The Motivation for an Education in Science

Roger Kingdon

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1. The Argument for Science Education

In the UK it is commonly held and accepted that science is an essential component of every child's education. The influential *Beyond 2000* report (Millar and Osborne 1998, Section 4.1) identifies five reasons for science education:

1. To pass on to students some of the interesting and important knowledge about the material world, and with it "the sense of excitement that scientific knowledge brings."

2. To convey an understanding of the role of scientific ideas in decision-making and to empower students "to hold and express a view on issues which enter the arena of public debate and, perhaps, to become actively involved in some of these."

3. To establish a level of 'scientific literacy' whereby students "are able to engage with the ideas and views which form such a central part of our common culture."

4. To enable students to "acquire and develop important skills and understandings" that "can then be used in a wide range of contexts and settings in later life, in vocational and social contexts."

5. "We need, as a society, to train and educate new generations of scientists and technologists to maintain the technological tools and systems we value and to develop new and better ones to meet new needs and solve new problems. School science is, for some young people, the start of the process which will enable them to become the scientists and technologists of the future."

There is nothing wrong with any of these points, or indeed with the resulting laudable aspiration that "For the majority of young people, the 5-16 science curriculum will be an *end-in-itself*, which must provide both a good basis for lifelong learning and a preparation for life in a modern democracy" (Section 4.2). Nevertheless, these arguments are an insufficient basis for the belief, and the associated policy implication, that science is an essential component of every child's education. There are three main problems, as follows.

Firstly, for several decades many countries including the UK have suffered a major crisis of confidence in science. *Beyond 2000* acknowledges that the sciences "by no means tell us everything, or even the most important things we want to know about the world," but follows this with the powerful rejoinder that the sciences uniquely "offer a knowledge that can be relied on for action" (Section 4.1). However, for a variety of reasons we are now living in a world in which 'action' of this kind is seen as – at best – a double-edged sword, and as a consequence many areas of science and technology have become crippled by inaction. I have a bitter personal experience of this creeping paralysis. In 1987 I commenced my first job, working for the UK Atomic Energy Authority. The same year construction began on Sizewell B, a new type of nuclear power station that was intended to be the first of many in the UK. This ambitious engineering project was completed to time and cost, and the reactor has proved to be safe and reliable, providing 1.2 GW of electricity to the National Grid for over seventeen years. But in the last twenty-five years no further nuclear power stations have been planned or built in the UK, and as a result the domestic nuclear industry has died, as have my hopes of a fulfilling career as a nuclear scientist.

Secondly, the inexorable decline of manufacturing in the UK has meant that only a small proportion of students hope or expect to utilise their science education in their subsequent employment.[1] At the same time, it is increasingly the norm that students will make their own assessments both of their immediate learning attainment levels and of their broader capabilities and ambitions. There is nothing wrong with this, in principle; but it does have the unfortunate consequence that the majority of students will weigh the knowledge imparted to them in the science classroom against their likely future careers away from science, and with cold calculating rationality they will conclude that they are wasting their time.

Finally, and most importantly, the decline of confidence in science described above has been accompanied by a catastrophic decline of confidence in *scientific method*. *Beyond 2000* (Section 5.1) acknowledges that "young people need an understanding of how scientific inquiry is conducted," but takes the view that "the argument that an

[1] As of June 2012, 'Professional scientific & technical activities' were undertaken by just 8% of the UK workforce, compared with 15% in the 'Wholesale & retail trade', for example (ONS Labour Market Statistics, September 2012).

understanding of the methods of scientific inquiry is practically useful in everyday contexts has been over-emphasised. For most purposes a systematic, common-sense approach will suffice." However, there is no discussion of what this "systematic, common-sense approach" involves, or whether it might be of educational benefit to raise this question in the classroom. And, whilst this report is expressed in balanced, nuanced language, it is clearly reflecting an underlying unease with the notion of scientific method. This unease is much more forthright – to the point of outright opposition – in the educational research literature, where it is now commonplace to see scientific method being labelled as a 'myth'. For example, one of the *Beyond 2000* authors has identified "the myth that there exists a singular scientific method" as one of seven "fallacies" of contemporary educational practice (Osborne 2007), while Rowbottom and Aiston (2006) have chosen to entitle their paper "The Myth of 'Scientific Method' in Contemporary Educational Research." But if scientific method is a myth, then how can science teachers have any confidence that the sciences uniquely "offer a knowledge that can be relied on for action," and that in their lessons they are enabling students to "acquire and develop important skills and understandings," as *Beyond 2000* espouses?

In conclusion, it remains to be proved that science is an essential component of every child's education. This is a real and practical problem, because if I (as a science teacher) have difficulty believing that science is an essential component of education for all students aged five to sixteen, then how can I expect my students to be motivated in the subject? This 'problem of motivation' is addressed in Part 2.

2. The Problem of Motivation

The brief review in Part 1 concludes that it remains to be proved that science is an essential component of every child's education, and it highlights a consequent problem, the motivation of students in school science lessons. This 'problem of motivation' was also a personal challenge for me at the commencement of my initial teacher training, having spent the previous quarter-century trying and failing to establish a career as a research scientist. My experience in the nuclear industry I have already mentioned. Having spent eleven years with the UKAEA and its privatised progeny, AEA Technology plc (which today is a small fraction of its original size, and has withdrawn entirely from the nuclear sector), I moved to defence research and development, only to find that this sector likewise was in decline. Whilst in possession of a secure full-time job as a UK government scientist, I found that over time the nature of the work became increasingly focused on management and bureaucracy, with the result that in due course the job involved no scientific research at all. After a succession of roles that made no use at all of my qualifications and experience in scientific research, I concluded that my occupation would never give me the opportunity to make a meaningful and fulfilling contribution to society, and accordingly I resigned my post and turned to the teaching profession. But, having had such a negative experience as a UK government research scientist, how on earth was I going to convey enthusiasm and interest in science to my future students? Put another way, since my own motivation was so low that I resigned from my job, how was I going to motivate my students? This was the (profoundly depressing) question that occupied my mind at the start of the PGCE course. However, as *Beyond 2000* confidently asserts, the sciences uniquely "offer a knowledge that can be relied on for action," and I would not be much of a scientist if I could not think of practical ways to address my doubts, however depressing they may be. The following points are my thoughts on the problem of motivation in science education.

First of all, it is necessary to exclude those factors affecting motivation over which we (as teachers) have no control, such as the UK government's policies towards science and education, international and national workforce trends, cultural attitudes, prevailing societal perceptions of benefits and risks, and so on. It is important to be aware of these factors and to take them into account, but they cannot be changed within the classroom. A more practical way forward is to focus on motivation factors that can be influenced by the teacher. It is convenient to divide these into task-based and individual-based factors, as follows.

In essence, task-based motivation factors[2] comprise a variety of teaching tactics that are designed to stimulate and maintain interest in the topic. These include starter activities, video clips, and following topical news items. Science teaching also has the particular advantage of practical demonstrations, field trips, hands-on experiments, physical models, and computer-based simulations and applications. A tactic that I have found particularly useful is to ask *interesting* questions. This approach originates from Sotto's 'theory of teaching' (2007, p250), which holds that "a teacher's task is to help learners discover that they don't know something worth knowing, and then to help them find information so that they can learn that something in a reasonably orderly and satisfying way." Thus in teaching physics I have sought to stimulate interest by posing questions that are sufficiently intriguing that their answers are thereby "worth knowing". For example: why do the hands of a clock go clockwise; what are the phases of the moon in the Southern Hemisphere; why isn't there a lunar eclipse every month; when I let go of an object it accelerates downwards, yet there does not appear to be any force acting upon it, so does this violate Newton's First Law of Motion; and so on. Plus of course there is a wide variety of practical experiments whose results are sufficiently counter-intuitive that on first sight they pose their own fascinating puzzles.

Individual-based motivation factors[3] are largely derived from insights from various different theories of psychology, such as Maslow's hierarchy of needs, Vroom's expectancy theory, Weiner's attribution theory, Ames' mastery goals, and Zusho's notion of self-efficacy. In contrast with task-based factors, with individual-based factors it is unwise to 'cherry-pick' particular teaching tactics, as it is usually necessary to understand (and sometimes necessary to implement) all of the other aspects of the framework theory. This is particularly difficult where the theories are seen to contradict one another. One way to get round this theoretical impasse is to conduct empirical surveys of motivation-related attitudes in the classroom, and this is the approach taken by the various major studies reviewed by Osborne, Simon and

[2] That is, those aspects of classroom practice that are determined by the nature of the task and in turn affect student motivation.

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Collins (2003). This review gives particular attention to a study by Cooper and McIntyre (1996), which identifies eight "common aspects of teaching that were perceived to be effective by both teachers and pupils."[4] These are: setting clear goals; communicating these goals to the students; previewing and reviewing lesson content; helping students to relate lesson content to their background experience and knowledge; involving students in goal and agenda setting; providing a supportive social context; allowing for different cognitive styles; and taking into account individual student circumstances. These eight aspects of effective pedagogy are all eminently practical and achievable, and only one of them (the need to allow for different cognitive styles) appears to require a deeper knowledge of the underlying theory.

These teaching tactics and techniques may satisfy some or most students, but not all. In particular, some people (like myself) need to *believe* in what they are doing before they can become motivated and engaged in it, and for such people a display of tactics and techniques is unlikely to be of interest. Indeed, if my own attitudes are anything to go by, for such people the credibility of a performance is inversely proportional to its virtuosity. Belief, of course, is a complex phenomenon, operating for some people on a personal or practical level, and for others on an ideological or abstract level. And it is not for the humble secondary science teacher to emulate a charismatic guru or an inspirational visionary. Nevertheless, and again from my own experience, it can make all the difference to a belief-motivated student if the teacher displays a degree of personal commitment to the subject being taught. It is my view that, in the case of science education, this commitment necessarily requires a clear understanding and appreciation of the notion of scientific method.

It so happens that I know quite a lot about scientific method. In 1983-84 I undertook an MSc in Logic and Scientific Method under the tutelage of members of the Philosophy of Science department at the London School of Economics. This research department was set up by Sir Karl Popper, the founder and arguably the foremost exponent of the modern study of the philosophy of science. That year I saw him on three occasions, and although he was in his eighties it was clear that he had retained a formidable intelligence. This experience made a deep and lasting impression on me,

[4] As Osborne, Simon and Collins note, the Cooper and McIntyre study was of students and teachers of history and English, not science. Their findings appear to resonate across all subjects, however.

to the extent that for many years now it has been my habit to address each new research project using my own version of 'scientific method' (or maybe I should say *versions*, since my understanding of the methods of science has evolved progressively over the years). Therefore it is with considerable authority and confidence that I can assert that educationalists who perceive scientific method as a 'myth' are wholly mistaken. I do not know, and I am not inclined to find out, why this particular misunderstanding has propagated and persisted. But, for the reasons already discussed, I do find it necessary to set out a clear, plausible and widely-accepted definition of scientific method, thereby demonstrating that it is anything but a 'myth'.

Learned bodies and academic departments tend to look down on definitions drawn from the internet in general, and from Wikipedia in particular. For the discerning, however, Wikipedia contains much knowledge, some of which has been drafted and redrafted many times by a small army of highly-competitive perfectionists. The following definition of scientific method, from Wikipedia (2012), corresponds closely with my own working definition:

> The scientific community and philosophers of science generally agree on the following classification of method components. These methodological elements and organization of procedures tend to be more characteristic of natural sciences than social sciences. Nonetheless, the cycle of formulating hypotheses, testing and analyzing the results, and formulating new hypotheses, will resemble the cycle described below.
>
> > Four essential elements of a scientific method are iterations, recursions, interleavings, or orderings of the following:
> >
> > - Characterizations (observations, definitions, and measurements of the subject of inquiry)
> > - Hypotheses (theoretical, hypothetical explanations of observations and measurements of the subject)
> > - Predictions (reasoning including logical deduction from the hypothesis or theory)
> > - Experiments (tests of all of the above)
>
> Each element of a scientific method is subject to peer review for possible mistakes. These activities do not describe all that scientists do but apply mostly to experimental sciences (e.g., physics, chemistry, and biology). The elements above are often taught in the educational system as 'the scientific method'.

(Educationalists persisting in the belief that scientific method is a myth should give particular attention to the last sentence of this extract.)

As defined by Wikipedia, then, ‘scientific method’ is a process of iterative development that has been applied to the sciences, that is, to learning about the objective material world. ‘Iterative development’, which is another (and better) name for the “systematic, common-sense approach” mentioned in *Beyond 2000,* is a well-established generic process that is used in many fields of human endeavour. For example:

- For many decades the philosophy and practices of ‘kaizen’ (Japanese for ‘improvement’) have been implemented by Japan’s manufacturing and management sectors. Also termed ‘continuous improvement’, ‘just-in-time management’, or ‘total quality management’, kaizen is the process of iterative development applied to business. Intriguingly, City Montessori School in Lucknow (India) implements a version of kaizen in order to encourage its students to become ‘Total Quality People’.

- Until the 1990s, computer programs were written by ‘software engineers’ following a development process borrowed from established engineering practice that was known as the ‘waterfall’ method. This method followed a sequence of well-defined steps (typically, ‘Define’, ‘Design’, ‘Build’, ‘Test’ and ‘Deliver’), each of which had to be completed before moving on to the next. After very many applications and failures of this method, it was discovered that a much better approach was to undertake *all* of the waterfall steps for a very simple ‘skeleton’ version of the required product, and then to cumulatively ‘flesh out’ this skeleton in a rapid sequence of development cycles, each of which also implemented all of the waterfall steps to the appropriate level of fidelity. This new methodology, variously termed ‘rapid’, ‘iterative’ or ‘spiral’ development, is now the industry standard. And software engineers are now termed ‘programmers’.

- In the 1970s, USAF Colonel John Boyd devised the ‘OODA loop’ concept for application to combat operations. OODA is the acronym for ‘Observe’, ‘Orient’, ‘Decide’ and ‘Act’, and the OODA loop concept is the repeated rapid iteration of these elements in the required application. The particular value of this concept to military doctrine derives from its formulation of ‘operational tempo’. Put simply, if Force A can routinely complete its OODA loop faster than Force B can complete its OODA loop, then Force A will defeat Force B in combat, even if Force A is (on paper) the smaller and/or the weaker of the two. The OODA loop is now a standard military concept, and as a result it has been applied also to civilian management and learning processes.

- No management training course is complete without an exposition of the ‘Kolb learning cycle’, devised by David Kolb in the 1980s. Like the OODA loop, the learning cycle iterates over four elements, which in this case are ‘Have experiences’, ‘Reflect on experiences’, ‘Formulate ideas’ and ‘Test ideas’. In addition Kolb has defined four ‘learning styles’ (the ‘Activist’, the ‘Reflector’, the ‘Theorist’ and the ‘Pragmatist’), each of which characterises a discrete element of his learning cycle. Individual learning is then a matter of developing sufficient competency in each of the learning styles such that one can complete the cycle with ease, while team working is a matter of finding colleagues with complementary learning styles such that the team can collectively complete the cycle with ease. Again the key feature of the Kolb learning cycle is iterative development.

- The University of Exeter ‘Model of Reflective Practice’ is likewise a learning cycle that iterates over four elements, which in this case are ‘Evaluate’, ‘Reconceptualise’, ‘Plan’ and ‘Act’. The correspondence between this model and the OODA loop and the Kolb learning cycle is striking, given their very different origins.[5]

It turns out, then, that iterative development is a well-established generic method of enquiry that is far better understood than the authors of *Beyond 2000* (and others in the field of education) would have us believe. It follows that ‘scientific method’ is likewise well-established and understood, as being the application of iterative development to learning about the objective material world. Because of the objectivity of the application, science is much the easiest field in which to demonstrate the efficacy and utility of iterative development, which explains the

[5] As it says in the Exeter 2012-13 PGCE Secondary Science Handbook (p28), “This Model of Reflective Practice draws on the work of several theorists and researchers in the field of teacher education.”

particular potency traditionally ascribed to scientific method. It also turns out that the debate amongst educationalists regarding the existence and nature of scientific method is something of a red herring, and a distraction from the far more interesting and important (re-)discovery of the generic process of iterative development. For it is now not difficult to make the case that it would greatly assist learning for this process to be taught in schools. And there is no better way to understand this process than to become engaged in its practical application in learning about the objective material world; that is, in science education.

The prospect of students learning and implementing iterative development fills me with relish, and clearly solves *my* problem of motivation. But how does any of this address *their* problem of motivation? Of course, learning and implementing iterative development is no panacea; that is, it does not (and need not) replace the various teaching tactics and techniques summarised earlier. As an additional approach, however, iterative development has great potential, particularly for students who (like me) are predominantly process-driven. And in science education I can think of two specific and practical activities that relate directly to the iterative development process, as follows.

Firstly, when writing a report of a scientific experiment it is usual to have section headings entitled Aim, Introduction, Theory, Experiment, Results, Conclusions and Recommendations. There may be some variation to this pattern, for instance, replacing Introduction with Review, or replacing Theory with Hypothesis and Prediction, but one cannot go far wrong if one starts with this standard template. This format is sufficiently well-known and well-established that its use extends far beyond the science classroom, for example, it is often used when writing research papers for journals or project reports for commercial laboratories. Indeed, a large number of scientific journals insist on these (or similar) headings, as do journals in other fields with an empirical content, such as the social sciences. Now, it does not require a great leap of imagination to suppose that an individual scientific experiment will correspond to a single cycle of the iterative development process. In other words, as part of the process of 'normal science' (Kuhn 1970), one can expect the Aim of any particular experiment to be determined by the Recommendations of previous experiments in the field, just as its Recommendations will go on to determine the Aims of future experiments in the field. Furthermore, having mapped an individual experiment to a single cycle of the iterative development process, it is not difficult to establish a correspondence between the section headings of the experiment report and the discrete elements of the iterative cycle. One way to do this is to correlate the constituent elements in a table. For example:

Wikipedia scientific method element	**Exeter Model element**	**Experiment report section heading**
Characterizations	Reconceptualise	Aim, Introduction
Hypotheses, Predictions	Plan	Theory
Experiments	Act	Experiment, Results
Experiments	Evaluate	Conclusions
Characterizations	Reconceptualise	Recommendations

Clearly, as well as comparing the different interpretations or applications of iterative development, this tabular approach may be used to further refine our understanding of the precise nature of their constituent elements. It must be emphasised, however, that this prospect of further refinement is a matter of fine-scale adjustment rather than large-scale reconstruction. In particular, it does not mean that we do not have a clear and reliable definition of scientific method. On the contrary, it helps to establish just such a clear and reliable definition. The present table is a case in point, showing that the standard format of the report of a scientific experiment indeed relates directly to scientific method and to other interpretations of the iterative development process.

Secondly, an important problem in the philosophy of science is to identify the key constituents of an acceptable scientific explanation. This problem (which is often assumed to inhabit the ‘too hard’ category, and consequently neglected) was partially addressed by the empiricist philosopher David Hume, who famously advocated the burning of all books “of divinity or school metaphysics” that did not contain “abstract reasoning concerning quantity or number” or “any experimental reasoning concerning matter of fact and existence.” More recently, Kuhn (1977, pp321-2) has identified five “characteristics of a good scientific theory,” these being ‘Accuracy’, ‘Consistency’, ‘Scope’, ‘Simplicity’, and ‘Fruitfulness’. Drawing on these ideas, I have compiled a tentative list of the criteria that must all be fulfilled for a scientific explanation to be deemed acceptable, as follows:

- It must be *complete*, that is, it must take into account all relevant information;
- It must be *concise*, that is, it must be more compact and simpler than that which it is purporting to explain;
- It must be *consistent* with that which is observed;
- It must be *coherent*, that is, not self-contradictory;
- It must have been *competed* with alternative explanations and thereby shown to be superior (as judged by each of these criteria).

In the science classroom these 'Five Cs' would constitute a practical and reliable checklist for evaluating the acceptability of a scientific explanation. With a little imagination it is possible to map these criteria to the discrete elements of the iterative development cycle, just as we did for the section headings of an experiment report:

Wikipedia scientific method element	**Exeter Model element**	**Experiment report section heading**	**Scientific explanation criterion**
Characterizations	Reconceptualise	Aim, Introduction	Complete
Hypotheses, Predictions	Plan	Theory	Concise
Experiments	Act	Experiment, Results	Consistent
Experiments	Evaluate	Conclusions	Coherent
Characterizations	Reconceptualise	Recommendations	Competed

As before, this table helps to establish the correspondence between the iterative development cycle and the scientific explanation criteria, and it provides a means by which our understanding of these criteria might be refined.

In summary, whereas at the start of the course I had great doubts about whether I would be able to convey a positive impression of science to my future students, through reflecting on the factors affecting motivation in the classroom I have been able to identify a number of practical and constructive ideas that collectively allay most of my concerns. Chief amongst these ideas is the realisation that educationalists currently seem to be unaware of the iterative development process, despite its long-established and widespread use in many fields of human endeavour, including manufacturing, business, programming, warfare, psychology, and scientific research (in which application it is commonly termed ‘scientific method’). And I can see no reason why students should be deprived from knowing about this valuable tool and from applying it in their own learning. Indeed, I see the teaching of the iterative development process (as scientific method) as the necessary and sufficient justification for maintaining science as an essential component of every child’s education. Anticipating the objection that the iterative development process is far too abstract for the classroom, I have shown that in fact it can be related to two specific, practical and relevant learning activities, namely, the writing of a report of a scientific experiment, and the adoption and use of a set of criteria by which we might judge a scientific explanation to be acceptable.

I conclude that, for myself at least, I have been able to resolve the ‘problem of motivation’. Of course it remains to be seen whether and to what extent I will be able to resolve the problem of motivation for my future students.

3. Synthesis: "Different People Learn in Different Ways"

The Part 1 review finds that there are three problems with the proposition that science is an essential component of every child's education: the prevailing crisis of confidence in science; the decline of manufacturing and other occupations that require a science education; and, most importantly, the catastrophic decline of confidence in scientific method. Part 2 looks at the consequent problem of motivation in the science classroom, identifying a number of constructive responses, principally, the finding that there is a widely-accepted interpretation of 'scientific method' that has practical applications in schools. This interpretation, which sees scientific method as the application of iterative development to learning about the objective material world, is central in addressing both the problem of motivation and the main objection raised in Part 1.

When using dialogical (or, as some call it, 'dialectical') criticism to analyse a problem it is not unusual to find that the eventual resolution (or 'synthesis') uncovers several other observations which, although incidental to the main argument, are interesting in their own right, and open up new avenues of enquiry. The present analysis is a case in point. During my preliminary experience week in a primary school I was struck by the following deceptively-simple observation of the teacher of the Year 5 class that hosted me: "Different people learn in different ways." At the time this reminded me of the different learning styles that characterise the discrete elements of the Kolb learning cycle (see Part 2). Whilst I accept the reservations of Coffield *et al* (2004) about the use of learning style techniques in the classroom, and I have doubts about Kolb's particular choice of four learning styles, at the same time I can see the utility of the model in application to education in general and science education in particular. Specifically, the model accepts that different students will naturally prefer to specialise in different parts of the learning cycle, but indicates that for effective individual learning each student must be able to undertake the less-preferred parts of the cycle as well, to some level of competency at least. Clearly, this conclusion has important implications for pedagogy, placing emphasis both on differentiation and on variety in the classroom. And this is an emphasis that puts science education at a particular advantage, because of its characteristic mix of theory, experiment, research, and reflection, that is, all parts of the learning cycle. But the most encouraging feature of this proposed applicability of learning styles is that it only makes sense in the context of the Kolb learning cycle, which is one interpretation or application of the iterative development process described in Part 2. It follows that the observation of my Year 5 host gives (somewhat unexpected) additional support to the creation of a coherent teaching philosophy based on the iterative development process. And it is the development of just such a teaching philosophy that I have in mind for the remainder of my initial teacher training.

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