superposition

**Wave superposition and interference**

**Key Inquiry Question:**
How do waves interact when they pass through the same space at the same time?

**Content:**
1. Superposition principle
2. Stationary waves
3. Diffraction
4. Interference
5. Two-source interference patterns
6. Diffraction grating
9.1 Wave motion: Map of key concepts and ideas covered at upper secondary level

General properties of waves

**Key inquiry question:** How can we describe wave motion?

1. Wave description
   - Waves *transfer energy* through vibrations without transferring matter (e.g. vibrations in ropes and springs and water waves).
   - Wave motion is described by its speed \( v \), frequency \( f \), wavelength \( \lambda \), period \( T \) and amplitude \( A \). Wave speed is given by \( v = \frac{\lambda}{T} = f \lambda \).
   - The line that joins all the peaks of a wave or all identical points on a wave is called a *wavefront*.

2. Longitudinal and transverse waves
   - *Transverse* waves travel in a direction perpendicular to the direction of the vibrations (e.g. electromagnetic waves, waves on ropes). *Longitudinal* waves travel in a direction parallel to the direction of vibrations (e.g. sound waves).
   - Transverse and longitudinal waves may be represented using *displacement-position* and *displacement-time* graphs.
Students’ Knowledge and Difficulties in Wave motion

Students’ prior knowledge of Wave motion

*Primary level:*

Students will not have been introduced to the concept of wave motion.

*Lower secondary level:*

Students will not have been introduced to the concept of wave motion. They would learn about the kinetic model of matter.

Students’ common misconceptions and learning difficulties in Wave motion

Students have difficulty understanding that waves transfer energy from a disturbance to other places without the transfer of matter.

Students often think that:

- waves transport matter;
- there must be a medium for a wave to travel through;
- waves do not have energy;
- all waves travel the same way.
9.2 Sound: Map of key concepts and ideas covered at upper secondary level

Sound propagation

**Key inquiry question:** How do we describe the characteristics and propagation of sound?

1. Transmission of sound
   - Sound waves are *longitudinal* waves produced by vibrating sources which causes *compressions* and *rarefactions* of air particles.
   - A medium is required in order to transmit sound waves and its speed is fastest through solids, and slowest in gases.

2. Pitch and amplitude
   - The *pitch* of a note depends on its *frequency*; high frequency relates to a high pitch.
   - The *loudness* of a sound wave is related to the *amplitude* of the sound wave.

3. & 4. Applications of sound
   - The speed of sound in air may be determined using an *echo* method. The reflection of sound may produce an echo, and may be used for measuring distances.
   - *Ultrasounds* are sound waves with frequency greater than 20kHz which has many medical and commercial uses (e.g. ultrasound scanning, sonar, quality control).
Students’ Knowledge and Difficulties in Sound

Students’ prior knowledge of Sound

*Primary level:*

Students will not have been introduced to the concept of sound.

*Lower secondary level:*

Students will not have been introduced to the concept of sound. They would learn about the kinetic model of matter.

Students’ common misconceptions and learning difficulties in Sound

Students have difficulty understanding that all sounds are produced by vibrations and require a material medium to travel through.

Students often think that:

- sound is due to the physical property of materials that makes the sound;
- sound does not need a medium as air is empty space.
Content map of Light

9.3 Light: Map of key concepts and ideas covered at upper secondary level

Light propagation

**Key inquiry question:** How do we describe the interaction of light with different media?

1. **Reflection of light**
   - We can see objects when the light they *emit* or *reflect* enter our eyes.
   - Laws of reflection:
     - the *incident* ray, *reflected* ray and the *normal* at the point of incidence all lie in the same plane;
     - the *angle of incidence* = *angle of reflection*.
   - *Ray diagrams* are constructed to show the reflected rays and image formed from a plane mirror.

2. & 3. **Refraction of light**
   - When light changes direction (or bends) as it passes from one medium to another, *refraction* is said to take place. Light travels slower in an optically denser medium than vacuum (or air).
   - Laws of refraction:
     - the *incident* ray, *refracted* ray and *normal* all lie in the same plane;
     - the ratio \( \sin i / \sin r \) is a constant, where *i* is the *angle of incidence* (in vacuum or air) and *r* is the *angle of refraction* (in the medium).
   - *Refractive index* \( n \) of the medium = \( \sin i / \sin r \) (vacuum or air has refractive index = 1; all other medium has \( n >1 \)). Refractive index \( n \) of a medium is also given by the ratio of speed of light in vacuum and in the medium (\( n = c/v \)).
   - For *total internal reflection* (reflection within the denser medium) to occur:
     - incident ray must travel from an optically denser medium towards a less dense medium;
     - angle of incidence > *critical angle* of the medium. Critical angle is the angle of incidence in the denser medium when the angle of refraction in the less dense medium = 90°.
   - Total internal reflection is applied in optical fibres in telecommunication allowing for long range transmission of signals with negligible signal loss.

3. **Action of thin lenses**
   - A *thin converging lens* converges rays of light passing through it; a *diverging lens* diverges (spreads out) the rays of light.
   - The *focal length* of a lens \( f \) is the distance between its *optical centre* and *principal focus*.
   - Ray diagrams are constructed to show *real* and *virtual* images of an object formed by a thin converging lens.
Students’ Knowledge and Difficulties in Light

Students’ prior knowledge of Light

Primary level:

Students will have learnt that:

- Light is a form of energy that helps us see. Sources of light are objects that give off light; objects that do not give off light reflect light into our eyes.
- Light travels in straight lines. When light is completely or partially blocked by an object, a shadow (dark area) is formed; the shadow of an object depends on its position and orientation.
- Transparent objects allow light to pass through them; translucent objects allow some light to pass through them; opaque objects do not allow light to pass through them.

Lower secondary level:

Students will have learnt that:

- Luminous objects produce light. Most objects are non-luminous and we can see them when light is reflected from them.
- Light travels in straight lines and obeys the law of reflection. A clear image is seen in a mirror because of regular reflection; no clear image is seen from a rough surface as diffuse reflection occurs.
- The image formed by a plane mirror is: at the same distance as the object distance; upright: same size as the object; virtual; laterally inverted.
- Light changes direction (undergoes refraction) when it travels from one transparent medium to another due to change in speed of light (slow down in denser medium). Light bends towards the normal when it moves from less dense to denser medium, and bends away when it moves from denser to less dense medium.
- Refraction can: cause objects to appear nearer to the surface; disperse white light that passes through a prism into its spectrum.
- When white light shines on a coloured object, we see the colour reflected, not the colours absorbed.
- Light travels at 300 000 km/s.

Students’ common misconceptions and learning difficulties in Light

Students often think that:

- The eye is the active agent in gathering light, rather than just being a receiver of reflected light;
- Light helps us see simply by illuminating objects and making them visible;
- White light is colourless and pure;
- Different colours of light are different types of waves;
- The addition of all colours of light gives black;
- The speed of light never changes;
- There is no interaction between light and matter;
- In refraction, the frequency (colour) of light changes.
9.4 Electromagnetic Spectrum: Map of key concepts and ideas covered at upper secondary level

Electromagnetic waves

**Key inquiry question:** How do electromagnetic waves affect our lives?

1. Properties of electromagnetic waves
   - All electromagnetic waves are *transverse* waves that travel with the same speed in vacuum \((3 \times 10^8 \text{ m/s})\).
   - Electromagnetic waves are due to the simultaneous vibrations of electric and magnetic fields.

2. Applications of electromagnetic waves
   - Examples of the use of electromagnetic waves are:
     - radiowaves (e.g. radio and television communication);
     - microwaves (e.g. microwave oven and satellite television);
     - *infra-red* (e.g. infra-red remote controllers and intruder alarms);
     - *light* (e.g. optical fibres for medical uses and telecommunications);
     - *ultra-violet* (e.g. sunbeds and sterilisation);
     - *X-rays* (e.g. radiological and engineering applications);
     - *gamma rays* (e.g. medical treatment)

3. Effects of electromagnetic waves
   - Electromagnetic waves with high frequency (short wavelengths) e.g. X-rays and gamma waves, have high energy *ionising radiation* that can remove electrons from neutral atoms. Ionisation is harmful to living cells and may destroy or cause modifications in living tissues.
Students’ Knowledge and Difficulties in Electromagnetic Spectrum

Students’ prior knowledge of Electromagnetic Spectrum

*Primary and Lower Secondary levels:*

- Students at the primary and lower secondary levels will not have learnt the concept of electromagnetic waves.

Students’ common misconceptions and learning difficulties in Electromagnetic Spectrum

- Electromagnetic spectrum is an abstract concept that students at the lower levels would generally not have encountered and therefore they would be unfamiliar with the examples of the electromagnetic waves and their characteristics in the electromagnetic spectrum.
In Part III, we focus on the teacher as an inquirer of teaching and learning.

Chapter 10 “Teachers as learners, teachers as researchers” highlights the importance of teacher research as a form of continual professional development for all teachers. Descriptions of action research and lesson study are provided to illustrate two common examples of teacher-research used in schools. Teacher networks are also highlighted as a means to extend and sustain teachers’ professional development through collaborative physics learning communities.
Chapter Overview

As early as 1904, John Dewey emphasized the importance of teachers being students of teaching. He further advocated that teachers should develop their understanding of teaching and learning through reflection of their own practice. This chapter highlights the importance of networked learning and teacher-research as means for professional development to grow teacher researchers to become reflective practitioners. Two common examples of teacher-research used in schools - action research, and lesson study will be discussed. At the end of the chapter, professional network is highlighted as a means for teachers to participate in continual, collaborative communities for professional development.

In the previous chapters, we see that good physics teachers differ from good subject matter experts in their knowledge of how physics content and concepts may be organized, transformed and represented in ways that are comprehensible to a diverse range of students’ abilities. This knowledge, known as pedagogical content knowledge (PCK), has been shown to produce positive differences in student achievement in learning. However, PCK cannot be meaningfully acquired through teacher training, particularly in the traditional form of short-term generic workshops using a dissemination approach. Often, these training workshops have little effect on changing the way teachers teach in their classrooms. This may be attributed to the lack of follow-up and support after the training to motivate teachers to implement the new knowledge and skills in their teaching. Another, more important reason may be due to the contextualized, local, and situated nature of teaching and learning, which makes it very difficult for teachers to apply generic pedagogical theories in their specific context in school (Florio-Ruane, 2002). Research suggests that instead of ‘one-shot’ workshops, long-term, site-based professional development opportunities better engage teachers in learning, build from their current knowledge and practices, and help them examine their beliefs with intent to transform practice (Lassonde & Israel, 2010).

Teacher-research

A new genre of professional development, referred to as practitioner inquiry or teacher-research involves teachers doing disciplined and systematic inquiry into their own practices. The underlying conception of teacher-research is that teachers assume the role of reflective practitioners, developing theoretical understanding of teaching and learning through reflecting on their own practices. While experience provides the basis for learning, teacher reflection is essential for making new meaning and gaining alternative perspectives, and views about teaching and learning. Two modes of teacher-research that are currently adopted in many schools are (1) Action Research, and (2) Lesson Study.
Action research

Action research is a deliberate, solution-oriented investigation that is group or personally owned and conducted. It is characterized by spiraling cycles of problem identification, systematic data collection, reflection, analysis, data-driven action, and, finally, problem redefinition. The linking of the terms “action” and “research” highlights the essential features of this method: trying out ideas in practice as a means of increasing knowledge about and/or improving curriculum, teaching, and learning (Kemmis & McTaggart, 1982).

Action research is designed, conducted, and implemented by the teachers themselves to improve teaching in their own classrooms. Through their research, teachers identify the specific needs of their students, develop and implement changes in their practice to address these needs, and evaluate the outcomes from these changes. This self-evaluation aspect of action research allows teachers to build their personal practical knowledge of teaching and learning in their specific context.

Sagor (2004) described the action research process as consisting of four sequential stages:

Stage 1: Vision/target setting - the action research team aligns their research and development to their school’s vision

Stage 2: Theory articulation - this is where the teacher researcher makes explicit his “theory for action” in tackling the identified problem

Stage 3: Action/data collection - lesson plans, assignments and student work provide the evidence of learning and the effectiveness of the research’s “theory of action”

Stage 4: Reflection/action planning - this is where the most important professional learning occurs, focusing on attaining greater self-knowledge and a deeper understanding of one’s own practice. The process is enriched through the involvement of colleagues in collaborative analysis of the classroom data and action planning for subsequent teaching in a similar context.

To represent the continual, cyclical nature of action research, a simplified representation consisting of four phases (reflect, plan, action, observe) is often used (Figure 10.1).

The action researcher will go through the action research cycle to systematically tackle the identified problem. In practice, one cycle of planning, acting, observing and reflecting, usually leads to another, in which improvements are made to the initial cycle.

Figure 10.1. Cyclical nature of action research
Lesson study

Lesson study, which first originated from Japan as a teaching improvement process in the Japanese elementary education, has spread from Japan to many other countries around the world. It is a powerful teacher-driven and student-focused professional development practice with many features that are similar to action research. One prominent distinguishing feature is that in lesson study, unlike in general action research, collaboration is not an option and includes teachers working together in developing a lesson as well as observing students working in the classroom.

Lesson study is effective for the professional development of teachers in that it is able to meet the following four critical attributes:

1. It must be intensive, ongoing and connected to the classroom practice
2. It must focus on students’ learning and subject matter knowledge
3. It must be aligned with the school improvement and goals
4. It must build strong working productive relationships among teachers school wide

What is Lesson study?

Table 10.1  What is and what is not lesson study.

<table>
<thead>
<tr>
<th>What is lesson study</th>
<th>What is not lesson study</th>
</tr>
</thead>
<tbody>
<tr>
<td>It is a CYCLE in which teachers work together to consider their long term goals for students and bring those goals to life in actual research lessons (Lewis, 2002)</td>
<td>A particular teaching strategy or philosophy of teaching</td>
</tr>
<tr>
<td>It is a PROCESS in which teachers jointly plan, observe, analyse, and refine actual classroom lessons called “research lessons” (Lesson Study Group at Mills College, n.d.)</td>
<td>A demonstration lesson</td>
</tr>
<tr>
<td>Lesson study is a form of collaborative research as it involved a systematic data collection and data analysis in the Research Lesson</td>
<td></td>
</tr>
<tr>
<td>It is a PROFESSIONAL DEVELOPMENT PRACTICE in which teachers collaborate to develop a lesson plan, teach and observe the lesson to collect data on student learning, and to use their observations to refine their lesson.</td>
<td>A perfect lesson</td>
</tr>
<tr>
<td>It is a PROCESS that teachers engage in to learn more about effective practices that result in improved learning outcomes for students (Stepanek, Appel, Leong, Mangan, &amp; Mitchell, 2007)</td>
<td></td>
</tr>
</tbody>
</table>
**Why Lesson study?**

Lesson study provides the following opportunities/benefits for teachers to:

- Think deeply about *long-term goals* for students
- Carefully consider the goals of a particular content area, unit, and lesson
- Study the best available lessons as a group
- Plan lessons that bring to life both short-term and long-term goals
- Deepen *subject matter knowledge*
- Develop *instructional knowledge*
- Build capacity for *collegial learning*
- Develop the “*Eyes to See Students*”

Arising from the above opportunities of lesson study are the following benefits of lesson study to the professional development of teachers:

- Reduces teacher isolation
- Helps teachers learn to *observe and critique*
- Deepens teachers’ understanding of *content* and *curricular scope and sequence*
- Allows teachers to develop ability to see lessons through children’s eyes
- Creates shared expectations for and understanding of *student thinking* and *learning*
- Increases *collaboration* and respect for each other
- Improve *student learning*
- Provides a natural platform for *collaborative mentoring*

**How is lesson study done?**

Lesson study is carried out in the form of a 4-stage cycle (Lewis, 2002) as shown in the Figure 10.2.
Working in a small group, teachers meet for 3 main activities:

**Activity 1: Collaborative Planning (GsP)** where teachers collaborate with one another to identify goals for student learning and long-term development. The teachers will collaboratively plan instruction designed to bring to life these learning goals, including a “research lesson” that will be observed.

**Activity 2: Research Lesson (RL)** whereby one planning team member conducts the research lesson while the rest of the teachers follows an observation protocol to collect data on student thinking, learning, engagement, behavior, etc. using a detailed observation checklist.

**Activity 3: Discussion/Revision of RL (LD) and Consolidation of Learning (CoL)** whereby teachers meet to share and analyse the data collected at RL to look for empirical evidence that the goals for student learning and development are fostered and if desired, refine and re-teach the RL before writing a report that includes the lesson plan, student data and reflections on what was learned.

Figure 10.3 below gives a summary of the tasks that the teachers engaged in during each stage of the lesson study cycle.

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**2. Research Lesson (RL)**
- One planning team member teaches classroom lesson while other team members collect data on student thinking, learning, engagement, behaviour etc.

**1. Goal-Setting & Planning (GP)**
- Identify goals for student learning & long-term development
- Collaboratively plan instruction designed to bring to life these goals, including a “research lesson” that will be observed.

**3. Lesson Discussion (LD)**
- Share & analyse data collected at RL
- What is the evidence that goals for student learning & development were fostered?
- What improvements to the lesson & to instruction more generally should be considered?

**4. Consolidation of Learning (CoL)**
- If desired, refine & re-teach the lesson & study it again.
- Write report that includes lesson plan, student data & reflections on what was learned.

*Figure 10.3. Tasks within each stage of the Lesson Study Cycle*
For the research lesson, some categories of useful data for collection are:

**Academic Learning**
- In their journals, what did students write as their learning?
- Did students ask questions to deepen their understanding of concepts?

**Motivation**
- Percent of children who raised hands
- Body language, “aha” comments, shining eyes

**Social Behavior**
- How many times do students refer to and build on classmates’ comments?
- How often do the five quietest students speak up?
- Are students friendly and respectful?

**Student Attitudes toward Lesson**
- What did the students like and dislike about the lesson?
- Are students more focused?

For effective implementation of lesson study, some critical factors to be considered include:
- School leaders’ support in terms of time-tabling, resources for Teaching and Learning
- Teachers must buy-in and believe that this will work for the better of their students.
- Support in terms of access to knowledgeable others for content and pedagogy
- Mindset of teachers to de-privatize their classroom for observation by other teachers in the group.
- Centralised resources to save time
- Reduction of paper work by weaving the research elements into the observation checklist besides formal survey

**Sustaining teacher professional development - Professional Networks**

In the Singapore context, the concept of professional development as the systematic and formal attempts to advance the knowledge, skills and understanding of teachers in ways that lead to changes in their thinking and classroom behaviour has evolved towards a more job-embedded paradigm, to effect a shift from a MOE-driven excellence to teacher-led excellence.

This paradigm shift towards teacher-led excellence can be achieved through the idea of forming professional networks among teachers to promote networked learning. “Networked learning can be said to take place when individuals come together in groups from different environments to engage in purposeful and sustained developmental activities informed by the public knowledge-base, utilizing their own know-how and co-constructing new knowledge together” (Networked Learning Communities, 2005) (Figure 10.4). Teachers who are network learners are actively engaged in meaningful learning conversations to learn from both the experts and peers.
Examples of professional networks include networks by subjects (such as Physics Subject Chapter in the Academy of Singapore Teachers), by roles (such as the Lead Teacher-Senior Teacher Network) or by professional interests (such as ICT). Through networked learning, teachers work collaboratively to address shared professional concerns, issues and challenges as co-learners to co-create solutions.

For a more detailed understanding of subject chapters as professional networks, refer to the Academy of Singapore Teachers’ website: http://www.academyofsingaporeteachers.moe.gov.sg/.

**Moving Forward**

In conclusion, the way forward for a sustainable professional development of physics teachers lies not just in the professional learning communities (PLCs) at the school level, but also through Professional Networks (PNs) by design or emergence among physics teachers within and across schools.

While the Physics Subject Chapter is led by Master Teachers, with representatives from schools and zones, Academy of Singapore Teachers, National Institute of Education, Curriculum Planning and Development Division, and Educational Technology Division, it is imperative for all teachers in Singapore teaching physics to know that they are members of the Physics Subject Chapter.

To this end, we welcome all physics teachers to be willing to step forward to contribute to the twin goals of the Physics Subject Chapter which are:

1. To equip Upper Secondary/Junior College physics teachers with impactful and innovative pedagogies that are underpinned by sound learning theories, experimentation and research.

2. To raise the wonder of physics and the joy of learning physics to students so that:
   (a) O-level students, who have the passion and ability in physics will consider physics as one of their choice subjects at the JC level;
   (b) A-level students, who have the passion and ability in physics will consider opting for a physics or physics-related course at the University Level.

![Figure 10.4 Three fields of knowledge (Network Learning Communities, 2005)](image-url)
Chapter 1


Chapter 2


Chapter 3


**Chapter 4**


Chapter 5


Chapter 6 - 9


Chapter 10


Relevant Websites

Lesson Study resources - http://lessonresearch.net/index.html


Physics Instructional Models/Strategies

Lecture-based models/strategies
- Interactive Lecture Demonstrations (ILDs) - http://physics.umd.edu/perg/ILD.htm

Tutorial-based models/strategies

Studio/Workshop models/strategies
- The Physics Studio - http://www.jackmwilson.com/ArticlesTalks/index.htm#Studio%20Courses
- SCALE-UP - http://scaleup.ncsu.edu/

ICT-enhanced models/strategies
- Physlets - http://webphysics.davidson.edu/physlet_resources/
- PhET - http://phet.colorado.edu/index.php
- Virtual Reality - http://www.physics.ohio-state.edu/~physedu/vr/

Students’ alternative conceptions
- Abstracts of research on student alternative conceptions - http://www.sagepub.com/liustudy/abstracts.htm
- Student difficulties in physics - http://www.physics.montana.edu/physed/misconceptions/

Syllabuses