Review of Leaving Certificates in Physics, Chemistry and Biology

Per M. Kind

School of Education

Durham University

p.m.kind@durham.ac.uk

Recommendations

To create emphasis on relevance and scientific literacy

- More emphasis could be made in the Units of study in the Physics Leaving Certificate to define topics with relevance in society.
- All three Leaving Certificates could offer better explanations for how topics in the Units of Study link to learning objectives for understanding ethical, historical, environmental, and technological aspects of science and making informed conclusions about contemporary physical and environmental issues.

To bring in a current understanding of scientific inquiry and link scientific inquiry to all parts of the science curriculum

- Rewriting Unit 1 and using the *science practices* as organising topics rather than *science method*. Learning objects in these topics should point both towards what students should be able to do *and* to know.
- When presenting learning objectives for 'hypothesising' (i.e. developing and using science conceptual knowledge), more attention should be given to models and modelling in science.
- Evaluation and argumentation of scientific claims should be linked to students learning and reflection on scientific conceptual topics, to analysing data and drawing conclusions in experiments, *and* to debates raised about socio-scientific issues.

To bring in learning progression

- Information about learning progression should be added to each Unit of analysis in the Leaving Certificates. This could be a text, for example, pointing towards three levels of proficiency, identifying concepts, ideas and skills belonging to the different levels.

Introduction

Any new standard document faces the challenge of finding an appropriate balance between being 'traditional' and 'modern'. On one hand, the document is developing from, and has a responsibility for, maintaining an existing educational culture. On the other hand, attempts should be made to adapt the document to new political challenges and priorities, new trends in educational practice and new discoveries and theories in educational research. The document is an opportunity to adjust the course of the educational community towards new priorities and knowledge. Importantly, the standard document is written for participants in community and has little value without their support and commitment.

This report analyses the new *Leaving Certificates* in Physics, Chemistry and Biology for Ireland in light of three current trends in science education and assessment research. The aims are, to present information about the trends, to identify criteria and questions arising for standard documents and to evaluate the Leaving Certificates relative to these. The aims will serve as a structure for the document, which in each section a) describes a trend/issue, b), identifies question and criteria with relevance for standard documents, c) evaluates the Leaving Certificates and d) make suggestions for changes.

Scientific literacy and contextualising of the school sciences

The first issue, on one hand, may seem of little relevance for the Leaving Certificates, since this is a trend that mainly has affected compulsory science education. *Scientific literacy* represents an intention to make science relevant to all and to have the general public being familiar with science knowledge and thinking. On the other hand, scientific literacy has triggered debates about the aims and purposes of teaching science and about the structures of science curricula that have relevance to science education more generally. For example, it raises questions about the *relevance* of science education, about recruitment and students' interests, and about principles for organising the curriculum. First a short history.

Scientific literacy became a topic in the 1950s, when it was pointed out that the general public did not have sufficient understanding of science, and turned into a debated about the purpose of compulsory science. An argument was put forward that compulsory science too strongly had an academic orientation and did not prepare students for life. This, it was claimed, was unreasonable as only a small proportion of the students actually went on to study science at higher levels. In the beginning, however, the debate did not gain much attention. Educational reforms, for example, in the 1960s were triggered firstly by the need for preparing future science, rather than the need of all students, and when these reform projects later became oriented towards improving the pedagogy of science teaching, it was learning psychology and not curriculum debate that served as the motivation. Instead, it was the STS movement in the 1970s, which argued students should learn about the relationship between science, technology and society, that brought the debate forward. The STS movement gradually turned into an argument that science should be taught in relation to the personal needs of the students and in relation to important aspects of the contemporary society, rather than as a 'preparation for university studies'. The argument had a clear democratic orientation, pointing out the need of citizens to be able to identify, analyse and engage in science-related social issues. During the late 1980s and into the 1990s this idea was picked up by many science education researchers, who started to see scientific literacy as the leading idea in a new curriculum reform movement. In short time, it became a world-wide phenomenon, and today is seen as an 'obvious' mentioning in any new science curriculum.

One stimulus to the trend has been OECD's PISA project. More than 60 nations have participated in this international assessment study, which tests 15 years old students' competency in science-, math- and reading literacy. The science literacy movement became apparent in the UK in 1998, with the document *Beyond 2000* (Millar & Osborne, 1998). This led to changes in the National Curriculum for England (Qualifications and Curriculum Authority, 2007) and a new science course, the *21st Century Science* that is taught across the nation.

In the late 1980s and early 1990s another movement started in the US parallel to the scientific literacy movement and also spread to a world-wide phenomenon. This was the 'standard reform', which was motivated by globalisation and the need for the U.S. to compete for the highest level of educational achievement. One document triggering the movement was *A Nation at Risk: The Imperative for Educationa*l by the National Commission on Excellence in Education. It used the international school surveys (which at that time meant TIMSS) to argue that academic standards had fallen in mathematics and science in the U.S., and claimed that this had caused declining economic position in the world market. We should think this movement would have worked counteractive to scientific literacy and moved focus back to a traditional academic-oriented curriculum, but this has not been the case. Instead, the two movements have merged into a common focus on clarifying *what* students should learn in science education and what '*level'* their achievement should have. In the US, for example, the influential document *Science For All Americans* (American Association for the Advancement of Science, 1989) had strong influence on the first national science education standard (National Research Council, 1996). The standards document attempted a compromise between scientific literacy and an academic oriented science by stating that 'to keep pace in global markets, the United States needs to have an equally capable citizenry' (p. 2). In other words, a leading position in the global market, they think, can be achieved by making *everybody* good at science.

This attitude, that education should aim for both 'literacy' and 'specialism', is widespread among educators and politicians, however, not without tension. As DeBoer (2000) points out, spending time on teaching *about* science and engaging students in *socio-scientific debates* gives less time to other issues. Millar (2011: 175), analysing the National Curriculum in England, also claims that 'any single course that tries to achieve both purposes will come to feel like an unsatisfactory hybrid that achieves neither well'. Arguments in the press, have gone even further, claiming that the attempts to produce scientific literacy-oriented courses is a ''dumbing-down' of science teaching. These comments, however, are directed mainly towards compulsory science. In post-16 physics, chemistry and biology courses, the situation is different. 'Specialism' is the obvious priority, and the question is more about adjusting the courses and bringing in some elements of scientific literacy. It means that a wider set of careers have to be considered and that courses should demonstrate some relevance for society and personal issues. Studying science at post-16 level should not be just a preparation for reading the subject at university level, but also a broader training towards citizenship.

Questions and criteria for standard documents

The following questions and criteria can be put forward for evaluating the Leaving Certificates. Firstly, how do they prioritise the purposes of the post-16 science teaching, as a balance between preparing studying science at the university, other careers and citizenship. Although a much higher proportion of the students doing biology, chemistry and physics at this level will actually go on to study science than in compulsory education, this is still an important question. It is important that the document explains the purpose, but also that the purposes are reflected in the objects and content of the courses. An expectation is also put forward that some priority is given to other purposes than just preparing students for university studies in the sciences.

Secondly, the science literacy issue relates to a question about *relevance* of the science syllabus. Traditionally, relevance has been a matter of making abstract ideas concrete and linked to students' experiences with the physical and biological world. In the literacy-context, however, this has changed to linking science to society more widely. A criterion, therefore, is that the science syllabus should *not* teach science knowledge in isolation but take a wider perspective and involve technical, political, social and personal issues relating to the science theories. Educational research suggests students increasingly choose to study subjects they find relevant for personal development and not just work prospects (Schreiner & Sjoberg, 2007)). This issue, therefore, relates also to recruitment and students' motivation for choosing and learning science.

Thirdly, scientific literacy is not just about *what* topics and issues should be included, but also how these should be organised and presented to students. Some reform project, like the *Advancing Physics* by IoP (http://www.advancingphysics.org/), have gone far in embedding science concepts in topics meaningful to the students. The alternative is embedding literacy issues within a science conceptual structure. One organising principle is not more 'right' than another, but a standard document should be explicit and give advice on how science courses could be organised.

Evaluation of the Leaving Certificates

Interestingly, none of the Leaving Certificates in Physics, Chemistry and Biology points towards further studies in the sciences as the main purpose, although this may be assumed as a main purpose. Rather the general vision is to '*develop learners* [who] *can interact with the world around them and understand how scientific concepts can be used to make sense of the physical world*' (p. 6). The literacy-perspective is embedded in the description of the Senior Cycle, which promotes learning strategies '*relevant to participation in, and contribution to, a changing world where the future is uncertain*' and aims for '*development of the learner as a person and as a citizen*' (p.1 and p. 2 in all documents). These points are followed up as learning objectives:

- develop a deeper understanding of the ethical, historical, environmental, and technological aspects of physics, and of how physics contributes to the social and economic development of society
- develop qualities that enable them to make informed conclusions about contemporary physical and environmental issues, including those that raise ethical questions

All three sciences have a section in the introduction relating the curriculum to 'community and society' and pointing towards developing students' appreciation of social and cultural perspectives. Naturally, the objectives also point to developing knowledge and skills in physics, chemistry and biology. The conclusion is, therefore, that the Leaving Certificates aims for both literacy and in-depth subject understanding for further studies. The documents, however, do not explain what exactly the purpose of courses is beyond developing the learner. In other words, what careers or activities the students are prepared for after having achieved the Leaving Certificate.

Looking at the syllabi there are differences between the sciences in their priorities between science content and topics with relevance to personal and social issues. All three sciences have a topic called 'social aspects of scientific evidence' in the unit of study for scientific methods. This topic, however, is about science method (see below) and less about science in society. The biology syllabus has included several topics with social, ethical or environmental relevance in all the Units of Study. For example, teaching *genetic engineering* and *human impact on the environment*. The chemistry syllabus has a less explicit emphasis, but a unit for *environmental chemistry* and a topic on *everyday organic compounds* in the organic unit. The physics syllabus has the least emphasis of social and personal relevance. Looking at the syllabus structure at p. 12 in the Leaving Certificate, there is no obvious topic where social, ethical or environmental issues will be taught. Moving to the detailed outlines of the topics, however, ethical issues are raised in the discussion about *consequences of energy supply* and *cost of space research*.

On one hand, the difference described above may be a consequence of the nature of the subjects. Biology research, currently, has obvious ethical issues related to genetics engineering and the human impact on the environment, while physics research is less ethically and politically controversial. On the other hand, the different syllabus groups seem to have put different effort into tracing relevant socio-scientific issues and opportunities for linking science with society. This makes different impressions about their relevance. The biology syllabus seems most, and the physics syllabus least, linked to society.

Missing in all the three standard documents, however, is an explanation connecting the syllabus structure to the learning objectives. This explanation could clarify in what ways and to what extent topics in the Units of study should promote learning objectives for scientific literacy stated above. It would serve as useful guidelines for teachers and other users of the documents.

Advice for further development:

- More emphasis could be made in the Units of study in the Physics Leaving Certificate to define topics with relevance in society.
- All three Leaving Certificates could offer better explanations for how topics in the Units of Study link to the aims and learning objectives in general and the two learning objectives for scientific literacy in particular.

Science inquiry and its role in the school science curriculum

Agreement has existed since its conception that school science should teach both 'processes' and 'products' of science. *Processes* are associated with scientific methods and reasoning strategies commonly used in science, while *products* are the science theories, laws and concepts. Beyond this agreement, however, there has been much debate about the relative weight of the two facets, sometime with extreme views on both sides. One problem has been to settle a theoretical framework explaining scientific inquiry in school science. This problem has been apparent in debates about practical work, teaching about science and use of inquiry strategies as a pedagogical tool. It has been made more complicated because of disagreement within the *science studies*, that is, among philosophers, historians and sociologists of science, about how science actually works, and also by poor communication between this field and the *learning sciences*, that is, groups studying cognition and learning. Science educators, typically, have ascribed to one of these academic fields only, i.e. either to the science studies or the learning science, when searching rationales, and thereby established too narrow or simple explanations. Over the last decades, however, new perspectives and theories have started to emerge within the science studies and the learning sciences that provide a more coherent rationale for teaching and learning of science inquiry. This rationale will be presented here and used as a comparison for the Leaving Certificate in Physics, Biology and Chemistry.

The rationale denies any attempt to establish *the* scientific method, because problems investigated in science, within and across science phenomena and fields, are far too different and varied. Some methods and procedures, of course, are common to many research areas, but this is different from having a general method. The consequence has been to move attention away from methods and more towards the purposes and principles underpinning science, suggesting science is manifested in five different *practices*:

1. Developing theories and explaining nature (hypothesising);
2. Conducting experiments and testing scientific theories (experimenting);
3. Evaluating and coordination scientific evidence (evidence evaluation);
4. Communicating scientific knowledge, data and argumentation (communicating); and
5. Using scientific knowledge to solve practical problems (engineering).

The three first practices are the basis for scientific inquiry: scientists put forward a hypothesis, test this in an experiment and evaluate the evidence to draw a conclusion. The last of these three is essential, because data never speak for themselves. Scientists have to construct an argument explaining *why* data apply as evidence for a conclusion, evaluating the quality of the data and including theoretical frameworks. Each practice can be divided into sub-categories. Hypothesising, for example, relates to raising questions, establishing and defining meanings of concepts and developing models. There are good reasons *not* to call these practices a *scientific method*, because they appear differently in different contexts and can be carried out in different orders. Their common elements are the purpose and the underpinning principles. The fourth practice, communication, is essential because science is a social activity, as will be described below. The last practice relates to technology rather than science, but these two fields are intervened and separating them is not always straightforward. Many have therefore argued its place in the science curriculum.

The underpinning principles of the practices relate to epistemic perspectives and criteria scientists have to follow. Scientific theories, for example, should be general and describe many situations, falsifiable in empirical experiments, logically coherent, align coherently with other theories, and so forth. These are criteria, defining ‘scientific knowledge’ and there are similar criteria defining ‘scientific measurements’. Anyone operating in science has to understand and be able to use these criteria, which means they need *epistemic* and *procedural* knowledge in addition to science *conceptual* knowledge. The epistemic and procedural knowledge can, but does not need, to be declarative. Much understanding about how to do science is kept as 'functional understanding' (Allchin, 2011), rarely made explicit except when asked to explain actions or put forward explicitly for assessment (for example in a scientific review process).

Importantly, scientific practices operate at both individual and social levels. The individual can carry out an argument comparing a hypothesis to available evidence and existing knowledge, and from this draw his or her own conclusion. A much wider social argumentation and agreement, however, is necessary to establish a new scientific discovery. Importantly, scientific criteria are firstly social criteria established within the science community. Anyone coming new to science has to learn and adapt to the criteria and apply these in his or her own scientific work.

Describing scientific inquiry in this way has support in both science philosophy (Giere, Bickle, & Mauldin, 2006; Kuhn, 1962; Toulmin, 1958) and learning psychology (Klahr, Fay, & Dunbar, 1993; Vygotsky, 1978). For this reason, it applies both to teaching students *about* science and *to do* science. The rationale also applies to describing school science itself, which is an introduction into all five practices. Students typically learn *hypothesising*, e*xperimenting*, *evidence evaluation* and *science communication*, although, the practices are often weighted differently. *Engineering* is a practice involved in some science curricula, but not all. When the practices, are carried out in the school context, they are underpinned by the similar epistemic and procedural criteria as operating in 'real' science.

The implication of the new rationale is that students should have a systematic introduction to all the mentioned science practices (hypothesising, experimenting, evidence evaluation and communication), and that this requires teaching of epistemic and procedural knowledge, in addition to science conceptual knowledge. As mentioned, epistemic and procedural knowledge can be 'functional' rather than 'declarative', but listing the knowledge explicitly in standard documents is important so that teachers and assessors know what students should learn.

Questions and criteria for standard documents

The following questions and criteria can be put forward for evaluating the Leaving Certificates.

Firstly, what emphasis do the documents give to scientific inquiry and how is this topic explained. There is no 'right' balance between conceptual topics and inquiry, but we would expect an explanation for why students should learn scientific inquiry. Following the suggested rationale, scientific inquiry should be adapted to the different sciences and emphasise practices rather than methods.

Secondly, in what ways are scientific inquiry linked to other topics in the science curriculum. The expectation is that science inquiry, as different practices, is integrated in all parts of the curriculum.

Thirdly, in what ways are scientific inquiry emphasised as something students should *know* compared to something they should *do*. Following from the suggested criteria, students should learn procedural and epistemic knowledge, and these should be made explicit in the Leaving Certificates.

Evaluation of the Leaving Certificates

The three Leaving Certificates give high priority to scientific inquiry: firstly, the learning objectives suggest students should learn scientific inquiry skills and develop skills in laboratory procedures and techniques; secondly, practical activities are found in a variety (Experiments, Open-ended investigations and Issues investigations) and made compulsory for students; thirdly, activities are linked to science topics through specific activities mentioned on all Units of study; and fourthly, scientific inquiry and practical work are included in the assessment.

The Leaving Certificates, however, present scientific inquiry as something students should learn to *do* rather than *understand*. Neither the general objectives nor the learning objectives in Unit 1 mention *understanding* of science inquiry.

The rationale for teaching scientific inquiry also has strong focus on *scientific methods*, which is the title of Unit 1. Compared to the discussion earlier about theoretical rationales, much attention is given to *experimenting* relative to the other practices. Reading the learning objectives more in detail, they do suggests all practices, except from *engineering* are included. Students should formulate and develop hypotheses, conduct and analyse data, develop arguments to draw conclusions and communicate findings. By focusing on experiments and scientific method, however, it is not made clear that *all* part of the science curriculum contributes to learning scientific inquiry. It is made an impression that students learn about science and learn scientific reasoning *only* when doing experiments and practical activities.

Advice for further development:

The main suggestion for changing the Learning Certificates is rewriting Unit 1 and using the practices as organising topics. Learning objectives in these topics should point both towards what students should be able to do *and* to know.

When presenting learning objectives for 'hypothesising', attention should be given in particular to models and modelling in science. In physics, but also the other sciences, mathematical modelling has high importance.

The science practice most often left out by teachers and students is 'evidence evaluation'. Students often hold a naïve positivist view of science, seeing data as leading incontrovertibly to true knowledge. Evaluation and argumentation of scientific claims, therefore, should be linked to students learning and reflection on scientific conceptual topics, to analysing data and drawing conclusions in experiments, *and* to debates raised about socio-scientific issues. Students in this way get a more comprehensive training in scientific critical thinking.

One place to look for examples on how to describe scientific practices is new national K-12 Science Framework for the US (National Research Council, 2012), which identifies eight science practices. Another document is Osborne (Osborne, 2011).

Establishing 'development perspective' in the science curriculum and assessment practices

This last trend has grown out of two different initiatives. Firstly, educational research on *learning progression*, which has three focuses. One focus is progression of a learning topic. In other words, describing progression from simple to advanced understanding of a science topic. The second focus is learning pathways. This is trying to identify particular 'routes' students follow from simple to more advanced understanding. For example, this research is interested in particular misconception and 'threshold concept' students have to overcome. The third focus is progression in the teaching. The ideal, of course, is that teaching should have a progression which is matched to students' learning pathways, or at least take into consideration progression from simple to more advanced understanding of a topic. Research on these foci has expanded over the last years, much helped by decades of research into students' learning. Some learning progression research studies are meta-analysis on misconceptions and conceptual change research on particular topics in science. Importantly, learning progression research can cover different periods of time (e.g. progression through compulsory education years or within a single year of study), and be made with different breadth and grain size (e.g. a rough description of development in understanding force and motions in physics or a detailed description of Newton's third law).

Secondly, the developmental perspective has grown out of criterion and construct-driven assessment attempting to improve assessment's validity. Wilson (2005) presents this argument in detail, suggesting assessments should start by establishing a 'construct map' of the intended assessment area. This is a learning progression describing levels of understanding from the least to the most able students. This 'map', he claims, should guide all parts of operationalising the assessment into items, scoring rubrics and measurement scales.

It is easy to see the parallel between these two initiatives. They both suggest educators and assessors should establish understanding of learning progression before teaching or assessing student. The suggestion naturally includes standard documents, which defines the learning domain, and to some extent such documents are already involved. The s*tandard reform*, described earlier, has meant focus has changed from 'curriculum guidelines' towards describing at what *level* students should be proficient and understand school topics. Many nations now use criterion-based assessments and link assessment directly to levels in standard documents.

Questions and criteria for standard documents

The questions about the Leaving Certificates are if and how they identify learning progression. The criteria for evaluation are, firstly, that learning progression should be included, and secondly, that this progressions should be helpful to users of the certificate.

Evaluation of the Leaving Certificates

The analysis and evaluation is very short since little information is given about progression.

A common presentation is made of *differentiation* in all three Leaving Certificates. This describes two levels 'ordinary' and 'higher'. The ordinary level relates to 'concrete' understanding and moderate range of skills, while the 'higher' level relates to abstract thinking with depth and a broad range of skills. These are operationalised into some learning outcomes printed in bold. Nuances in level between learning objectives are also created with use of verbs at different levels in Blooms taxonomy (e.g. describe, use, explain, discuss, analyse etc.). The use of verbs, however, is never explained.

The conclusion is, therefore, that much more can be done in the Leaving Certificates to explain progression.

Advice for further development:

Different amount of knowledge exist within different topics about progression. It means that in one topic it is easy to separate low, medium and high understanding, because such levels have been identified in research literature. In another topic, identifying levels is more difficult because this knowledge does not exist. Wilson (2005) suggests progression 'maps' can be made by identifying highest level (what we ideally want students to learn) and the lowest level (where low level students will enter), and thereafter identify one or more levels between. The differences between topics, however, have to be taken into consideration when setting out progression in standard documents. Importantly, the main reason for including information about progression is to help and guide teachers and assessors. This can be done in different ways and any information is better than no information.

One example to help for further development is the new K-12 Science Framework in the United States (National Research Council, 2012). This document has added information about progression to each topic. This approach could be used in the Leaving Certificates as a description of progression in each Unit of study. This would mean a text, for example, pointing towards three levels of proficiency, identifying both concepts, ideas and skills belonging to the different levels.

References

Allchin, D. (2011). Evaluating Knowledge of the Nature of (Whole) Science. *Science Education, 95*, 518-542.

American Association for the Advancement of Science. (1989). *Science for all Americans: A Project 2061 report on literacy goals in science, mathematics, and technology*. Washington D.C.: Author.

DeBoer, G. E. (2000). Scientific Literacy: Another Look at Its Historical and Contemporary Meanings and Its Relationship to Science Education Reform. . *Journal of Research in Science Teaching, 37*.

Giere, R. N., Bickle, J., & Mauldin, R. F. (2006). *Understanding Scientific Reasoning*. CA: Belmont: Thomson Wadsworth.

Klahr, D., Fay, A. L., & Dunbar, K. (1993). Heuristics for scientific experimentation: A developmental study. Cognitive Psychology, 24(1),111-146. *Cognitive Psychology, 24*(1), 111-146.

Kuhn, T. S. (1962). *The structure of scientific revolutions.* . Chicago: Univ. of Chicago Press.

Millar, R., & Osborne, J. (1998). *Beyond 2000. Science Education for the Future* London: Kings College.

National Research Council. (1996). *National Science Education Standards*. Washington, D.C.: National Academic Press.

National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, DC: The National Academies Press.

Osborne, J. (2011). Science teaching methods: a rationale for practices. *School Science Review, 93*(343), 93-103.

Qualifications and Curriculum Authority. (2007). Science. Programme of study for key stage 3 and attainment targets. In *The National Curriculum 2007* (pp. 206-219). London: QCA.

Schreiner, C., & Sjoberg, S. (2007). Science education and youth's identify construction - Two incompatible projects? In D. Corrigan, J. Dillon & R. F. Gunstone (Eds.), *The re-emergence of values in the science curriculum.* . Rotterdam: Sense Publisher.

Toulmin, S. (1958). *The uses of argument*. Cambridge: Cambridge University Press.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Wilson, M. (2005). *Constructing Measures an Item Response Modeling Approach*. New York: Psychology Press.