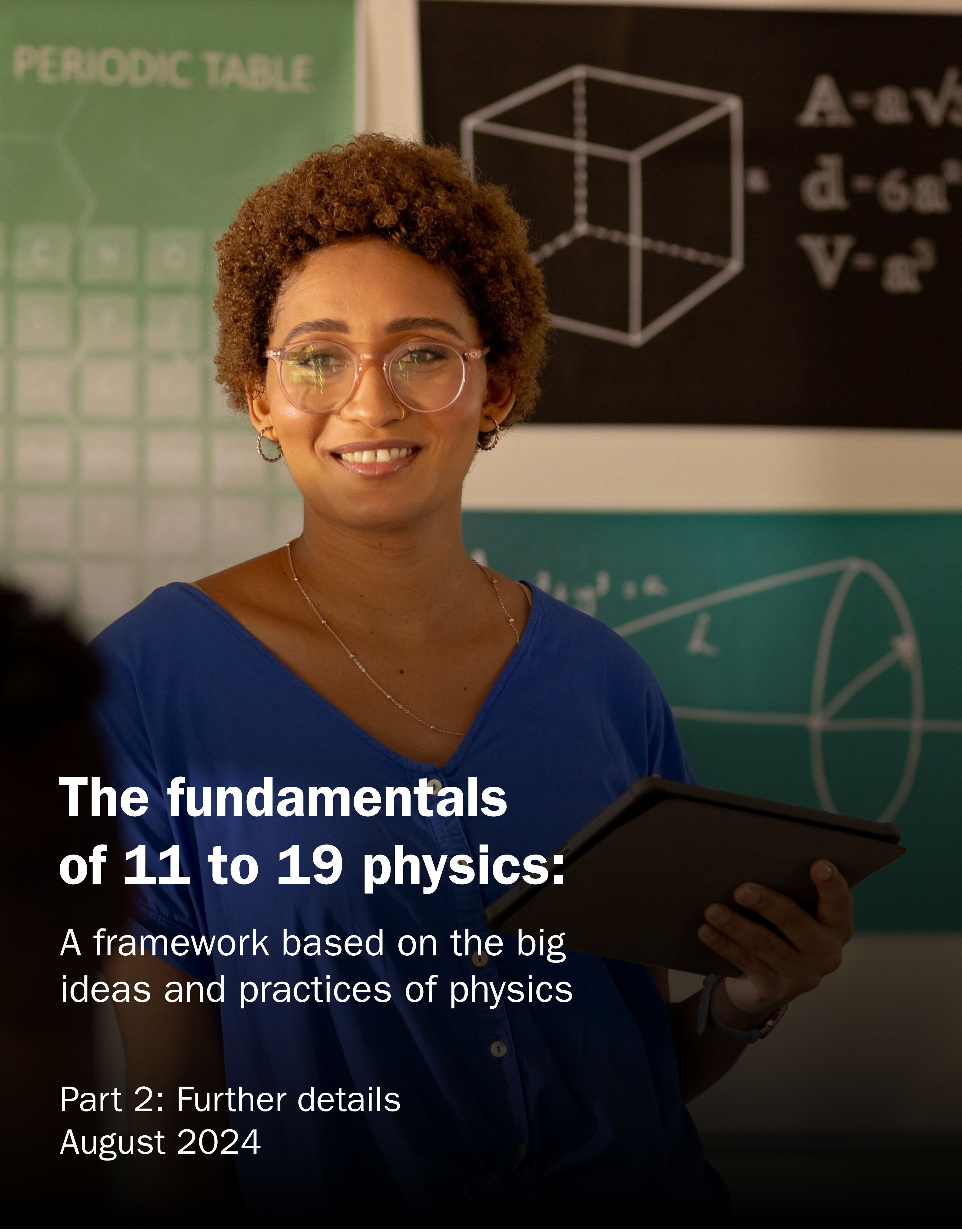

The fundamentals of 11 to 19 physics:

A framework based on the big ideas and practices of physics

Part 2: Further details
August 2024

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About this document

This document is the second part of a two-part framework. We recommend reading Part 1 first.

Part 1 provides an overview of our recommendations and design principles and is suitable as an introduction to, and synopsis of, what we are proposing.

In this part (Part 2), we develop the design principles and show how they will result in achieving the aims; and we provide some narrative background to the physics-related statements that are summarised in table 1 of part 1. Part 2 will help those who want to get into the detail of curriculum design.

These documents do not, in themselves, represent a physics curriculum. Nor are they specific to any nation or jurisdiction. They are intended to inform, guide and support the development of curricula and schemes of work in any context. We hope that the documents – and, in particular, the design principles - will be used to start and inform discussions relating to curriculum design at national, school and department level.

6. More on the purposes and aims of an education in physics

Detailing the aims

a) Deep knowledge and understanding of some big ideas of physics

It could not be claimed that someone has learned physics without them having some knowledge of the major ideas and claims that physics makes about the natural world. However, a common criticism of some recent physics curricula is that they are overloaded with a lot of disconnected bits of factual information which are coached solely for an exam and then largely forgotten. Students should discover, by the way in which they do and learn physics and by taking part in discussions of explanations, that physics can be built on a deep understanding of a relatively small number of laws and ideas that are used and reused to provide explanations of phenomena - both the everyday and the esoteric.

b) Lasting capability in the practices and ways of thinking of physics

An education in physics should explicitly aim to develop, by experience, an enduring capability in some of the highly prized practices and ways of thinking that characterise physics. Throughout their adult lives, students should continue to benefit from the considerable and transferrable skillset embodied in these practices and ways of thinking (creative thinking, problem-solving, interrogating evidence, reasoning, resilience, taking readings and so on). They will be able to apply them in familiar and unfamiliar situations and recognise when a phenomenon is being described in a 'physics way'.

c) Knowledge that established physics ideas are extremely reliable but open to challenge

An education in physics should leave students with a lasting trust and confidence in the ideas, explanations and practices of the discipline. At a time when many 'scientific' ideas, including some with little foundation, enter the public domain and compete for attention and commitment, students should be aware that the claims of physics are well-founded (in evidence and reason) and have been severely tested over time: physics is neither whimsical nor "just a few theories". For example, the statement that the temperature of the Earth is rising is not someone's view or opinion: scientists have measured this over a number of years, established the pattern, and explained the behaviour in terms of accepted mechanisms.

d) Ability to carefully assess information and scientific claims and make informed decisions on global issues such as climate change

Education in physics must prepare young people to deal with, amongst other things, the climate crisis. They should develop knowledge, understanding and capabilities that will help them make decisions about the climate, living sustainably, and other global challenges; they should be aware that physics will play an important role in solving these challenges and that they can be a part of developing those solutions.

e) Curiosity and a sense of wonder at the world and a desire to understand and explain how things happen

An education in physics should convey and engender a sense of wonder at the way the world works and our ability to explain so many phenomena. They should experience the satisfaction of good physics explanations and be motivated to ask questions and provide explanations themselves.

f) Recognition of the applicability of physics, its contribution to society and the opportunities it offers

Students should know about the applications of physics – particularly the multitude of occupations that rely on physics ideas and its ways of thinking. This knowledge will help them to make informed decisions about their next steps at both age 16 and age 18. It will help students build a positive view of physics and reinforce the utility and value of physics to improving wellbeing and addressing problems.

g) A deep rooted belief that physics is inclusive and that they can take part

Students should be able to see that physics relates to contexts that are relevant to their own interest. And, above all, they should know that physics is inclusive and can be for all. They should not feel that physics is "not for them" based on their group or characteristics.

7. Developing the design principles

In this section, we discuss in more detail the design principles that were summarised in section 2 in part 1.

A. The big ideas of physics

A. The big ideas of physics
Substantive knowledge should be expressed as a small set of big ideas taken from the canon of physics to develop a deep, lasting knowledge and understanding of those ideas.

Our first design principle is that the substantive knowledge is expressed as a small number of big ideas.

Focusing on big ideas is a conscious move to address the criticism of some recent curricula that they contain too much disconnected information with an over reliance on short term recall. And that most of the details are forgotten soon after the exams.

The big ideas represent the aspects of substantive knowledge that we can expect to persist. For example, someone might meaningfully take part in a conversation about the apparent movement of celestial objects some time after they leave physics (big idea 9).

How design principle A contributes to the aims

Each big idea will be underpinned and built up by a substantial amount of detailed content. The big ideas will help curriculum developers to choose that content – focusing on aspects of physics that earn their place by building towards a big idea.

The big ideas act as a destination for the detailed content. Being able to see where the detailed content is leading will help students to see purpose in studying the details. Whilst the detailed content is important at the time of study (to develop a deep understanding of the big ideas) it is those big ideas that are likely to endure (aim a).

The big ideas will help students to develop a lasting positive impression of physics (satisfying one of the purposes of a physics course). They will reinforce the notion that physics is built on a small number of ideas and explanations, which are coherent and interconnected and that, once they are understood, that small set of ideas provides the basis for explaining many phenomena.

An important role of the big ideas is to provide a platform for teachers to model the practices and ways of thinking and allow their students to deploy them. It is likely that most significant ideas in physics can be used in this way. Above all, each big idea should provide opportunities to discuss not just the idea but why physicists claim to know that idea.

B. The practices and ways of thinking of physics

B. The practices and ways of thinking of physics
The practices and ways of thinking of physics should be made explicit in order that they are taught in an organised way so as to develop lasting capability in them and to show students how they provide the warrant for accepting the substantive claims that physics makes, giving them confidence in its ideas, theories and explanations.

The value of a good education in physics is not only from exposure to its substantive knowledge, but also from giving students opportunities to develop capability in the practices and ways of thinking of the discipline – a capability that will stay with them and provide them with durable tools to consider many problems, both within and outside the domain of physics (aim b).

This capability is of value to all students – whether or not they choose to follow physics in the next stage of their learning (see section 4.3 in part 1).

Therefore, our second design principle is that students should experience and use these practices and ways of thinking and, through that experience, acquire lasting capability in them.

As is currently the case, the practices will include knowledge of experimental procedures (procedural knowledge). However, our recommendations go further; we are proposing to also include: the attitudes of physics (thinking critically, working collaboratively etc); ways of reasoning; the use of models; numerical and mathematical techniques; and solving problems (sometimes from first principles).

We are not expecting that every student will achieve mastery in all aspects of the practices and ways of thinking of physics. However, we are expecting that they will work towards acquiring proficiency in them and will have plenty of opportunities to develop them through the way that they are taught.

How design principle B contributes to the aims

It is certainly the case that, currently, good teachers often model and therefore develop their students' capability in these practices and ways of thinking. That is, they integrate them into the way they present the substantive knowledge. We are going a stage further and making them explicit within this framework so that they are given greater consideration in the development of curricula, schemes of work, and assessments. This delineation will ensure that they are not lost from the narrative of physics - because they are part of the essence of what physics is. And that they can be developed in an organised, deliberate, and scaffolded way in a sequence of teaching and through the way that the substantive ideas are described and represented. Being exposed to and using the practices and ways of thinking during their studies will provide students with some answers to the epistemic question: how do we know what we claim to know? By becoming familiar with the methods of physics and physicists, students will realise that the substantive ideas have been developed by those same methods: they are based in evidence, developed by reasoning, and strengthened by severe testing over time. This cycle of development can give them confidence in those ideas, thereby contributing to building a lasting trust in physics and its practices (aim c).

As well as making them attractive to potential employers, developing proficiency in the practices and ways of thinking of physics will help them to become considerate citizens who are able to make reasoned decisions at a personal and societal level (aim d).

Physics is more than solely a set of 'facts'. Experiencing the practices and ways of thinking will, we hope, provide student with a more authentic view of the endeavour of physics – that it aims to provide elegant and thoughtful explanations of phenomena based on evidence and reason – leaving them with a positive view of physics and allowing them to make a well-informed choice about following physics-based courses – as described in the purposes of an education in physics.

C. The characteristics of the endeavour physics

C. Characteristics of the endeavour of physics
The characteristics of physics should be described to help guide curriculum developers and teachers to provide a faithful representation of the discipline of physics within the school context and, as much as possible, develop a lasting positive impression of it.

The third design principle is to help ensure that a physics curriculum or scheme of work both frames and represents physics in an authentic way.

Although it is a challenge to accurately capture the endeavour of physics in a set of statements, this challenge was met by Jon Ogborn in a concise and cogent think-piece he wrote for the IOP's Curriculum Committee (See extract on page 7 in part 1). Based on that think-piece and continued discussions, we have itemised eleven features of the endeavour of physics (see section 8C).

The aim of itemising them is to ensure that they are borne in mind in the way that physics is represented in the classroom through curriculum design so that teaching will result in students developing a lasting faithful impression of physics. That is, the statements provide a destination (similar to the big ideas) for the impression that students form of physics from the exposure to it at school.

All of the statements that describe the characteristics of the endeavour of physics have an equivalent statement in one of the other three areas (big ideas, practices or applications). For those that are described in the practices, it is the intention that students will acquire capability and competence in those practices (for example, setting up and conducting experiments) that will also result in an enduring impression about some characteristic of physics (in this case, that physics is empirical).

How design principle C contributes to the aims

By making explicit the desired lasting impressions of physics, we hope that curriculum designers and teachers can audit the way that the discipline is being represented to ensure that it is reinforcing those features. This will contribute to the purposes: that students to whom physics might appeal get an experience that is faithful to the discipline and can make an informed choice about whether to continue with it.

Assessment of strand C

It is unlikely that this aspect can be sensibly assessed within existing systems. It is certainly not the intention that the features of the endeavour of physics will be learned as declarative statements nor are we proposing a curriculum that is “about physics” in which students are taught to recite statements or phrases that describe the nature of physics.

Instead, it is the way in which the big ideas, practices and applications (areas A, B and D) are taught that will result in a lasting impression that physics is underpinned by ideas, explanations and approaches that are powerful, rigorous, and reliable; that physics provides creative ways to solve problems and determine how the world works; and it has resulted in some effective ways of explaining the world which are important for our culture, technology and society. This intention is elaborated in table 2 below and is illustrated in figure 3 in part 1.

It is important to note that, as well as those who progress to undergraduate physics degrees, a large proportion of students who take post-16 physics qualifications go on to study or train in engineering. Therefore, the substantive content knowledge of post-16 physics programmes must lay the groundwork for both physics and many engineering degrees. However, the ways of thinking in physics and engineering can be different. Therefore, it is essential that any post-16 programme of study also gives students access to considering problems in an engineering way – either as part of a physics qualification or as part of a portfolio of qualifications. It is not for this document to describe what it means to think like an engineer. However, we recommend that engineering experts are consulted in the design of post-16 programmes.

Taught and assessed	**Lasting impressions acquired but not assessed**
A. Big ideas and explanations and recurring themes	C. Physics has generated, and will continue to generate, successful ideas and explanations that have great predictive power; many of the ideas are counter-intuitive and have opened up new and powerful ways of looking at the world; these ideas have been severely tested and endured because of their successful predictive capability.
B. The practices, ways of thinking. Ability to apply the practices, ways of thinking, ideas and explanations of physics in both related and unrelated fields.	C. Physics is underpinned by a refined set of effective practices and ways of thinking; those ways of thinking are powerful, rigorous, and reliable and provide creative ways to solve problems and determine how the world works.
D. Knowledge of applications of physics. Ability to apply big ideas and practices of physics in unfamiliar contexts.	C. Both the ways of thinking and the ideas can be applied in many situations and are valuable to the individual, to innovation and to society and are valued by employers.

Table 2. Acquiring lasting impressions through the way in which physics is taught.

D. Applications and space for contexts

D. Applications and contexts
Examples of major applications of physics should be provided and there should be space in the curriculum for teachers to give local and familiar examples to motivate students, make them feel included, and to show links with engineering and other scientific disciplines. Physics discoveries should be framed in a way that recognises the global historical context of the times.

The fourth and final design principle is to provide space in the curriculum to consider the applicability and ubiquity of physics ideas and practices through some carefully chosen contexts.

The discussion of contexts and applications will be integrated into the teaching of the substantive ideas of physics (see figure 3 in part 1). Many contexts work best if they are not directed or defined by a central curriculum; and therefore the role of the curriculum design is to ensure that there is space for teachers to provide contexts that are:

- familiar, local and personal,
- solutions to some of society's big questions (including the climate – see below),
- examples of solving everyday problems,
- illustrations of solving problems in other disciplines - within and outside the sciences,
- illustrations of occupations and employment,
- global and historical (see section 2.5 in part 1).

Sustainability and climate

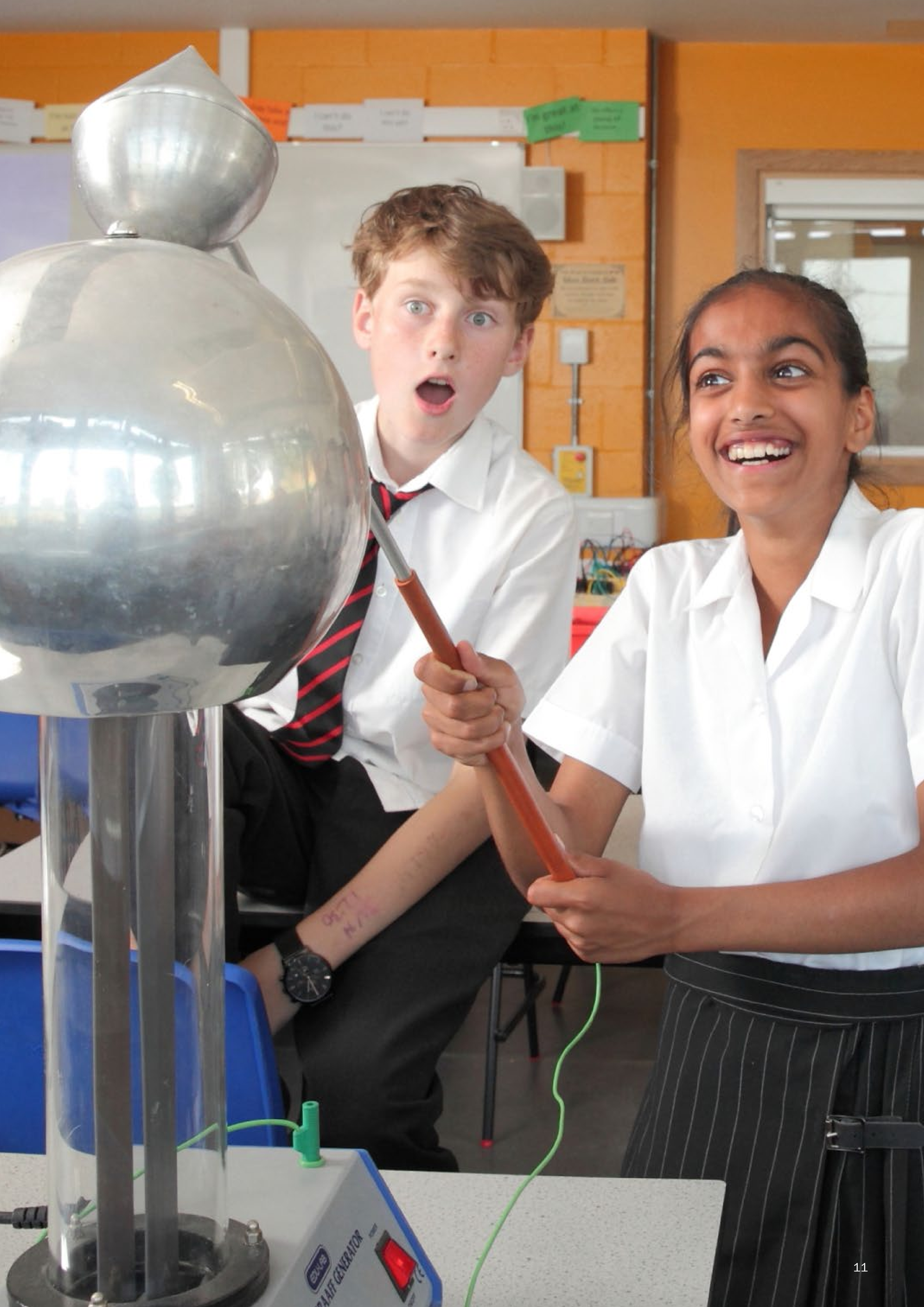
We are recommending that the curriculum should demonstrate how physics contributes to both understanding and addressing major global issues – most notably climate change. Education – especially an education in physics - should prepare young people to deal with and make decisions about this issue and living sustainably.

At this stage, it would not be appropriate to suggest definitively how climate issues and solutions might best be included in a physics curriculum or as part of the sciences. However, one possible approach is to have climate and sustainability contexts running through all the substantive knowledge of physics. For example, calculating the potential output of tidal generation across a small bay; or the flow rate of air required to drive a wind turbine. In order to encourage the use of those contexts, and to demonstrate the interdisciplinary nature of the search for solutions to the climate crisis, it is worth considering having a synoptic paper in the assessment scheme that comprises questions from across the sciences in the context of climate and sustainability.

How design principle D contributes to the aims

This design principle will contribute, along with the other design principles, to instilling a sense of curiosity (aim c). Drawing on contexts (both local and global) will help students relate physics to every day questions they might ask themselves and to see how physics can help address those questions.

Including applications and contexts will motivate students and contribute to a positive view of the discipline (aim f). Contexts can be used to illustrate the success of the discipline, both its ideas and explanations for improving comfort and wellbeing, and its practices as a way of thinking about phenomena and solving problems.



8. More details on the curriculum statements

A. Big ideas

i. Cross-cutting

1. **Reducibility: explaining phenomena based on constituents of a system and considering the mechanisms and processes that describe their behaviour**

   Most physics phenomena can be explained by them drawing on the relatively small set of established ideas, laws and models from across the discipline and applying to the behaviour of the constituent parts of a system.

2. **Equilibrium occurs when two or more external influences are in balance (statically or dynamically)**

   Many physical systems stay in the same state (e.g. of position, temperature) for a period of time. They are then said to be in equilibrium (e.g. mechanical, thermal, electrical and others). Static equilibrium means that the various influences on the system balance each other and add to zero. Dynamic equilibrium usually means that the rates of change of the inputs (of a given quantity) is equal to the rate of change of the outputs (e.g. that power in = power out, so temperature remains the same).

3. **Change is caused by difference**

   In large, complex systems, changes are driven by differences. For example, differences in temperature, pressure, and concentration. Additionally, the rate of change tends to be proportional to the size of the difference. These differences tend to drive the system towards equilibrium over time (see the first group of equations in item 20).

4. **Conservation: The idea that energy and other quantities are the same after an event as before; and this provides physicists with extremely powerful analytical tools**

   Energy is a quantity whose total value remains constant in a closed system – that is, it is conserved. It can be stored in different ways and we have relationships that determine the amount stored in each way. In any process a tally of all the changes in the amounts of energy stored differently will be zero. This makes energy an extremely useful analytical tool: we can find out whether an event can occur, and determine the likely outcome (or at least the limitations on the outcome). As well as energy, there are other quantities that are conserved and remain the same before and after a change – allowing us to carry out calculations and make predictions. Momentum is an important example; others include matter, charge and, in some situations, volume.

ii. Domain-based

5. **All matter is made of very small particles and this helps us to explain many behaviours of matter**

   Matter is made of atoms. All of the enormous variety of examples of matter are made of a small number of different atoms. Atoms have no volition, but their behaviour is described by the laws of physics and can be used to explain many properties. The motions of atoms and molecules (clusters of atoms) and the forces between them account for the characteristics and behaviours of solids, liquids and gases. Particles are in perpetual motion, with a speed that is dependent on the temperature of the sample of matter.

   We live at the bottom of an ocean of air and, as in other fluids, it exerts a pressure that acts in all directions

   Fluid pressure is important in discussing weather (and phenomena that will be affected by climate change). The idea of atmospheric pressure, and explanations based on it, were also one of the transformative moments in physics.

6. **Atoms are not indivisible – they have their own internal structure**

   Atoms are made of even smaller parts: within the nucleus, there are protons and neutrons and these are involved in nuclear decay and nuclear reactions. Outside the nucleus are electrons which are involved in models of chemical bonding, spectra and current electricity.

   In post-16 physics, in order to explain the behaviour of sub-atomic systems we draw on the ideas of quantum mechanics. Energy is quantised; positions, motion and stability are determined by probability and only become predictable for large numbers of constituents; and behaviours can be entangled. This field of physics arose at the beginning of the 20th century and has led to much of the micro-technology that we rely on today and remains at the cutting edge.

7. Objects interact with each other (by contact or at a distance) – giving rise to pairs of forces

When two objects interact (closely or at a distance) each exerts a force on the other. These forces are equal in size at every instant of the interaction, and opposite in direction. This symmetry can be used to show that momentum is conserved in collisions.

The four fundamental interactions are: gravitational, electromagnetic, strong and weak nuclear.

8. All matter emits radiation in a spectrum of electromagnetic waves

An object can affect another across a distance by emitting radiation which travels through space (either through a medium or a vacuum) between them. All matter (above absolute zero) emits radiation in the electromagnetic spectrum. The frequency of the radiation depends on the temperature of the emitter. Visible light is only a small part of this spectrum. Electromagnetic radiation can be modelled both as a wave or as a particle: the photon.

9. The Earth and planets orbit the Sun, one of billions of stars in our galaxy, which is one of billions of galaxies in the Universe

The Earth spins on its axis and the Earth and planets orbit a star that we call the Sun; and the Moon orbits the Earth. The Sun is one of billions of stars, separated by huge distances, that make up the Milky Way galaxy. In turn, it is one of billions of galaxies, separated by even bigger distances, that make up the universe.

10. An object will continue moving without a net force acting on it: it has inertia

When a force acts on an object, it causes its momentum to change; without a net force, velocity is constant.

This idea (Newton's first law of motion) is, at first, highly counter-intuitive. It is related to the bigger idea: being stationary cannot be distinguished from motion at constant velocity. That is, if you are in a closed frame moving at a constant velocity, there is no way of telling that you are moving or what your velocity is.

11. Charge is a fundamental property of matter and this helps us to understand electrical properties and effects

Electric charge is a fundamental property of matter. It exists in two forms: positive and negative. Two objects with the same charge repel each other; two with different charge attract. Many objects have equal amounts of positive and negative charge and so the charges they contain are not apparent.

12. Fields are regions in which an object may experience a force

Objects interact with each other across space (at a distance). Each object is setting up a field in the region around it and responding to the field of the other object. Examples are gravitational, electric (or electrostatic) and magnetic fields. This is the first of three ways in which we analyse changes and energy transfer that occur over a distance. The other two are waves and loops (see item 19).

13. Electricity and magnetism are two facets of a single phenomenon: electromagnetism

There is a magnetic field in the region around a wire carrying an electric current. A changing magnetic field around an electrical conductor can cause an electric current.

14. There are two ways to change the energy stored by a system: by working on it or heating it

In kinetic theory, we have a model that brings together the previously separate ideas of heat and work; and that energy is stored thermally as a result of the motion or arrangement of particles. This unification is consistent with the important idea that there are two ways of increasing the energy stored by a system: by heating it (by contact or by radiation) or by working on it (mechanically or electrically).

15. Dissipation: every event results in greater disorder if we take everything that is involved into account

Dissipation provides an arrow to the direction of time and it cannot be reversed. This relates to a tendency towards disorder (increasing entropy). Dissipation is often used in the context of energy analyses when energy ends up being stored in less useful ways. Often it is stored thermally by imperceptible temperature rises of the surroundings.

B. Practices and ways of thinking of physics

16. Procedural knowledge: proposing and testing explanations of phenomena; making measurements and observations and verifying explanations of phenomena through experiments

Physics is an empirical discipline. Physicists set up careful experiments to observe phenomena and test explanations. They:

- isolate phenomena,
- control variables,
- construct and manipulate apparatus
- make observations and measurements,
- analyse and interpret data,
- test plausibility of results,
- develop and refine explanations.

Students should have frequent opportunities to conduct experiments and investigations through which they develop their procedural knowledge including their technical and manipulative capabilities.

17. Attitudes of physics: thinking critically, working collaboratively, seeking deep understanding and consistency in explanations, setting aside preconceptions, and facility with scientific language.

There are some attitudes and states of mind that are common within the endeavour of physics (and other disciplines) that contribute to characterising physics. In each case, they can be worked up into a competency that students should be able to demonstrate the ability to:

- think critically: puzzling away at something and taking account of all possible objections to find the best explanation that they are certain works; being able to critique others' reasoning within explanations;

- collaborate in a resilient way: work with others to develop and test experimental methods, ideas, explanation and proposals and be willing to accept the explanation that fits best with the evidence;

- seek deep understanding: by looking for deeper and deeper explanations; not being satisfied with superficial descriptions;

- seek consistency: testing that answers are consistent with experience and all other areas of physics; approaching problems from different directions to see if the results are the same;

- set aside preconceptions: stepping outside immediate experience and accepting the consequences and implications of theories and evidence - even when they may go against ideas from everyday experience;

- employ scientific language: understand and use specialist words or terms and be accustomed to the difference between the everyday meaning and the physics meaning of some words.

18. Thinking and reasoning techniques: to solve problems and refine explanations using critique and logic

The ideas and explanation of physics have been developed, critiqued and refined using creative argument based on reason and logic. Physics problems can often be solved from first principles using a small number of ideas, explanations and laws. Students should have opportunities to develop their ability to use different types of reasoning including:

- geometric and algebraic proofs,
- deductive and inductive reasoning,
- categorisation,
- statistical (probabilistic) reasoning,
- inferring history of evolving systems.

19. Models and systems: defining systems and using models to think with and to make predictions

Physicists construct models to think with and make predictions. Students should have opportunities to use models to represent unseen or complex systems. They should be able to:

- develop their reasoning with a model in which they simplify a situation or system,

- explain the properties and behaviour of a system in terms of its constituent parts,
- predict behaviour using models.

Two specific and helpful types of modelled systems are:

- A closed loop for doing work remotely (such as in a series circuit or bicycle chain),
- The emitter, medium, detector model for radiation.

20. Quantities and relationships: using relationships that recur across physics

Many of the models in physics are mathematical. They are based on relationships that have been found between quantities that physicists have defined. Similar models and relationships occur in different areas of physics.

Students should be able to use some common types of relationship.

- Relationships that constrain a rate of change:

  $a = \frac{F}{m}$ $I = \frac{V}{R}$ $P = -KA\frac{\Delta\theta}{\Delta x}$ $\frac{\Delta\theta}{\Delta t} = \frac{P}{mC}$

- Energy can be stored in different ways:

  kinetically: $\frac{1}{2}mv^2$

  elastically in a spring: $\frac{1}{2}kx^2$

  electrically in a capacitor: $\frac{1}{2}CV^2$

  gravitationally in a uniform field: mgh

- There are two ways of changing the energy stored in a system: working and heating:

  $\Delta E_{working} = F\Delta x$ $\Delta E_{electrical\ working} = V\Delta q$

  $\Delta E_{heating} = mC\Delta\theta$

- A number of relationships can be analysed in terms of one variable compensating for another:

  $momentum = mv$ $density = \frac{m}{V}$ $PV = constant$ $moment\ of\ a\ force = Fx$ $stress = \frac{F}{A}$

- Rates and definitions:

  $I = \frac{dq}{dt}$ $v = \frac{ds}{dt}$ $a = \frac{dv}{dt}$ $P = \frac{dW}{dt}$ $f = \frac{cycles}{time}$

- Accumulations:

  $q = It$ $s = vt$ $v = at$ $W = Pt$ $cycles = ft$

21. Numerical and mathematical techniques: using numerical and mathematical techniques to analyse situations quickly and make predictions

Physicists use numerical and mathematical techniques and computational thinking to carry out calculations and predictions. Students should be able to use and apply a number of powerful techniques in their calculations and predictions, including:

- approximation and order of magnitude calculations,
- extreme case reasoning,
- developing operational definitions,
- algebraic reasoning,
- proportion and inverse proportion,
- ratio and compensation,
- change over time,
- rates and accumulation,
- working with large and small numbers,
- exponential changes.

C. Characteristics of the endeavour of physics

Students should be taught the substantive knowledge of physics and its practices and ways of thinking in a way that leaves them with an authentic, lasting perception of the discipline of physics.

Physics aims to develop ideas and provide explanations of phenomena that are:

a. Fundamental and universal

Physicists seek explanations of phenomena - both everyday and esoteric - in the material world. They think creatively to answer questions and find explanations that can be expressed economically and applied widely, perhaps even universally. The explanations go beyond the superficial and aim to be as fundamental as possible.

b. Reducible

Many phenomena are explained by considering the constituents of a system and the behaviour of those constituent parts – which follow the small set of basic laws of physics. Therefore, once they are understood, that small set of basic laws provides the basis for explaining many phenomena.

c. Synthesised and consistent

It is important that an explanation is consistent with all other ideas and explanations of physics. If not, something new may be required.

d. Empirical and based on measurements

The ideas and explanations of physics are based on evidence and reasoning rather than intuition or belief. Physicists devise carefully-designed experiments and ways of collecting measurements to explore phenomena and test explanations and models in controlled conditions using the iterative sequence of observation, analysis, model, prediction, experimental test and re-analysis – a process that is described by the procedural knowledge of physics and the sciences.

e. Reasoned and logical

Physicists analyse and interpret observational data. They use reasoning (deductive, inductive and statistical) to develop convincing explanations that are consistent with the evidence. Deductive arguments often involve a number of well-reasoned steps that can be scrutinised and, if necessary, modified in the light of any convincing counter-argument. Physicists will test that their argument is rigorously consistent within itself and with other areas of accepted physics.

f. Based on systems

Physicists define systems (collections of objects that interact) that are of interest and simplify them to their core elements. They determine which characteristics can be ignored without losing the essence of the system. They can then provide explanations based on the constituent parts of the system and the ways that those constituents behave.

g. Modelled

Physicists develop models to help account for the observed behaviours of objects and systems. They think with these models and draw on them to explain phenomena and make predictions. Some models are illustrative or descriptive; some are abstract and many can be expressed mathematically.

h. Mathematical and predictive

Physicists generally go beyond observing phenomena qualitatively; they define measurable quantities and make measurements of them. These defined quantities enable physicists to develop and test verifiable relationships between them. Many of those relationships are expressed mathematically in empirical laws.

i. **Severely tested and reliable**

Physics models, especially mathematical ones, are used to make precise numerical predictions that can be tested – enabling a model to be rejected or supported. An observation or series of measurements that agree with a prediction increases the confidence in the model. The accepted theories, laws and models of physics have survived severe and repeated testing over time – including scrutiny by others working in the field (peer review), thereby increasing the confidence in their reliability. Moreover, many reliable and functioning technologies have arisen from physics ideas and continue to work – further increasing confidence in those ideas.

j. **Open to revision**

Although reliable, physics explanations are always open to revision and improvement if there is evidence that brings them into question.

k. **Collaborative and global**

Physicists often work in teams across the world; our system of measurement enables ease of communication between communities of science practitioners.

D. Applications and context

Students should learn the substantive knowledge of physics and its practices and ways of thinking with reference to applications and contexts, many of which will be local and familiar to students. This will help them feel included in physics and show them the possibilities and opportunities opened up by studying physics.

l. **Physics ideas can be applied and add value in other domains of study that are both within the sciences and outside them**

The practices, thinking, ideas and explanations of physics can add value as they are brought to bear in other domains within and outwith the sciences.

m. **Physics ideas are important when considering society's big questions and tackling its big challenges, such as climate change**

Important questions and challenges facing society and citizens include: the climate, energy supply and demand, communications, transport, building and healthcare. These affect everyone's lives; physics and engineering can contribute to the analysis and clarification of the issues, and to finding solutions.

n. **Physics ideas enable engineers to improve our comfort and wellbeing by designing solutions to defined problems**

Many of the structures and artefacts that have improved human comfort and wellbeing have come about through engineering and physics. Physics can be applied to predicting how products and devices will behave to allow developers to choose between alternative solutions.

o. **Studying physics is preparation for many important, productive and rewarding occupations**

Both the substantive knowledge of physics and its ways of thinking are highly prized by employers. Having a good grounding in physics is essential or advantageous in many occupations. Physics contributes to many areas of the economy and a background in physics can lead to a wide range of occupations.

IOP Institute of Physics