Thinking like a physicist: design criteria for a physics curriculum

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ABSTRACT The physics curriculum is usually defined by content but this does not provide students with an authentic experience of the subject. An alternative is that physics is defined more as a way of thinking and this idea is explored in terms of the purposes of physics education, assessment and the relationship of the subject with other disciplines. A number of recommendations are made on how current systems, including examinations and practical work, could be altered to accommodate such an approach and on the best way to offer more challenge to the scientists of the future.

Identity

Most people are confident they know what a biologist is, and have experience of chemicals even if they confuse chemists and pharmacists. They have rather less idea of what physicists do. There are the high-profile areas, such as quantum theory, the cosmos and the Higgs boson, and these undoubtedly form part of the stuff of physics but how do we know they are physics beyond someone telling us it is so? Well, they are science, and they are not chemistry or biology… But can we do better than simply to define physics by default?

Dictionary definitions are of limited use: to paraphrase, biology is the study of living things and chemistry is the study of the elements and their compounds. The best physics definition I have found is 'the study of matter and energy', which is superficially plausible. However, since there is nothing but matter and energy, we are left with physics being the study of everything, which is appealing in one sense but hardly diagnostic.

It is a mistake to try to define physics in terms of its content. My own definition is that physics is:

a way of thinking, a reductionist view of the world where phenomena can be understood in terms of a relatively small number of physical laws and limited only by the complexity of a system or phenomenon.

There are many advantages to this approach. It defines physics as a way of thinking not tied to specific content, an idea that appeals to most practitioners. Furthermore, it does not impose artificial boundaries to the compass of the subject. Whether we do physics on a particular system is not decided by an arbitrary definition but by the limits to our ingenuity and computing power. Physicists do physics in such diverse areas as pharmacy and finance, usually making substantial contributions and sometimes changing the nature of the discipline.

The challenge is to provide physics education in schools that allows an authentic experience of this view of the subject.

Purpose of physics education

Table 1 shows the most popular university course destinations for both men and women with physics A-level (IOP, 2012a). For both men and women, the top ten subjects involve them using their physics in some way. Almost all, more than 95%, of the students who achieve A-level physics go to university, and a similar fraction study subjects that are science, technology, engineering and mathematics (STEM) related. Furthermore, around 85% of those taking A-level physics also take mathematics, a percentage that has risen considerably in recent years. These figures show that the purpose of A-level physics is almost exclusively to prepare students for university courses in which physics is a major or minor component.

In the lower age groups, where physics is a compulsory subject, the picture is quite different.

Table 1 The most popular university course destinations for accepted applicants with physics A-level in 2011; table from IOP (2012a); data from Higher Education Statistics Agency (HESA)

Overall		Males		Females	
Course destination	**%**	**Course destination**	**%**	**Course destination**	**%**
Physics	9.7	Mechanical engineering	10.9	Mathematics	10.5
Mechanical engineering	9.1	Physics	10.3	Physics	7.5
Mathematics	9.0	Mathematics	8.5	Preclinical medicine	5.7
Civil engineering	5.4	Civil engineering	5.8	Chemistry	4.5
Electronic and electrical engineering	4.1	Electronic and electrical engineering	4.8	Civil engineering	3.8
Computer science	3.8	Computer science	4.7	Mechanical engineering	3.4
Chemistry	3.8	Aerospace engineering	4.2	Combinations of three subjects, or other general courses	3.3
Aerospace engineering	3.7	Chemistry	3.6	Architecture	3.3
Preclinical medicine	3.6	General engineering	3.4	Subjects allied to medicine	2.5
General engineering	3.1	Preclinical medicine	3.0	Chemical, process and energy engineering	2.4

There are essentially three main groups to cater for:

A students who will move to further explicit study in physics, for example A-level;

B students who will use physics in the context of further study in a cognate discipline, for example, chemistry, geography or an engineering apprenticeship;

C students who will have no further explicit use of the subject.

An important question is at what point do we split the people who want to use their physics further, groups A and B above, from those in group C? Before addressing this question, I will make a few observations. First, before science was compulsory to age 16 in England, the numbers choosing to do physics at what was then O-level had been increasing monotonically for more than three decades (Smithers and Robinson, 2009). At the same time, A-level numbers were around 45 000, compared with around 33 000 at the time of writing, recovering from the nadir of 27 000 in the early years of the century. Second, very few students, ≪1%, who do not perform well at 11–14 (key stage 3 in England) carry on to A-level physics, and form about 2% of the cohort. Third, academic appointments to university physics departments are now heavily weighted towards people who have not been through the UK educational systems (IOP, 2012b). There is no corresponding flow of UK talent in the opposite direction, indicating that, in general, UK physics graduates struggle to compete with those from other countries.

These observations indicate to me that students in groups A and B are not being sufficiently challenged in their school education. Rather than raising the bar for all students, it would make more sense to allow students to choose general career paths at the age of 14, while allowing some flexibility at 16 for those who change their mind.

The big ideas of physics

Physics has a reputation as a difficult subject and yet many people, me included, chose it because they found it easier than most other disciplines. The apparent paradox is probably partly because brains work in different ways but another reason goes right back to the definition of physics and how it is taught. Unfortunately, curricula in schools usually follow assessment specifications, which are typically defined by their content, with some honourable exceptions such as the sorely missed Nuffield Physics. This drift away from the more innovative approaches has not been based on sound educational evidence; rather, it is a consequence of other factors, such as the high-stakes school accountability system in conjunction with the commercial competition between awarding organisations.

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. The mathematical character is often cited as the reason physics deters many students but another may well be related to the lack of any development of the underlying coherence and conceptual framework of the subject. Put simply, at school level, unless they have an exceptional teacher, students have no authentic experience of what physics actually is.

In a recent article in *Physics World*, Charles Tracy and I presented a list of concepts, the 'big ideas', that occur across the discipline (Main and Tracy, 2013). These were incorporated in a modified form in guidelines produced by the SCORE consortium for the science curriculum pre-16 (SCORE, 2013):

- **Reductionism**. Physics describes natural phenomena in terms of a small number of laws, which allow predictions to be made on whether and how things will happen.
- **Universality**. The laws of physics are universal – they work everywhere.
- **Unification**. There is a drive to reduce the number of laws to as small a number as possible, each one expressed in as economical a way as possible.
- **Synoptic nature**. Physics is an interlinked totality of ideas that must be consistent with each other. Problems can be approached from many different directions.
- **Cause and effect**. Events can be discussed and understood in terms of causes and effects: what makes things happen the way they do.
- **Mathematical techniques**. Physical laws can be expressed in a mathematical form. Physicists develop mathematical models to describe and predict behaviour.
- **Conservation**. Some quantities (charge, mass/energy, matter and momentum) are conserved. These conservation laws lead to powerful restrictions on behaviour.
- **Equilibrium**. Equilibrium occurs when two or more external influences are in balance – balanced forces, balanced moments, balanced pressures, equal flows in and out.
- **Differences cause change**. For example, temperature difference, pressure difference, potential difference, differences in concentration and unbalanced forces.
- **Inertia**. Things will tend to stay as they are unless something causes them to change.
- **Dissipation**. Many processes have an element that is resistive and dissipative. Dissipation is a result of the tendency of a system to become more disordered.
- **Irreversibility**. Dissipative processes are irreversible. For example, they limit the usefulness and the lifetime of a resource and determine the arrow of time.
- **Fields**. Action at a distance can be understood in terms of fields.
- **Energy**. There is a useful accounting tool – energy – that allows us to do calculations to find out, for example, how long sources will last, or whether some events can happen.

Some of these items might appear in a specification of a physics curriculum, but only as part of a specific topic – for example, equilibrium might be covered while discussing forces – and almost never as a unifying theme. It is my view that this list should serve as the basis for a physics curriculum. There will still be a need to decide which particular content should be chosen, for example optics, cosmology, etc., but no content should be specified unless it both links to one or more of these ideas and is also useful later in developing the subject further.

My definition asserts that physics is more a way of thinking than a set of topics. The big ideas provide the infrastructure for that view but the SCORE guidelines also explain how to approach the ideas, what it means to 'think like a physicist':

- **critical thinking and scepticism**: puzzling away at something and taking account of all possible objections to find an explanation that works;
- **deep understanding**: looking for deeper and deeper explanations, not being satisfied with a superficial description, looking for the most fundamental answer that has predictive power across many domains;
- **seeking consistency**: testing that answers are consistent with experience and all other areas of physics;
- **reason and logic**: striving for logical consistency within arguments;
- **quantitative understanding**: realising that quantitative analysis is necessary for proper understanding;
- **models**: developing models (often mathematical) of systems to make predictions of their behaviour in a variety of circumstances;

- **simplification**: simplifying physical situations to their core elements to enable the use of quantitative models to explain or predict phenomena;
- **approximation and other techniques**: making back-of-the-envelope calculations to test the plausibility of ideas, using techniques that consider limiting or extreme cases;
- **isolating**: isolating physical phenomena to test ideas experimentally;
- **using experiments to test ideas**: refining models through the iterative sequence of experiment → model → prediction → test;
- **excising prejudice**: being able to step outside immediate experience and accept explanations that are beyond 'common sense'.

The list is largely one of skills, which are at the core of the physics curriculum; the overriding themes are critical thinking and logical reasoning. The two lists above, taken together, define what it is to be a physicist.

Interested readers can refer to the SCORE guidelines for a list of the domains of physics but there is no reason why the big ideas and skills outlined above could not be used to consider topics in areas traditionally associated with, for example, earth sciences, biology and even psychology. The speed of a signal along a nerve fibre places a heavy constraint on how the central nervous system can operate.

Finally, chemists and biologists who read these lists will recognise many of these big ideas as part of their own disciplines, which is hardly surprising, given the commonality of the process of science. With similar lists for those sciences, there is no reason why the sort of approach I am advocating for physics should not apply to all science subjects. Indeed, it could be argued pragmatically and philosophically that it would be impossible for physics to go it alone.

Assessment

A shift away from a content-led towards an ideas-based curriculum would be a major change, not least in assessment. As part of the preparation for this article, I compared a selection of English examination papers from 30 or 40 years ago with those of 2011, at both A-level and GCSE/O-level. I have been surprised in the past at how many people have done the same, with much more rigour (Coe, 2010), and yet emerged with conflicting views as to the relative difficulty. I do not really wish to be drawn into that debate but a few points struck me on even a cursory investigation:

- The O-level papers were undoubtedly at a much higher level than the GCSE ones, with content comparable in some areas with the current A-level.
- The step from GCSE to A-level now is much higher than the step used to be from O-level to A-level.
- In both sets of A-level papers, there was good use of multiple choice questions, which, in my judgement, were more challenging than the longer questions. But the difference in demand was striking: a 1983 Nuffield paper had 40 questions to be answered in 75 minutes, whereas a corresponding paper from AQA in 2011 had 25 questions of similar difficulty with 105 minutes available.
- The longer questions had markedly different levels of structure. Specifically, recent papers offer much more guidance to the candidates, not just providing formulae sheets but also often stating the physics to be used in answering the questions. Few questions require more than one step of reasoning.

An interesting comparison is the degree to which the assessments require candidates to 'think like a physicist'. Here, there is far more difference between the old and current papers, particularly comparing O-levels with GCSEs. One obvious difference is that the latter include aspects of working scientifically (formerly 'How science works'), which one might imagine could require some of the elements described in the big ideas of physics section above. Unfortunately, in practice, the majority of the assessment questions on working scientifically do little in this direction, although there are major differences between papers from the different awarding organisations. In some cases, questions require no scientific knowledge or expertise to answer.

The older papers, while still content driven, were much more likely to require skills of making estimates and approximations, synthesis of information and the construction of logical narratives, sometimes in unusual contexts. As an example, consider a question from a University of London O-level paper in the mid-1970s:

Explain (i) why a kettle of water with a steady supply of heat takes a much longer time to boil *dry than to reach its boiling point; (ii) how evaporation differs from boiling; and (iii) how the molecular theory of matter accounts for the drop in temperature which results when rapid evaporation of a volatile liquid occurs.*

The level is around current A-level standards but the main aspect of the question is that it requires candidates to have qualitative knowledge of latent heat, heat capacity and kinetic theory, as well as to be able to construct a model of what is happening. O-level papers did not comprise entirely questions of this type but there is certainly a fair sprinkling. I have been able to find few similar questions in the current A-levels and essentially none at GCSE level. Over time, assessments have evolved to become more driven by content and to represent less well the essential elements of physics.

Practical work

Experiment and analysis are what distinguish the sciences from other areas of study and are an essential part of a physics curriculum. In physics, practical work serves a number of different purposes, including:

a illustration and demonstration of physical phenomena;
b familiarisation with basic apparatus and techniques;
c data gathering and analysis;
d introducing scientific methods;
e designing a scientific investigation;
f reporting an investigation.

The question of how to deal with practical work is strongly interlinked with assessment and what outcomes are required for particular groups of students – the outcomes will be different for students who want to become scientists than for those requiring a more general scientific grounding. The latter group's requirements focus on points (a) and (d), whereas the scientists of the future should be provided with a structured programme covering all aspects.

Assessment is relevant in driving classroom experience. However, it is generally accepted that there are problems surrounding the assessment of practical work, possibly because there is no consensus as to what the assessment is trying to measure. Awarding organisations generally report very high marks and low discrimination. One reason for that is that many aspects of practical work require threshold competences that all students should acquire and which do not lend themselves to discrimination. One either knows how to wire a voltmeter in a circuit or one does not.

My model is that, from the age of 14, students wishing to study science beyond age 16 should embark on a structured laboratory programme based around levels of competence. Teachers would keep a record of what is done and which students have achieved which competencies. Senior school management would be responsible to regulatory agencies (which in England is the Office for Standards in Education, Children's Services and Skill (Ofsted)) for ensuring that the experimental programme has been carried out and there could be spot checks to ensure probity. Satisfying the competency requirements would be a necessary condition for passing the relevant examination but would not otherwise contribute to the mark or the school accountability, i.e. league tables.

In principle, data gathering and analysis could be part of the written examination at the end of the course, provided that the questions were sufficiently open-ended to allow a range of answers of differing levels. Part of the structured laboratory programme would be at least one project, to build upon the basic work and to introduce list items (d)–(f). Extended investigations, where different students pursue different topics, manage to combine high levels of student motivation and good discrimination while avoiding many of the issues surrounding malpractice that have dogged continuous assessment in recent years.

Recommendations

My first recommendation is that we should move away from a content-driven physics curriculum towards one that is more skills-based, incorporating many of the big ideas and elements of thinking that define the subject. One cannot neglect content completely and certain topics will need to be covered if only because they will not be covered elsewhere, for example forces, electricity and magnetism. But content needs to earn its place in the curriculum and should be included only if it contributes to the big ideas and only if it leads somewhere. These domains of physics are listed in the SCORE guidelines document but, with a curriculum based on thinking, there is nothing to prevent the physics approach being applied to non-traditional areas.

The second recommendation is that there is an urgent need to consider the curricula of the sciences and mathematics in a much more coherent manner. Physics is so strongly dependent on mathematics and the combination so important in accessing STEM subjects that they do need to proceed in tandem, with physics incorporating new mathematics as it is learned and also, inter alia, providing excellent examples of mathematics in action. Mathematics is too big a dog to be wagged by a physics tail but there is no reason why the physics curriculum should not be built around the mathematics, provided that is done consistently. One possibility is a joint qualification of physics and mathematics, for example a double A-level, which would have clear benefits in terms of coherence. Given that 85% of those taking physics A-level also take mathematics, such an idea would not be too large a perturbation on the system and individual, single qualifications would still exist. A report (IOP, 2011) published by the Institute of Physics indicated that the poor integration of mathematics in the physics curriculum was a serious handicap for students entering university courses in physics and engineering.

Coherence between physics and the other sciences could also be improved, particularly where common concepts are used. While not underestimating the difference in cultures between the disciplines, the sciences should reinforce one another rather than, as sometimes happens now, confuse the student. It is unsatisfactory if a student is told in physics that energy is conserved and in biology that energy is converted to organic matter.

Bringing together the sciences in this way might also encourage more girls to study physics. Research shows that context matters to girls and the traditional abstractions of physics offer less appeal. An inspection of Table 1 indicates the gender difference well and these are females who have chosen to take physics post-16. A greater coherence between the subjects would also perhaps indicate just how important physics is across a range of contexts.

My third recommendation concerns the question of when to separate those students who are going to specialise in science from those who are not. In England, this currently happens at age 16 and, because all students have to be accommodated to this point, a consequence has been a deepening step to A-level or other post-16 qualifications. There are also concerns about whether UK STEM graduates are really competitive with those from other developed countries. Recently, recognising this problem to some extent, the Office of Qualifications and Examination Regulations (Ofqual) has stiffened the challenge of GCSEs but, at the time of writing, the A-level reform process appears unlikely to result in a similar change post-16.

I suggest that the split should occur at around age 14; from that point, those continuing with physics as a major subject would undertake a revised curriculum of the type outlined above, including the structured laboratory programme. While many will see such a change as a return to an 11-plus style watershed with a concomitant waste of talent, statistics show that very few people indeed who do not perform well in science at 14 actually take physics beyond 16. Provided that there are suitable routes to re-enter the system for those who might regret their decisions, I can see no reason why such an arrangement would not be an improvement for both the science specialists and the other students, who would also benefit from a science course tailored to their needs. For the latter group, a thinking-led curriculum would also be appropriate but of a different type, with more weight given to critical analysis, to engender the types of skills they would need to understand the increasingly technological society in which they will live. Such a change could be seen as an extension to the approach taken in some GCSE courses, for example Twenty First Century Science, in which all students take ‘core science’ with the option of additional science for the enthusiasts.

As a final point, I turn to the question of whether we need physics at all in an increasingly interdisciplinary world. Indeed, I have argued above that physics is not defined by content and the curriculum would benefit from a broadening of contexts. But the reason that physics is so powerful and why physicists generally have impact in areas far removed from their traditional domain is precisely because their approach to science has the distinctive flavour of the big ideas and their way of thinking. That does not make physicists better than other scientists and engineers but it does make them distinctive. And, after all, one cannot have multidisciplinarity without disciplines.

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