Guidelines for future physics curricula

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Abstract The Institute of Physics curriculum committee has been looking at ways of framing school-level physics so that it gives students a rewarding and productive experience of physics and leaves them with positive views of the discipline and its cultural contribution, as well as lasting and detailed skills, knowledge and understanding. The result is some guidelines that make explicit the practices and applications of physics and express the destinations and structure of the discipline as a set of big ideas collected into three dimensions. It is our intention to work with stakeholders – especially teachers – to develop some school-level frameworks based on these guidelines.

This article is intended as a contribution to an ongoing discussion about the shape and content of a school physics curriculum to age 16. This round of discussions began with the review of the National Curriculum in England of 2010/11, when there was an all-too-brief suggestion to build curricula on sets of 'big ideas'. While that principle was not followed through, it set a number of people and organisations, including the Institute of Physics (IOP), thinking about what those big ideas might be. Along with our policy partners (the Association for Science Education, the Royal Society of Biology, the Royal Society of Chemistry and the Royal Society), the IOP published some early suggestions for the shape and details of big ideas within each discipline in 2013 (SCORE, 2013).

In the same year, the IOP set up its curriculum committee, chaired by Mike Edmunds from the University of Cardiff. What follows is based on its deliberations. It is my interpretation of the committee's work (see *Acknowledgements*).

By setting up the curriculum committee, it was our aim to draw on evidence and broad expertise to develop a description of physics at school level based, in part, on big ideas. This work will result in a guidance document that will be published later in 2018. That guidance document will help teachers and curriculum developers put together frameworks that reveal what physics has to offer intellectually, culturally and as a basis for further study. The IOP will set up working groups to carry out that work (see *Getting involved* at the end of this article). This two-step approach – of producing guidance that informs the development of frameworks – is similar to that used successfully by the National Research Council in the USA to develop their standards (National Research Council, 2012).

Practices, dimensions and big ideas

The curriculum committee started by considering big ideas. However, the work expanded and developed along three main strands. This article is structured around those strands. They are:

- **A** **Including the practices of physics** in a curriculum framework in order to make the study of physics at school more rewarding and for it to have more utility.
- **B** **Structuring the curriculum** in a way that incorporates both the practices and content.
- **C** **Expressing the curriculum in terms of big ideas** that provide a destination and clear purpose to detailed content of specifications.

I start with the journey towards 'practices'.

A. The practices of physics

At an early stage, the committee members expressed the strong view that there is more to physics than just its content knowledge. The discipline also includes, indeed is based on, some important, rewarding and highly valued ways of thinking. They wanted the curriculum to reflect this view. The committee started by looking at the characteristics of physics and physicists so as to capture the essence of the discipline, including its ways of thinking and behaving. One aim was to bring the ways of 'thinking like a physicist' to the forefront and ensure that they are considered in curriculum design as much as the content knowledge and to show that it was possible to avoid building the curriculum solely on content knowledge.

From 'thinking like a physicist' to 'practices'

While the phrase 'thinking like a physicist' was initially useful (and remains a helpful phrase in some circumstances), it does not cover all the attitudes and behaviours of physicists and neither does it include the characteristics of the endeavour of physics. A succinct word that does include all of those aspects is 'practices'. As well as being all-encompassing, it has two other advantages:

- It describes the idea that it is beneficial for students to practise them – in two senses: to experience and take part in them as well as to work on and get better at them.
- It sits comfortably with international descriptions such as the Next Generation Science Standards in the USA (Achieve, 2013).

Starting point – going beyond content knowledge

In 2011, the distinguished curriculum developer and education researcher Jon Ogborn kindly prepared a paper for an IOP working group. The following extract from his paper provides a succinct, clear and compelling sketch of the ways that physicists think and behave; the emboldened phrases are the beginning of a set of ways of thinking that will be included in the practices:

> ***Physicists*** *focus their thinking on developing insight into what* ***the observable world is made of*** *and* ***how its constituents behave****, trying their hardest to achieve a* ***deep understanding****.*
>
> *Physicists seek the* ***most fundamental*** *explanations that have utility and currency* ***across many domains****. They are* ***not*** *satisfied with* ***superficial*** *explanations.*
>
> *This involves* ***systematic criticism*** *of every idea and result. They have to bring to bear* ***a wide range of knowledge*** *to make sure each analysis is* ***consistent*** *with what is already known.*
>
> *They are forced to be very* ***creative****, always looking for new answers or new approaches.*
>
> *All this thinking is informed by* ***experiment, observation and measurement****, carefully and cleverly designed.*
>
> *Physicists aim for that sharper and deeper quantitative understanding based on* ***mathematical models*** *which they use and re-use in order to make predictions that work* ***universally****.*

One appealing aspect of this passage is that it begins to bring physics alive and make it personal. Physics is not only about universal laws: it is also about the people who consider them and how they think and act.

Taking Ogborn's ideas as a starting point, the committee identified other practices, along with a number of crosscutting themes. Initially, they were collected into the three lists shown in Table 1. These lists were exposed to the community through the journals *Physics World* (Main and Tracy, 2013) and *School Science Review* (Main, 2014). They represent some of the things that we would like students to take away from a physics education, both in terms of what they can do and in terms of their lasting impression of the discipline.

Organising the practices of physics

These lists were a good starting point. However, we wanted to find a way of arranging them that more closely reflects the student experience; that is, what students should work on during their studies and be able to do better by the end of them. We settled on the grouping shown below. It is based on six **areas of practice**, which are highlighted in bold. These areas of practice are used again in section C.

Students' experience of physics should help them to learn to:

1. Recognise and use **the characteristics of physics explanations**, knowing that they tend to be

Table 1 An early version of some characteristic of physics and its ways of thinking

Characteristics of physicists (attitudes, actions and ways of thinking)	Characteristics of physics	Crosscutting themes of physics
Physicists tend to: • seek deep understanding • use experiments and their results • seek consistency • think critically • set aside preconceptions • employ methods to test plausibility • use reason and logic • be creative • think with and construct models to predict behaviour • simplify descriptions, explanations and models • use parallels and analogies	Physics explanations are characterised by: • reductionism • universality • unification • consistency • synthesis • empiricism • mathematical formulation • applicability	Ideas that appear in many explanations are: • conservation • equilibrium • differences cause change • inertia • dissipation • irreversibility • fields • energy

fundamental, synthesising, unifying, consistent, simplified, economical and elegant; they may be counter-intuitive.

2 Employ and be aware of **the cycle of developing a physics explanation**, recognising that the strength of physics explanations comes from the way in which they have been developed and severely tested through a combination of observation, reasoning, modelling, prediction and testing.
3 Carry out **practical investigations**, performing practical tasks to develop laboratory techniques and aspects of procedural knowledge, including isolating phenomena, controlling variables, making observations and measurements, analysing and interpreting data, testing plausibility of results, developing and refining explanations.
4 Deploy and notice **the ways of thinking and reasoning like a physicist**, including geometric and algebraic proofs, deductive and probabilistic reasoning, and inferring the history of evolving systems (Kind and Osborne, 2017).
5 Know about and think with **physics models**, including making predictions, simplifying situations, considering and using constituent parts and their properties and predicting behaviour.
6 See and exploit the power of **mathematical formulations**, by using numerical techniques and computational thinking to define quantities and look for relationships between them, 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, exponential changes.

While practical work is an important part of these practices, it is not the only part. Physics is also an intellectual exercise (hence the earlier use of the term 'thinking like a physicist'): explanations of observed phenomena are based on thinking ('minds on') as well as doing ('hands on') (Millar and Abrahams, 2009). I am confident that the set of practices captures both aspects.

The power of practices

These practices go beyond what has been explicitly defined in previous curricula. We feel that making them explicit will improve teaching and learning in a number of ways:

- Students will develop capability in a well-regarded set of transferable skills; for example, as they study the model of electric current in terms of electrons, they will also develop the utility of being able to explain phenomena in terms of the behaviour of unseen entities.
- Making the practices explicit will help students see purpose in their studies; while they may never use their knowledge of circuits, they may well use the modelling technique described above.
- Knowledge of the practices contributes to the cultural contribution of a physics education by providing a lasting sense of the power and trustworthiness of physics ideas; in our age of relative truths and a mistrust of expertise, this is particularly apposite.

It is worth noting that these practices are likely to apply in the other sciences, possibly in a different combination and with different emphasis. It may even be that the different combinations of the practices are what distinguish the sciences (but that is for another article). However, the one specific practice of physics that has stood out for me is that it builds its explanations on measurable quantities that can be put into numerical relationships. It is hard to think of a physics explanation that does not involve a defined and measurable quantity.

B. Structuring the curriculum

Our next task was to include these practices in a curriculum structure. A good starting point is to consider what questions physicists (and other scientists) are attempting to answer. One way of framing a set of questions is described by Kind and Osborne (2017):

(a) What exists?
(b) Why do things happen?
(c) How do we come to know?
(d) What can we do with the knowledge?

First, I will put the four questions into three dimensions.

Four questions in three dimensions

As Ogborn described above, physicists address the first two questions, (a) *What exists?* and (b) *Why do things happen?* as a pair. The resulting explanations have two aspects, which are respectively:

(a) What we think the world is made: a set of entities (stars, planets, atoms, waves and so on).
(b) How we think its entities behave: a set of theories, laws and models.

This mapping is shown in Figure 1. The explanations and ideas in the right-hand square represent what we would traditionally recognise as the content of physics.

Question (c), the epistemological question *How do we come to know?*, is important to both scientists and

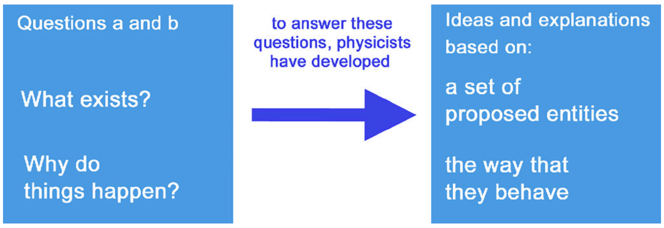

Figure 1 Questions (a) and (b) map onto the two aspects of the content of physics

citizens in order for them to have confidence in the ideas and explanations of physics (National Research Council, 2012). A good answer is that the explanations have been developed and refined through the practices of physics (see section A). They have not arisen by chance or whim. In other words, it is the implementation of these practices that gives us confidence in a physics explanation. This is illustrated in Figure 2.

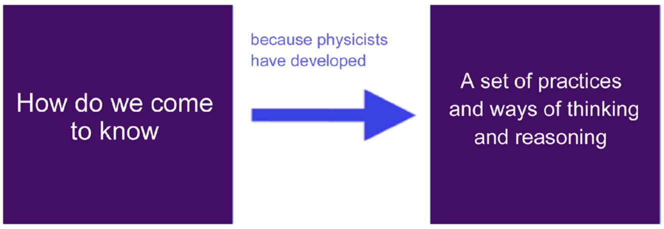

Figure 2 Question (c) can be answered by invoking the practices of physics

Question (d), *What can we do with the knowledge?*, is technological rather than scientific. It is included because applicability is one of the strengths of physics. Furthermore, it fits with UK education models in which school-level physics feeds into engineering and applied science courses in further education.

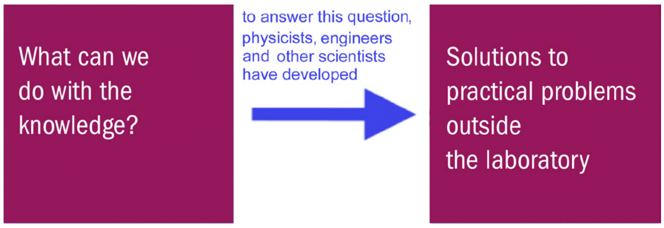

Figure 3 The technological question has led to physics being applied in engineering and other sciences

Three dimensions of the endeavour of physics

So far I have shown how the four questions map onto three suggested dimensions of the endeavour of physics. Those three dimensions are:

- practices;
- explanations and ideas;
- applications.

As we would expect, these three dimensions are themselves connected and interrelated. In Figure 4 the links are illustrated by putting the three dimensions above onto the front three faces of a cube. The top face is taken by the practices. Physicists have used these practices to derive the ideas and explanations of physics; these are shown on the left-hand face. Those ideas and explanations have been applied in engineering and the other sciences and, in turn, some applications have led to new physics (e.g. thermodynamics and flight).

To stretch the three-dimensional metaphor: I suggest that the left-hand face (the explanations) 'stands up' because it is given structural support by the top and right-hand faces of the cube. In an analogous way, the ideas and explanations of physics 'stand up' and have

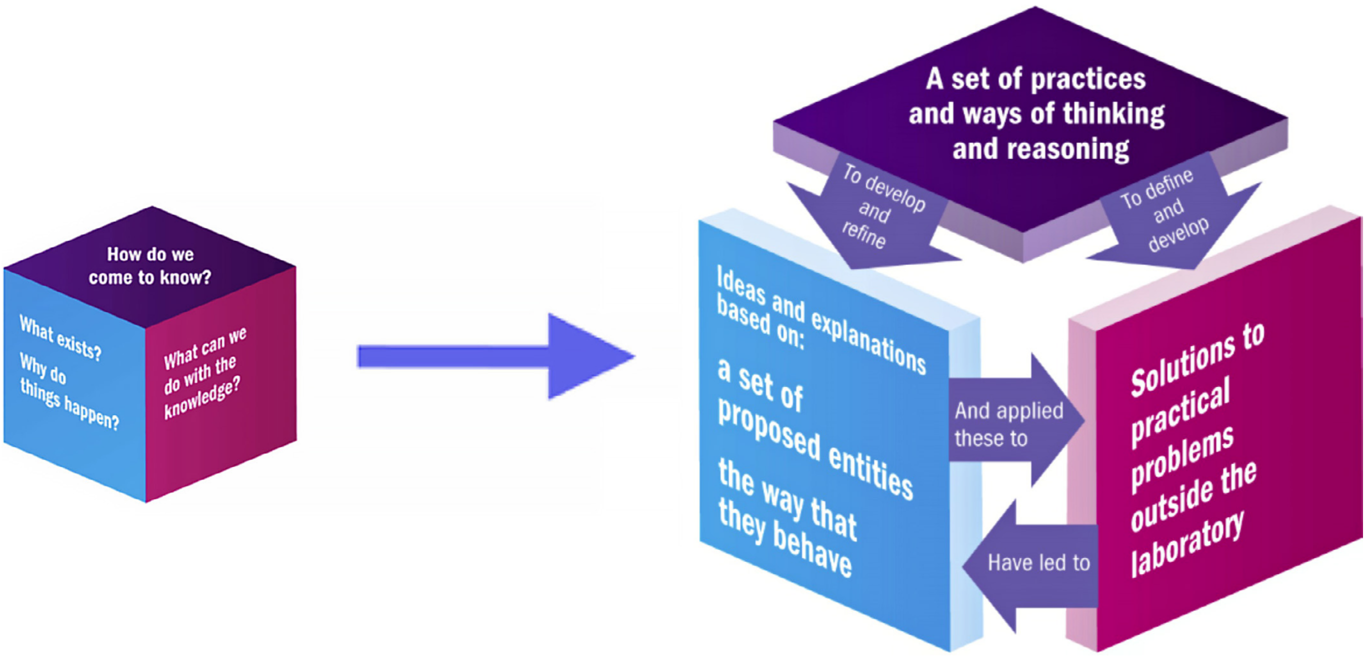

Figure 4 Four big questions for science arranged in three dimensions and a model of the endeavour of physics

survived because they have arisen from rigorous practices and they can be put to use.

In summary, all three dimensions are important in the endeavour of physics and therefore all three dimensions should be a part of the learning of physics. Building on the three dimensions will allow curriculum developers and teachers to present physics in a way that is representative of the discipline.

Relating the three dimensions to learning

A student's experience will (and should) be different from the endeavour of physics: they are learning physics, not practising it. However, by structuring that learning using the same three dimensions, their experience can be made representative and reflective of the endeavour without requiring them to be fully fledged physicists. This mapping is shown in Figure 5.

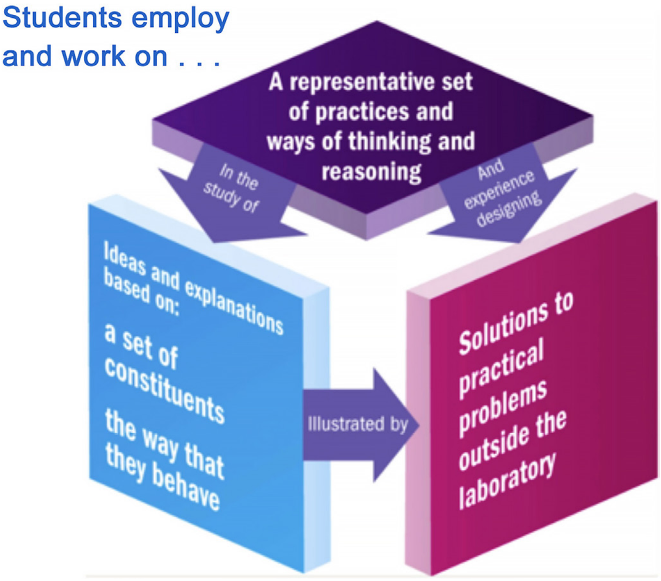

Figure 5 The three dimensions of learning reflect the dimensions of the endeavour of physics

Note how the 'practices' are linked to the 'explanations' by the phrase 'in the study of'. We are not proposing a strict inquiry-based approach or that students should be thinking and behaving like physicists in order to learn or discover physics. Direct instruction is likely to be a core element of their learning, but in a way that reflects the discipline of physics by including practices and application as well as content.

C. Expressing the curriculum in terms of big ideas

Many specifications are derived from and based on detailed statements of content knowledge. Peter Main has previously described how such curricula will be unsatisfying and unlikely to provide an authentic flavour of the discipline:

> *So many students see physics as a mess of disparate elements and miss completely its real beauty, which lies in its interconnectedness and the power and simplicity of its basic concepts.* (Main, 2014: 47–48)

In this section, I discuss how identifying a set of big ideas within each of the three dimensions will help overcome this lack of connection by providing structure, destination and purpose for the detailed content and, one can hope, a sense of its beauty.

We have identified big ideas in all three dimensions. Taken together they should give a lasting sense of what the discipline of physics is. Students will study and work on the detail so that they gain detailed skills and knowledge within each dimension. This will be useful in and of itself. At the same time, they will build up a deep and lasting picture of a small number of important, overarching conceptions in each dimension. We have expressed these as big ideas.

What is a big idea?

I suggest that there are four main features of a big idea:

- *It should be chosen and described so as to provide a destination and purpose to the detailed content.* Doing so will help answer the question 'why do I need to study this?' and provide continuity within and across the levels of study.
- *It should be long lasting.* The big ideas are what students will take away with them after their formal education in physics is complete. They are what remains, say, five years after they stop studying physics. Each big idea has plenty of detailed knowledge or procedural knowledge behind it. And while that detail is important (at the time and in developing the deeper sense of the big idea), the detail may not be retained – unless the individual stays in the field or uses a skill transferably.
- *It should express an idea that is core to physics and valuable to the individual.* This should be equally true for those who continue with academic physics, follow a technical route or pursue an unrelated route from 16.
- *It should illustrate the cultural value of physics* (Harlen, 2010, 2015). We are living in the scientific age. It is important that students understand the origin, beauty and contributions of physics to our culture and way of life. These cultural contributions map well to the three dimensions of practices, explanations and applications.

Furthermore, by expressing the curriculum in terms of big ideas, we can stand back from the detail, get a sense of the whole student experience, see its coherence, and determine which of them are important enough to form their lasting impression of the discipline.

Big ideas in three dimensions

The big ideas are listed below and illustrated in Figure 6 in the same three dimensions that I introduced in section B of this article. Harlen introduced the terminology of the big ideas 'about' and 'of' science. We have added 'from' and extended the phrases to make the contents of each dimension clearer. Therefore, we have:

- Big ideas *about* physics and its practices.
- Big ideas *of* physics and its explanations.
- Big ideas *from* physics in applications.

Below I describe the big ideas in more detail.

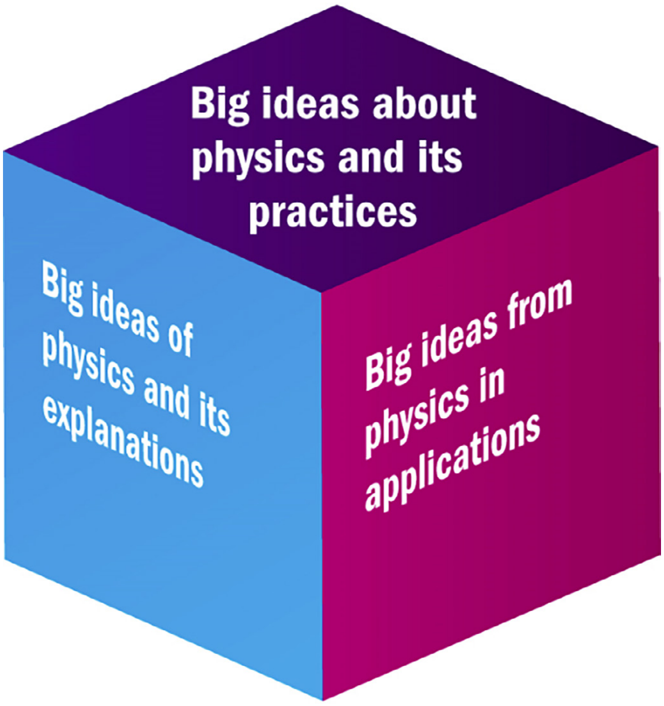

Figure 6 We have followed Harlen's convention of using 'about' and 'of' to describe the first two dimensions; we have used 'from' for applications

Big ideas about physics and its practices

In section A, I outlined the six core areas of the practices of physics. The list below expresses them, under the same headings, as big ideas.

1. **The characteristics of physics explanations.** Physics aims to provide the most fundamental explanations possible in terms of constituents of the universe and how they behave.
2. **The cycle of developing a physics explanation.** Physics explanations are durable and reliable because of the way in which they have been developed and severely tested.
3. **Practical investigation.** Physics is an empirical discipline: its explanations are grounded in observations of phenomena and experimental measurements.
4. **Thinking and reasoning.** Physics explanations are developed from data, using reason and logic and refined by argument and critique.
5. **Modelling.** Many explanations are based on models with which to think and to make predictions.
6. **Mathematical formulation.** Some models result in powerful mathematical relationships between defined quantities.

Students' learning will work towards and contribute to a lasting sense of these big ideas as well as an enduring confidence in the explanations that have arisen from these practices. In order to get that lasting sense, students will have to work on the detail behind the big ideas. By doing so, they will develop their capability and proficiency in a powerful, transferable and highly regarded set of skills (which are detailed in section A) and learn the difference between an opinion and a well-reasoned explanation.

Big ideas of physics and its explanations

Choosing content

While they are fundamental to the study of physics, the practices on their own cannot form a useful curriculum. Neither can they be used to generate the content. Therefore, we need to make direct choices about the ideas and explanations that should form the core of physics to age 16 and express them as big ideas.

Our suggestions for the 'big ideas of physics and its explanations' are shown below. They were chosen on the basis that, as a totality, they:

- cover a representative set of domains of physics;
- provide opportunities for authentic experiences of physics;
- prepare students for further study or employment in physics, engineering, the other sciences or technology;
- cover all the important ideas with which someone who stops their education at 16 ought to be familiar.

However, this set of big ideas is neither perfect nor fixed. I have highlighted some concerns beneath the list. These big ideas will be iterated as part of discussions that will follow the publication of this article and inform the IOP's guidance document.

The big ideas of physics and its explanations

As with the big ideas about physics and its practices, each of the big ideas below will have an associated narrative that will develop and describe the detailed content. It is worth noting that five of these were also expressed in Harlen (2015).

7 The Earth is a planet orbiting the Sun – one of many stars in our galaxy, one of many galaxies in the universe.
8 All matter is made of small particles and this can explain many of its properties.
9 Waves carry information without causing a permanent change in the intervening medium.
10 Objects interact with each other (by contact or at a distance) – giving rise to pairs of forces.
11 A force acting on an object causes its velocity to change; without a net force, its velocity is constant.
12 An electric current is the flow of charged particles; charge and current are conserved.
13 In any event, energy is conserved, but is also dissipated – becoming less easy to put to use.
14 Equilibrium occurs when two or more external influences are in balance (statically or dynamically).
15 Magnetism and electricity are linked phenomena.
16 Atoms are not indivisible – they have their own structure.

Challenges with big ideas of physics

There remain some concerns about this formulation of the big ideas:

- There are ten of them. In the other sciences, there are fewer (relating to content) and they come across individually as significantly bigger. This may well be an inevitable result of the way that physics has developed over time: its practices have been brought to bear on many domains of study of the material world.
- Some of the ideas appear to be more far reaching than others and, in that sense, bigger. For example, the big idea about electricity feels less 'big' than Newton's first law.
- They feel quite conservative and traditional.
- There may be too much in this dimension; in order to provide sufficient depth to some of these explanations and to provide space for the big ideas in the other two dimensions, it is quite likely that some content will have to go. However, it is worth noting that each big idea represents the destination for more than just two years of study.

Although these statements illustrate how this format can provide a basis for choosing content and presenting content in a coherent and purposeful way, they remain a work in progress. As such, I am inviting comments (see *Getting involved* at the end of this article).

Applications of physics

The third dimension of our structure relates to applications. Including applications as a specific dimension serves a number of purposes:

- It develops the ability to apply the practices and explanations of physics in unfamiliar situations.
- In doing so, students develop the sense that applying physics can be of benefit to the sciences and society.
- Knowledge of the applications contributes to the cultural dimension of a physics education for all (along with the practices and explanations).
- Students will learn about specific applications of physics in other sciences: earth science, oceanography, climate science and environmental science (as well as biology and chemistry).
- In the UK, physics is an important part of a route to engineering courses, both technical and academic. Therefore, students should experience (within the context of physics explanations) some of the ways of thinking that engineers might use.
- Contextualising physics and using local and personal contexts will help students to identify with the discipline (Godec, King and Archer, 2017); finding out about the multitude of occupations that lead from physics can encourage them to pursue it.

The list of 'big ideas from physics in applications' below captures those intentions.

Big ideas from physics in applications

17 Physics ideas can be applied in other domains of study within and outside the sciences.
18 The consideration of society's big questions and big challenges benefits from the explanations, ideas and practices of physics.
19 Physics explanations and ideas enable engineers to improve our comfort and wellbeing by designing and building solutions to defined problems, optimising those solutions and compromising efficiently.
20 Studying physics is preparation for many important, productive and rewarding occupations.

Summary

The intention of this work is to improve the experience of learning physics by developing a set of big ideas that are expressed in three related dimensions, with the explicit inclusion of practices and applications. The big ideas will allow curriculum developers and teachers to provide destinations and structure to teaching schemes. The three dimensions provide opportunities to enrich content by linking it to practices and applications. And the explicit description of practices will enable students to acquire important, transferable skills while developing their understanding of how physics explanations arose.

Students will study and learn about physics and its applications in a way that leaves them with lasting, positive and connected knowledge of the discipline's content. They will also have cultural awareness of the big ideas, their power and their beauty.

Closing remarks

There is time to get this right. Quite rightly, there is no appetite for curriculum reform at the moment. Even the normal cycle of GCSE review has been suspended as a result of the major overhauls of the early 2010s. However, we can start a discussion about what we would like an education in physics to look like and be ready for the next change.

Many of the suggestions in this article and the IOP's forthcoming document, can be implemented without curriculum reform. They can be used as ways to enrich and develop existing curricula and to encourage students to think like a physicist and to see applications in context.

Getting involved

Our intention is to work with teachers to turn the guidance into a framework and to produce links and suggestions to support this way of teaching – with or without specification change.

If you would like to comment on any aspect of the proposals outlined here, please do contact me (see email at the end). Or you can contribute to a discussion on *talkphysics*: www.talkphysics.org/groups/big-ideas/.

Acknowledgements

This article is based on five years' work of the IOP's curriculum committee. It comprised academics (physics and education), ITE tutors, teachers and recent students. There was a huge amount of expertise from a mix of disciplines, including engineering and the other sciences. The discussions and feedback from draft papers were challenging, enlightening and well informed. This article represents my own interpretations of those discussions and the notes to date.

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