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The natures of scientific thinking: creativity as the handmaiden to logic in the development of public and personal knowledge

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Abstract: One aspect of the nature of science is that it is characterised by particular modes of thinking. Science is commonly seen as a rational process that uses logical arguments to develop explanatory schemes and theories. Philosophers of science have proposed models for how science proceeds, and science education aspires to find intellectually honest accounts of 'the scientific method' that are suitable for presenting as target knowledge in the school curriculum. There are a number of recognised challenges here, such as the abstract nature of philosophical models; inconsistencies between the different models available; the intellectual readiness of young people to engage in logical argument. However the focus on what has been called 'the context of justification', important as it is, needs to be balanced by consideration of 'the context of discovery': without which there would not be any scientific knowledge claims requiring logical argument from evidence to support them. Science education is often perceived by students as being about learning well-established facts, rather than being about exploring the strengths and weaknesses of the creative products of imaginative minds. Theories, models, teaching analogies and figurative metaphors presented by teachers may all be understood as intended to have the same – realist – ontological status. This not only ignores the creative origin of the models and theories taught in science, and so the value of students' own imaginative suggestions, but leads to many students acquiring an undifferentiated menagerie of ideas that obscures the logical grounds for accepting well-established models and theories. This chapter considers the nature of creative thought in the scientific process, and in learning science; and argues that science teaching needs to be more explicit about the nature and status of different ideas presented in the classroom to help students fully appreciate both the creative and rational aspects of science.

Key words: teaching nature of science; authentic science in the curriculum; scientific thinking; creativity in science; creativity in science learning

Introduction

In this chapter I am going to make an argument for giving more emphasis to the role of creative thought in science education. Part of my argument will be that we currently underemphasise the creative aspect of science compared with the 'logical' aspects. I will also argue that there is also insufficient attention to the creative aspects of teaching and learning science – and that this may contribute to some of the problems faced by teachers and learners.

I will approach this theme from two starting points. One of these relates to the well-recognised limitations in student understanding of the nature of science (NOS). In particular I will consider the centrality of models in learning science: models are ubiquitous in science teaching, but may commonly be understood by students to be intended as realistic representations of reality, when many of them have a very different (partial, provisional, limited) status as either scientific or teaching models. The other starting point is an example of a common way that students think about a key area of science – where they demonstrate ideas that are flawed, illogical, un-naturalistic; yet quite creative in their own way.

After briefly reviewing the focus of logical thought in the sciences, the chapter will then turn to consider the role of creativity in the scientific process, and argue that this as important as logic. The chapter will conclude by considering the role of creativity in learning science.

An authentic nature of science for science education

In recent years there has been an increasing focus on how NOS is reflected in science education, especially at school level (Clough & Olson, 2008). The debate about the aims of science education – science for all, or science for future scientists – has been developed through an increasing focus on 'scientific literacy' (Millar & Osborne, 1998), the understanding of the NOS that is appropriate for people to function effectively in modern technologically advanced societies, and in particular in democracies struggling to balance industrial development with environmental stewardship. School leavers should be ready to be critical readers, savvy consumers, and informed voters, who are able to evaluate scientific claims and arguments.

It has been argued that this focus on scientific literacy is detrimental to those wishing to specialize in science – as it excludes much traditional 'content' and practical work, and reduces the knowledge base for students appreciating the abstract nature of science (Perks, 2006). However, I would argue that a focus on the processes of science not only supports the aim of education for all, but can also be seen to be central to understanding science for those looking to take advanced courses. After all, it is less important to know that carbon has an atomic mass of twelve, or that there was an 'explosion' of new species in the Cambrian, than to have some notion of how such claims come about and then come to be widely accepted in science. This is certainly not an argument that science education should exclude or downplay the products of science (theories, models, laws etc) but rather than there should be a balance of engagement with both products and processes. That is, it is better to be more selective about the scientific products presented in school science, but to teach about them in the context of an understanding of scientific processes.

It is worth quoting here one strong critic of the shift in science syllabi towards teaching for scientific literacy, David Perks. Perks argues that 'traditional' teaching approaches focused on learning facts are misrepresented, but rather support sophisticated learning processes,

> "Mastery on the part of the pupil involves acquiring factual knowledge and building models to incorporate this knowledge. As children progress the begin to realise that the models they have been taught are insufficient and need to be replaced, to accommodate new facts they are meeting about the way nature behaves. As well as refining the models they use to describe nature, students gradually become conscious of what it means to build and try out new models themselves. All the time they need to be confronted with the need to test their ideas against experimental evidence."
>
> (Perks, 2006, p. 19)

This is an interesting claim, as I would totally agree with Perks that this is what we might hope for (Taber, 2010b). However, I am less sure that Perk's model would withstand much testing against the experimental evidence: at least in terms of most of the thousands of students I have come across in my own time working in and visiting schools and colleges. This is a good aspiration, but – as will be illustrated below – it does not reflect how most students experience meeting the sequences of models presented in school science.

Teaching NOS to support learning of the science

There is a range of arguments put forward for the focus on NOS in science education, in terms of what it is most important for students to learn to support them as future citizens. However, there is also a strong argument for teaching about NOS to support teaching about the products of science themselves (Taber, 2010b). There is a considerable literature showing both that students commonly struggle to understand many scientific concepts, and that they often develop their own alternative understandings at odds with the scientific models (Duit, 2009). Scientific ideas are often very abstract, if not even counter-intuitive. Learning something of the process by which scientists have gradually come to adopt the ideas they have (with a taste of the evidence, and the debates, and the false paths and cul-de-sacs) can help students appreciate that even the scientific greats that they learn about went through a process of struggle, usually including rejecting many initial ideas, before formulating the scientific principles that are now widely accepted. This gives a much better impression of NOS than the catalogue of outcomes met in many science curricula – the so called 'rhetoric of conclusions' (Niaz & Rodriguez, 2000).

A more historical approach can also help learners appreciate that some of their own 'wrong' ideas are actually very similar to those scientists had seriously considered, and tested (Piaget & Garcia, 1989). As generating ideas to test, a creative act discussed below, is an essential step in the research process, students should be encouraged to award themselves merit for generating such ideas. This does not imply a relativistic notion of science education– along the lines that students' ideas are just as worthy as the science in the curriculum, even when they are clearly contrary to accepted scientific ideas – a potential perspective which has been rightly criticised (Matthews, 2002; Scerri, 2003). Rather, such ideas should be valued in their own terms – as starting points for scientific investigation, that support a key part of the research process.

A related point is the difficulty pupils have in appreciating the status of many scientific 'products': school children often demonstrate very limited understanding of the types of entities created in science (Driver, Leach, Millar, & Scott, 1996; Taber, 2006):

- They may associate science with facts, and see models as intended to be replicas;
- They may consider theories to be hypotheses that have been tested and shown to be true,
- or alternatively they may consider theories as no more than ideas that have not yet been proven, but which becomes converted to laws once they have been proved true by experiments.

A key issue is that science teaching, like science, relies heavily on the use of various forms of model. *In science* these models are often used as thinking tools to help explore ideas, as much as representations of what research has found out. *In teaching*, models are used both to simplify complex science (Taber, 2000), and to find ways of making connections with what students are already familiar with. None of that is in itself problematic, but unfortunately the nature of the models presented in teaching is not always explicit to learners - so, students often tend to take them as realistic representations of proven accounts of the world. These notions are not only epistemologically simplistic: they can act as significant pedagogic impediments to effective learning (Taber, 2001b, 2005).

In my own work I have talked to students close to despair at how some science teachers seem to take great pleasure telling a new class that the ideas they worked hard to learn the previous year are not actually right, and that *this year* they will need to learn how things really are. Besides being a distorted view of how science is represented in curricula, such pronouncements can be completely disheartening to students who have put real effort into making sense of learning the ideas they were taught in school science.

The problem of teaching without making modelling explicit

Even when teachers do not act in such a careless way, our teaching may make a difficult and challenging subject more problematic for pupils than is necessary. I will illustrate this with an example from the physical sciences, from the area of representing matter at the submicroscopic level.

When lower secondary students are introduced to the particle model for the three states of matter (e.g. at around 11 years of age), that model is usually presented as if the particles are non-interpenetrating spheres that are close-packed in solids (like tiny billiard balls, to use a common teaching analogy). These properties help explain the properties of the solid state (e.g. being rigid and hard to compress). In a liquid these particles are able to move passed each other (so it can flow), and in a gas they are well separated in space (so it can be readily compressed)

And yet, when these same pupils are taught about thermal expansion, perhaps a year or two later, *this* phenomenon is explained in terms of a particle model where there is considerable space between the particles in a solid – and they are told that heating increases the spacing further. The solid retains it fixed shape, rigidity and hardness - but the model has changed, dropping the features which explained those properties.

Moreover, students are likely to be told that during thermal expansion the particle size does not change, but the space between those particles increases. They may even have it pointed out that if they get this wrong, and suggest in a test or examination that the particles themselves get bigger (as students commonly do), this will be marked wrong.

Thermal expansion leads to fewer particles per unit volume, so the average volume per particle increases. On the close-packed particle model (that students have been taught, and - not appreciating the nature of models - have largely accepted as the way the world is) this would imply that during thermal expansion each particle has greater volume (i.e. gets bigger), but this is considered ‘wrong’ according to school science, as *in this context* that is the wrong model to apply. This must seem nonsense to many young people attempting to make sense of the particle model of matter. It certainly seems nonsense to me.

Often the explanation for why the particles move further apart (to occupy a greater average volume, without getting any bigger!) is that heating provides energy that allows the solid particles to vibrate more. This is a fair reflection of the scientific model, but does not logically lead to any measurable expansion: if all the particles were to vibrate in phase then greater magnitude of vibration does not require the particles to move further apart.

If these students later select to study science in advanced courses they will find that they are given a new reason why greater vibration leads to expansion: this is explained in terms of the asymmetrical nature of the force-separation curve between particles. In other words, we teach secondary students an explanation that does not logically do the job, and only years later do we offer (a minority of students: those who have managed not to get put off the subject or confused by our apparently inconsistent and irrational explanations) a more sophisticated model that does a better job of explaining the phenomena.

I have never known a student to query the ‘greater vibration’ explanation. Perhaps this is because it fits intuitions, or because it is accompanied by convincing teaching models (‘imagine it was very hot in here, and the class was all squashed together in one corner of the room: wouldn’t you all try and move a bit further apart?’) I suspect also that this is largely because the molecular world is such a mystery that most students are in no position to question what we teach them (Taber, 2001a).

There is more to this story. When students learn about the periodic table and atomic structure, the ball-like particles which they were introduced to some years before, and which they are now getting comfortable with, suddenly develop a complex structure. Those particles that were non-interpenetrating so that solids remained rigid, now turn out to mainly be empty space and comprised of atoms, which are themselves made of subatomic particles. Pupils generally just accept that the electrons occur in shells, and that the first shell fills up with two electrons, but the second eight. Many books at this level incorrectly imply that the third and subsequent shells also fill at eight electrons – but again students seldom ask why there is not room for more electrons in the larger shells. Perhaps one of the most telling points is that students seldom even question why the negatively charged electrons in these molecules and atoms seem to be able to link up in pairs (as in common representations in chemistry). They largely accept the model – presumably because they have learnt that science lessons are about receiving the ‘facts’ that scientists have discovered about the how the world is, as communicated through the authority of the teacher and the textbook.

When they study chemical reactions, these learners find that the particles that behaved like solids balls at the start of their secondary schooling, will now in certain situations interact with each other – often in quite telling ways (reflected on the macroscopic scale with colour changes, bangs, flashes, smells etc). These interactions are not the elastic collisions of earlier grade levels, but involve the splitting, joining and exchanging of components, often associated with considerable releases of energy.

When chemical reactions are studied in secondary level, a lot of this is not well explained: and teachers commonly use the language of electrons being 'shared' between atoms and 'donated' and 'accepted' during transfers, or forming 'seas' in metals. This creative language is metaphorical, but where the teacher assumes it is obvious the metal lattice has to be neutral overall, students may imagine a vast excess of electrons acting as a sea around the cations (Taber, 2003). Students may have genuine difficulties in appreciating how anthropomorphic descriptions of the lives of atoms can apply figuratively in a factual subject such as science (Taber & Watts, 1996/2005).

Very commonly, in the 'exploratory vacuum' of secondary science, students come to develop an understanding of chemical phenomena in terms of atoms wanting to obtain full shells, or needing to get octets of electrons (Taber, 1998). They will often even explain a reaction as occurring *because of* the need for atoms to fill shells – even when given a chemical equation for the reaction which clearly shows all the reactants already meet that criterion (Taber, 2002b) – hardly an example of scientific thinking. (See the example below.)

Yet of course, if they take their study of chemistry to a more advanced level, they then find that the notion of shells is largely supplanted by a very different description that instead has orbitals describing electron probability densities. At this point I have found some students get very frustrated at being offered (and asked to learn) such apparently contradictory accounts. Yet much of the frustration comes from not having the nature of the models discussed made explicit throughout the stages of learning school science.

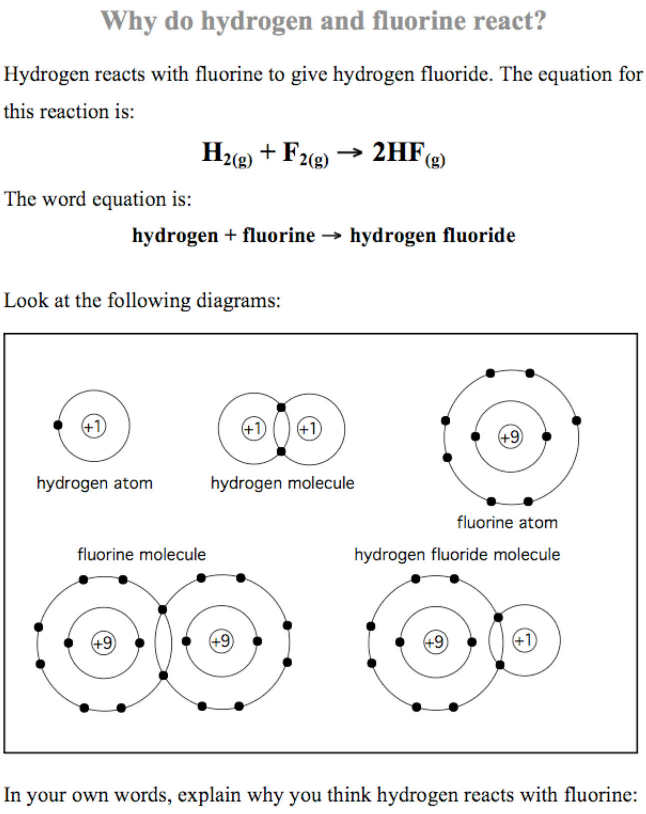
All of the models these students are asked to consider have their uses, even if they may seem inconsistent. Such inconsistency is hardly a desirable feature for teachers: but it is not the problem it may seem to students who think they are being provided with scientists' realist accounts of how the world actually is. Models of the atom as fuzzy fields of force may be much more sophisticated that the introductory model of close packed spheres: but that latter model still has its uses. Scientists have no problems understanding what is mean by the labelling of the structures of many metallic crystals as 'close packed' – with cubic or hexagonal close packing – *for which purposes* those touching and non-interpenetrating spheres do a perfectly adequate modelling job.

The problem here is that learning *about models* is not authentic science education unless the teaching and learning is *explicitly about* models. Science education aims to help young people think scientifically, not just know some scientific facts. As Perks (2006) acknowledges in his critique of teaching for scientific literacy, *thinking through constructing and exploring models is a key part of scientific thinking*.

The problem of student learning in science

Given that much science teaching does not make the NOS, and the modes of scientific thought which are associated with it, explicit to learners, it may unsurprising that students do not always demonstrate the desired modes of scientific thinking that teachers wish to encourage. There is a vast literature on aspects of student thinking in science, and often it is found that students' ideas are rather at odds with the target knowledge which is set out in the curriculum (Duit, 2009; Taber, 2009b). Here I will focus on one example that links with the previous section, but similar arguments could be made about many areas of students' learning in the sciences.

Consider the following question and response (see figure xx.1):



Why do hydrogen and fluorine react?

Hydrogen reacts with fluorine to give hydrogen fluoride. The equation for this reaction is:

$$H_{2(g)} + F_{2(g)} \rightarrow 2HF_{(g)}$$

The word equation is:

hydrogen + fluorine → hydrogen fluoride

Look at the following diagrams:

In your own words, explain why you think hydrogen reacts with fluorine:

Figure xx.1: A question about reactivity.

This question was part of a set of probes developed for teachers to use during a project funded by the UK's Royal Society of Chemistry (Taber, 2002a). The reader might just wish to pause and consider what they would consider an acceptable level of response from students who had done well in school science and were studying chemistry in post-compulsory college ('sixth form') courses.

It was found that when students were set this question, they produced a wide range of answers. However, even among advanced students (studying chemistry at University entrance level in post-compulsory education), a good many of the responses were along the lines of the following examples (Taber, 2002b):

> "Fluorine is a halogen and has 7 outer electrons. To be stable it would like 8 electrons in its outer shell. By covalently bonding with the hydrogen atom which would like 2 electrons in its outer shell they form hydrogen fluoride which is stable"
>
> "Hydrogen has 1 valence electron in its outer shell, whereas, Fluorine has 7 outer electrons. As a full outer shell of electrons is wanted by both particles, the H atom will donate an electron to the Fl atom forming a paired bond completing both particles outer shell number"
>
> "Fluorine atoms have 1 'gap' where an electron is 'missing'. This means that in its valency shell, it only has 7 electrons. Hydrogen atoms have 1 'gap' where an electron is 'missing', though it is only meant to have 2 in its valence shell. Therefore the two atom react to form full shells, the fluorine with 8 electrons, the hydrogen with 2 electrons."

Illogical thinking

These, and many other responses, shared the following properties:

- they described the driving force of chemical reactions to be related to the attainment of stable electronic configurations (octets of electrons, full outer shells);
- the explanations were often focussed on the what individual atoms 'wanted', 'needed', and did.

Yet, the question referred to hydrogen and fluorine, both substances that exist as diatomic gases. In case students did not know or realise this, the question gave the formulae equation which specified the reactants as $H_{2(g)}$ and $F_{2(g)}$ (see figure xx.2).

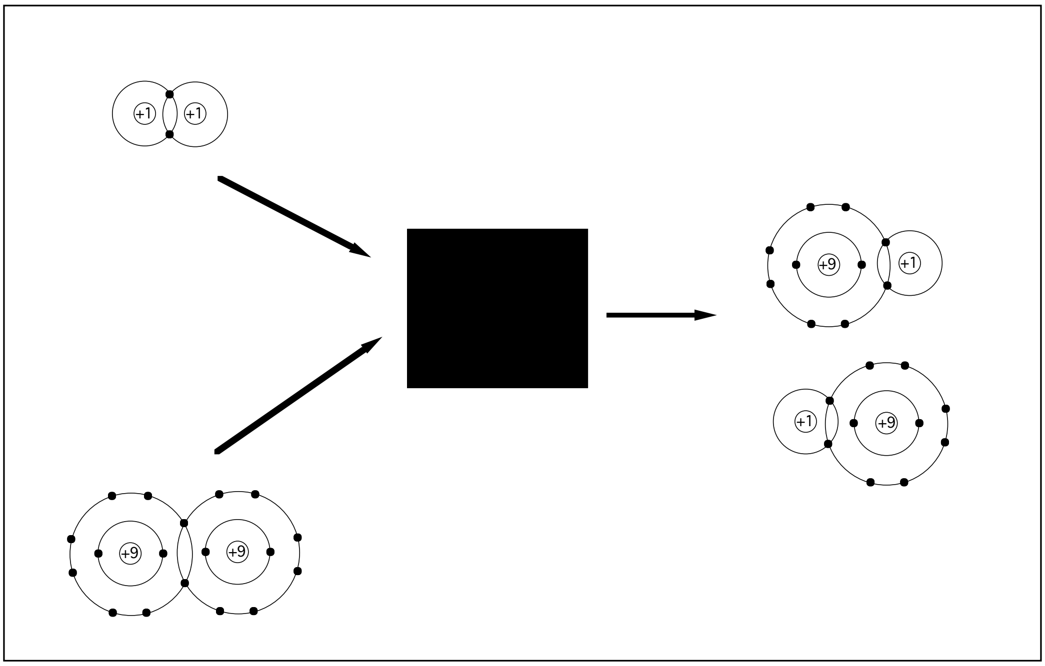


Figure xx.2: A schematic representation of the reaction

Given the information in the question, the responses presented here are illogical. It is irrational to explain the interactions of hydrogen molecules and fluorine molecules in terms of the properties of different species entirely - the atoms (which are far too unstable to exist in any significant concentrations under normal conditions).

The ideas that are presented here by students may be labelled as ‘misconceptions’ or ‘alternative conceptions’, and indeed have been claimed to be part of a common way of thinking about chemistry among students at this level (Taber, 1998). Whilst it seems very likely that student thinking in chemistry is strongly influenced by ‘intuitive’ notions of the world (Taber & García Franco, 2010), it also seems clear that explanations of chemical phenomena in terms of the properties and ‘behaviour’ of atoms and molecules develop as a result of science teaching (rather than being intuitive theories of the world, or the kind of folk-theories of the world which are often believed among lay people). After all, atoms are not objects of direct experience; and nor are they the subject of choice for social conversation among most adolescents.

Scientific thinking

We are entitled to be concerned about such matters if part of the aim of science education is to teach scientific thinking – when we find the *outcome* of science education is often thinking about scientific concepts in such ‘unscientific ways’. In the example discussed above we find illogical responses (in that the explanations contradict the premises of the question) that rely on non-natural agency: the desires, needs, preferences of inanimate atoms. If we want to encourage scientific thinking, and we hope to develop logical and critical modes of thought, then something seems to be going very wrong.

Yet perhaps it would churlish to be too critical of the ‘illogical’ responses of students, given the nature of the teaching they commonly receive. If solids are hard and cannot readily be squeezed because they consist of close packed spheres with no space between them, but they also expand on heating because the space between the spheres gets bigger, then why not explain the reaction of molecular materials in terms of the properties of atoms. If it seems science is flexible when it comes to explanations, then perhaps we can just select whatever premises best support a viable explanation.

Of course, the teacher may respond that using different (apparently contradictory) models of the submicroscopic structure of matter to explain different properties of solids is a scientifically acceptable procedure, whereas it not scientifically acceptable to explain the behaviour of molecular substances in terms of discrete atoms. That might however seem an *ad hoc* response from the students’ perspective: defending ‘sleight of hand’ (switching the model for one that does the job) by simply stating that it is a scientifically acceptable procedure does not seem to be in the spirit of science (as practice based on logical analysis of empirical evidence and critical thinking). It is no wonder so many students see science education as about receiving facts that are the outcome of some else’s thinking – someone who has already been inducted into the great mysteries of the subject.

Logical thinking

Despite these problems in science *education*, it is certainly the case that a key part of scientific thinking is being able to think logically. Science is based upon rational processes, so that knowledge claims are backed up by an argument chain (Toulmin, 1972). The following short extract from Sir Peter Medawar's speech accepting the 1960 Nobel Prize for Physiology of Medicine (for his work in immunology) gives a flavour of the kind of 'if-then' argumentation found in science:

> "…if living cells from a mouse of strain CBA are injected into an adult mouse of strain A, the CBA cells will be destroyed by an immunological process, and the A-line mouse that received them will destroy any later graft of the same origin with the speed to be expected of an animal immunologically forearmed. But if the CBA cells are injected into a foetal or newborn A-line mouse, they are accepted; more than that, the A-line mouse, when it grows up, will accept any later graft from a CBA donor as if it were its own."
>
> (Medawar, 1960)

Often in school science students are expected to learn a heuristic for 'the scientific method', although modern philosophers of science have shown there is no such simple set of steps that describes a universal scientific method (Taber, 2009a). Scientific thought, although logical, is often more nuanced than the simple 'if this, then that' version of hypothesis testing found in some representations in school science.

The logic of scientific discovery

Early approaches to exploring the scientific method were based on the trustworthiness of observation and measurement and on what might be considered a faith in human reasoning faculties. Simple logical considerations would suffice: e.g., if X occurs when Y is not present, then Y cannot be considered the cause of X. More difficult than excluding possibilities, was (and is) the question of what needs to be demonstrated to justify considering something as the cause for something else.

The problem of induction – proving general rules from testing any number of specific instances – hung like a cloud over science for many years. How can we prove that all samples of copper conduct electricity without actually testing all samples of copper? Again such complications tend to be underplayed in school science. A student asked to connect a piece of copper wire into a test circuit, and who observes the lamp glow, is expected *not* to conclude that this particular sample of copper conducts, but rather than copper, in general, conducts. Logically, this is another nonsense, of course, not because the procedure is inherently invalid as a learning activity (it can be a useful classroom demonstration for how we can test the conductivity of materials), but rather because the rich context that makes this a suitable practical activity to do in a school classroom is seldom clear to the students.

The great twentieth century philosopher of science, Sir Karl Popper, initially made his reputation in *the Logic of Scientific Discovery* (*Logik der Forschung*), where he demonstrated the intellectual courage to acknowledge that induction could never be justified in an absolute sense on logical grounds (Popper, 1934/1959). However, he did focus on the logical grounds for refuting ideas in science, and championed a demarcation criterion for scientific conjectures in terms of specifying the conditions under which an idea should be considered refuted. His 'hypothetical-deductive' model of how to test scientific ideas has been very influential, for example in notions of 'the scientific method' considered in school science. Of course others argued cogently that such logically clear procedures were in practice complicated in various ways, and scientists could sometimes have rational reasons to hold on to ideas that had failed some tests (Kuhn, 1996; Lakatos, 1970; Taber, 2009a).

Research design may often appear straightforward in the natural sciences where there are often well-established paradigms, but this only means that a whole host of assumptions are considered as the shared commitments of that particular research community (Kuhn, 1974/1977). Such strongly shared commitments within a research programme are less common outside of the natural sciences (Lakatos, 1970; Taber, 2009b), and are no assurance of infallibility in any disciplinary context.

Decision making in the scientific process

When graduate students prepare to become researchers in education, they are taught about the logic of the research process: that research questions should derive from a critical review of existing research; that it is important to be clear about the ontology of what is being investigated (what kind of thing are we dealing with here?), which allows careful consideration of epistemology (what kind of knowledge is it possible to have about this kind of thing?), and so informs viable methodology (Taber, 2007b). Their thesis is to be just that – a coherent and cogent argument – and there must be logical consistency throughout – so knowledge claims really do follow from an analysis which is appropriate for the kind of data collected; which is in turn suitable for answering the research questions; which themselves are informed by the ontological and epistemology analysis carried out to inform the methodology (e.g. see figure xx.3)

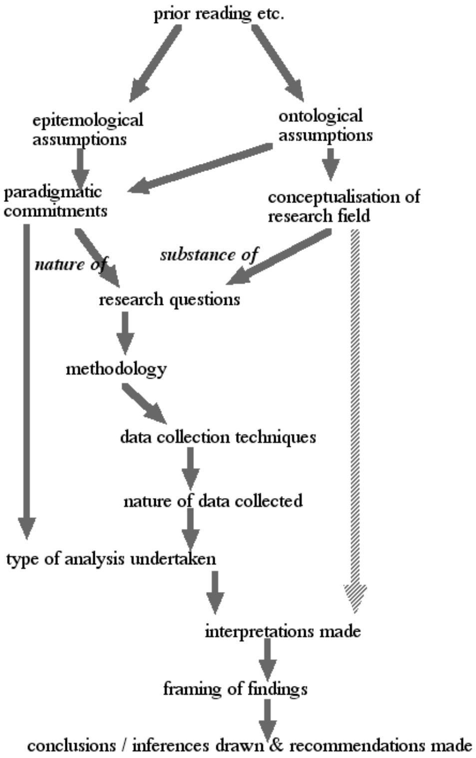


Figure xx.3: The research process – a logical flow of decision-making

Of course, the process set out in figure xx.3 is quite complex. Arguably, research scientists trained within a well-established disciplinary matrix (Kuhn, 1974/1977) may be less aware of the basis for some of these steps in their research than social scientists who may find every assumption challenged by peers, teachers, reviewers and examiners.

At various points in a research project, decisions are made based on one's understanding up to that point (e.g. about the nature of what is being studied, based on prior reading; about what kind of knowledge it is possible to obtain in research, based upon the conceptualised nature of what is being studied; about what methodology might be appropriate, based upon the understanding of the kind of knowledge that is possible; and so forth). These are, or should be, all logical decisions.

Is the scientific paper a fraud?

However, logical decision-making gives no assurance that research will go as planned. Peter Medawar, the Nobel laureate quoted earlier, complained that scientific reports offer a very tidy account of a process that is actually often anything but tidy. Moreover, he suggested that the format of most scientific papers represented "a totally mistaken conception, even a travesty, of the nature of scientific thought" (Medawar, 1963/1990, p.228).

In particular, Medawar criticised the way research reports are based around an inductive model of scientific work, which underplays the role of the creation of scientific hypotheses,

> "…the scientific paper is a fraud in the sense that it does give a totally misleading narrative of the processes of thought that go into the making of scientific discoveries. The inductive format of the scientific paper should be discarded. The discussion which in the traditional scientific paper goes last should surely come at the beginning. The scientific facts and scientific acts should follow the discussion, and scientists should not be ashamed to admit, as many of them apparently are ashamed to admit, that hypotheses appear in their minds along uncharted byways of thought; that they are imaginative and inspirational in character; that they are indeed adventures of the mind."
>
> (Medawar, 1963/1990, p.233)

Scientific papers focus on the ‘context of justification’, that is the logical argument for why what is claimed might reasonably be believed to be so. However, in doing so, they tend to ignore the ‘context of discovery’: the processes by which the research initially thought of a particular idea (Hoyningen-Huene, 2006).

In one sense, this is fine, because the main purpose of a scientific research report is to justify knowledge claims. Yet there would be no such claims or justifications without the creative process by which scientists produce their original ideas.

The role of creativity in science

Creativity is certainly a central part of science, and indeed part of the expectation of the major qualification for any researcher, the Ph.D. degree, is that work should be original. Originality in this context, means offering something that is new to the literature in the field concerned. The originality may be of various kinds: applying existing ideas in a novel context; developing new instrumentation or analytical techniques; offering a new synthesis of disparate literature and so forth. However, the key is there needs to be some novelty. Arthur Koestler argued that science, art, and humour, all relied on the same creative processes of bringing together previously unrelated ideas into a new juxtaposition.

> “Creativity in science could be described as the art of putting two and two together to make five. In other words, it consists in combining previously unrelated mental structures in such a way that you get more out of the emergent whole than you have put in. This apparent bit of magic derives from the fact that the whole is not merely the sum of its parts, but an expression of the relationship between its parts; and that each new synthesis leads to the emergence of new patterns of relations - more complex cognitive holons on higher levels of the mental hierarchy.”
>
> (Koestler, 1978/1979, p.131)

When Lise Meitner and Otto Robert Frisch puzzled over results from Meitner’s laboratory which suggested nuclear processes leading to daughter nuclei much smaller than the parent nuclei (which did not fit any of the then-known decay processes), they proposed the possibility of nuclear fission on the basis of an analogy between a heavy nucleus and a liquid drop,

> "On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops."
>
> (Meitner & Frisch, 1939, p. 239)

Meitner had fled Germany to escape Nazi persecution, leaving her experiments in the hands of her colleagues Otto Hahn and Fritz Strassman. However the 'laboratory of the mind' (Brown, 1991) goes with us whether we are, and Meitner was able to think of a novel explanation for the results her colleagues reported.

Regardless of whether one is a naive realist (seeing science as capable of producing a true account of the world) or more of an instrumentalist (accepting that positivism is an unrealistic goal, and considering science as about developing models that fit well enough to reality to work for human purposes), there is a need for someone to produce the idea that will then be tested to see if it is how the world is, or at least how we can currently best model the world.

Yet how we have such novel ideas is not well understood. In logical thinking conclusions are in a sense already implied by the premises, and so the logical work to be done is routine if sometimes difficult. However, creative thinking means coming up with something that goes beyond the information available; that is, something that is not logically justified (but of course can subsequently be put to the test).

In logical thinking, the thinker is aware of what they are doing. In creative thinking there is no set procedure or set of steps to follow – although of course various heuristics and techniques have been applied to encourage creative thinking (Bruner, 1961/1963) – rather the processing occurs subconsciously and an idea just appears in consciousness (Taber, 2008a).

The nature of the creative process

Indeed, there are many stories of how creative thinking is best supported by relaxed distraction. Whether focused concentration actually interferes with the creative process, or simply makes one aware of the lack of apparent progress, there are many reports of how creative ideas arrived in the mind only when the problem was not being consciously considered. An early, and well-known, example concerns Archimedes. Set the task of finding a non-destructive way of determining the purity of a gold crown, Archimedes is reputed to have solved the problem as he took a bath. Supposedly, as he lowered himself into the bath, Archimedes had the insight that if the gold provided to the jeweler had been adulterated with another metal, then although it would have the expected mass (as the jeweller would have substituted for the same mass of gold to misappropriate some of the original gold), the crown would have a different density, and would displace a different volume of water than the same mass of pure gold.

Perhaps Archimedes had already developed the first part of this argument, and was puzzling over how he would measure the density. Living at a time before the establishment of the modern scientific paper, Archimedes does not seem to have felt the need to disguise the origin of his insight; and the analogy between the familiar context and the target problem ('if water splashes out when I get in a full bath, then…') is of interest here, as analogy has been proposed as one major source of creative ideas in science (Muldoon, 2006).

Another famous example concerns the chemist Friedrich August Kekulé who suggested a viable molecular structure for the compound benzene. This had been a question of interest because although a formula had been established, no feasible structure had been suggested which fitted (i) the formula, (ii) the known structural patterns of organic chemistry and (iii) the actual properties of the substance itself. Kekulé solved the problem by suggesting that rather than being some form of chain, like other structures accepted at that time, the structure was a actually a ring. Kekulé later claimed that the solution had come to him whilst we was dozing: that he had an image of a snake biting its own tail, and woke up to realise that image transferred to a chemical structure that solved the problem,

> "I turned the chair to face the fireplace and slipped into a languorous state. Again atoms fluttered before my eyes. Smaller groups stayed mostly in the background this time. My mind's eye, sharpened by repeated visions of this sort, now distinguished larger figures in manifold shapes. Long rows, frequently linked more densely; everything in motion, winding and turning like snakes. And lo, what was that? One of the snakes grabbed its own tail and the image whirled mockingly before my eyes. I came to my senses as though struck by lightning."
>
> (Translation quoted in Rothenberg, 1995, p. 425)

There seems to be some question over the precise circumstances of this insight (as several versions seem to be in circulation), and it has been suggested that Kekulé himself may have told variations of the story, but it has none-the-less passed into scientific folklore.

Another case would be that of the Nobel laureate Barbara McClintock. McClintock worked on plant genetics and is most famous for proposing the notion of 'jumping genes'. McClintock's way of working was to be involved with her plants in the field as well as in the laboratory studies – so the tissue she examined under the microscope came from plants she knew and had watched grow (Keller, 1983). She claimed that her long close association with her material led to a level of understanding that was based on thinking that was not fully conscious. She developed what her biographer, Evelyn Fox Keller, called 'a feeling for the organism'.

This is the use of intuition in science. Intuition should not be confused with instinct, genetically coded behaviours, for intuition can be developed by extended familiarly with a target domain. It can be understood in perfectly natural terms, as part of the way the brain learns over time to interpret patterns in information. However it works at a subconscious level: at the level between the body receiving sensory information and presenting percepts to conscious (Taber, Forthcoming). As such pattern-recognition processes are subconscious they are fast and automatic, which is very useful when they are accurate, but also gives scope for them to mislead us. Such processes have been hypothesized to be important in the development of alternative conceptions in physics (diSessa, 1993) and chemistry (Taber & García Franco, 2010).

McClintock was aware that her brain 'integrated' information prior to her consciously being aware of the results, and found the inability to elucidate the process by introspection frustrating on the occasions when her results contradicted her intuitions. However, generally she was comfortable relying on this process as part of her scientific thinking,

> "I read the paper and when I put it down I said, 'This can be integrated'. My subconscious told me that. I forgot about it, and about three weeks later I went into the laboratory one morning at the office. I said 'This is the morning I'll solve this'."
>
> (Quoted in Beatty, Rasmussen, & Roll-Hansen, 2002, p. 282)

Although, as Medawar points out, most scientists do not tend to report on this aspect of the scientific process of discovery in their research reports, this is a key part of science. Michael Polanyi (1962), the chemist and philosopher, wrote about the importance of tacit knowledge in the work of scientists, recognising that this was a critical feature of scientific work. Although this can be considered a form of knowledge, it may well be processed in non-verbal forms in brain circuits that are encapsulated, and only present the outputs of processing to consciousness (Karmiloff-Smith, 1996). Unlike the scientific paper, the scientific intuition ignores the context of justification and only offers us the discovery.

It is this tacit knowledge, this subconscious cognition supporting intuition, which offers the scientist a feel for what to do next when there is no obvious logical basis for decision-making. Like Koestler, Myers argues this is akin to artistic processes,

> "Creativity in science shares with the arts many of the same impulses: self-expression, an aesthetic appreciation of the universe, and a search for truth and a view of reality…It is 'imagination in search of verifiable truth' , requiring a 'feeling for the order lying behind the appearance'…Scientific revelation brings order to chaos."
>
> (Meyers, 1995, p. 763)

However, whereas the artist can simply act on the impulse and produce work for the field to critique later; the scientist uses such impulses as starting points for work that will have to be logically justifiable before it is presented to the scientific community.

Einstein is commonly quoted as suggesting that "the intuitive mind is a sacred gift and the rational mind is a faithful servant. We have created a society that honors the servant and has forgotten the gift". Einstein was one of a number of scientists who have described how much of their creative thinking was imagistic (Miller, 1986). Nersessian (2008) has described how scientists form mental models, often represented in images, which act as mental simulations that can be run so that the outcomes can be compared with the target phenomenon.

Kind and Kind review the role of creativity in science education, and argue that

> "imagery and imagination are important skills for scientists. When developing new theories they use the ability to imagine and visualise physical phenomena and 'play' with possible outcomes. Examples include simple analogies, as when Einstein, while working out the general theory of relativity, imagined what it would be like to ride on a ray of light and Faraday visualised electromagnetic field lines."
>
> (Kind & Kind, 2007, p. 22)

The role of creativity in learning science

Creativity is clearly then important in the development of the public knowledge of science, because it is essential to the discovery process, even if formal research reports are focused on the context of justification, and leave the context of discovery as material for anecdote, after-dinner speeches or memoirs. As creativity is so essential to science, any authentic science education should reflect that.

Creativity and learning about NOS

Teaching students about NOS has often focused on enquiry processes, which in practice has often meant the testing of hypotheses. We can ask the student to suggest the hypothesis to be tested, and the methodology to be used, and that potentially is a creative process. That might be one area where US science education tends to fare somewhat better than UK science education, at least when inquiry teaching is done well (Lawson, 1985).

Under the English National Curriculum that was in place during the last decade of the twentieth century and much of the first decade of this century (DfEE/QCA, 1999), forming a hypothesis became a step in scientific 'inquiry' rather lacking in any genuine creativity. The formally assessed practical work which contributed marks towards grades in the high status school leaving examinations degenerated into exercises that were devoid of any real notion of creativity, or spirit of inquiry (Taber, 2008b).

Nominal focus of scientific enquiry:	Factors influencing electrical resistance	Factors influencing rates of reaction
Materials provided include:	Test circuit Meters Samples of copper wire of different lengths and radii	Magnesium ribbon Hydrochloric acid of concentration 2 mol dm^{-3}, 1 mol dm^{-3}, 0.5 mol dm^{-3} Stopwatches Glassware, Bunsen burners
Background knowledge:	Resistance is proportional to length Resistance is inversely proportional to cross-sectional area	Rate of reaction usually increases with increased temperature Rate of reaction is proportional to concentration
To investigate:	Effect of length of copper wire on its resistance; or Effect of diameter of copper wire on its resistance	Effect of temperature of acid on time taken for length of magnesium ribbon to completely react; or Effect of concentration of acid on time for length of magnesium ribbon to completely react.

Table xx.1: Caricature of the type of practical exercises commonly used in English schools to assess Scientific Enquiry skills under the 1990-2007 curriculum

Table xx.1 gives an impression of the practice that developed under that curriculum regime. Teachers would set up practical exercises where nominally the student chooses what to test. However, the equipment and materials available often limited rationale choice to one of a small number of well-defined variables. Moreover, the 'enquiries' usually related to demonstrating well-established principles that were specified in the examination syllabus, class notes and textbooks. The students effectively had to show they could demonstrate accepted relationships. The actual level of choice available to students was minimal, which is unfortunate, as choice seems to be highly motivating to students in science classes (Taber, 2007a).

To be fair, when the decision to introduce assessed practical work in science as part of the national examination system was taken, many teachers initially responded by generating imaginative and interesting ideas for practical work. However, as often happens with high-status testing, over time it was found students got better marks if the teaching become more focused on supporting students in meeting the criteria, rather than learning about science. For example, the way marking schemes were set up, any 'inquiry' that did not produce results suitable for plotting a line graph would be ineligible for scoring full marks, so it is understandable that teachers came to channel students so strongly. Teachers understandably did what they could to maximise examination results that would be used to select students for college courses, to judge teacher effectiveness and to rank schools in public 'league tables'. However, such restrained 'scientific inquiry' seems unlikely to whet scientific curiously and creativity:

> "Never mind thinking up paradoxes Albert, go back to your photoelectric work: that gave a nice straight line graph. Well, yes, that's an interesting idea Charles, but you have a rather eclectic collection of data: maybe you could plot average beetle mass against latitude? You only have an hour for this work Marie, so perhaps you should stop trying to isolate new elements, and help Pierre obtain a decay curve. Please stop doodling Richard, if you can't think of anything to measure you may as well give up on passing science and concentrate on practicing your drumming."

Creating scientific conceptions

Yet that is not to suggest that students do not naturally show creativity in their science lessons. The vast literature on alternative conceptions shows that learners have collectively generated immense catalogues of alternative ways of thinking about scientific concepts Some of these conceptions seem to be common across many learners, but others are idiosyncratic. One student I worked with had managed to misconstrue the basic formalism used in chemistry to indicate the charges on ions: yet managed to almost complete her college chemistry course finding ways to interpret teaching, reading and her peers' comments to be consistent with her own idiosyncratic formalism (Taber, 1995). Indeed, the matter was only diagnosed because 'Annie' volunteered to take part in a sequence of in-depth interviews exploring her understanding of chemical topics.

Given any class, in any school or college, students will be able to offer wide range of ideas about light, sounds, plants, energy, acids, planets, the weather and so on. Some of these ideas will match scientific ideas, even when there has been no formal teaching of the topic. Often, however, these ideas will be inconsistent with science, even after formal teaching. Sometimes students will strongly believe their ideas – even when they flatly contradict accepted science. Other times students will offer a range of alternative ideas that they have considered, without necessarily being committed to any of them being right. Here we have a vast resource for creative science teaching and learning. Moreover, the alternative nature of many of those ideas need not be seen as inherently problematic: indeed, rich conceptualisation seems to be a useful prequel to later effective learning of the science (Ault, Novak, & Gowin, 1984). In science learning, as in science, entertaining a range of ideas, would seem be preferable to having a strong attachment to one.

Of course it may be argued that students, especially in school, are hardly likely to come up with truly original ideas – and that indeed few scientists come up with highly significant new ideas. But in education we should be interested in creativity in personal knowledge, not by the standards of public knowledge. A student that I interviewed invented the idea (but not the label, of course) of van der Waals' forces between molecules as she answered one of my questions. This was a creative act of bringing together several existing ideas to form a novel synthesis – and no less impressive because Johannes Diderik van der Waals had beaten her to it.

My informant did not invent the idea of van der Waals' forces from first principles – she already had a lot of the background knowledge in place, but as she worked through her thinking she brought this knowledge into a new juxtaposition, and made, as Koestler would have said, a new bissociation – new at least for her. That is the creative act – the same creative process that leads to novel ideas in science where professional scientists also build upon on their background knowledge and understanding to posit genuinely new ideas.

We all learn through an iterative process, and in build up new ideas by forming new constructions from the existing conceptual resources we have available. As figure xx.4 suggests, students who come to science classes have already been undertaking this construction process form many years, drawing upon a range of sources.

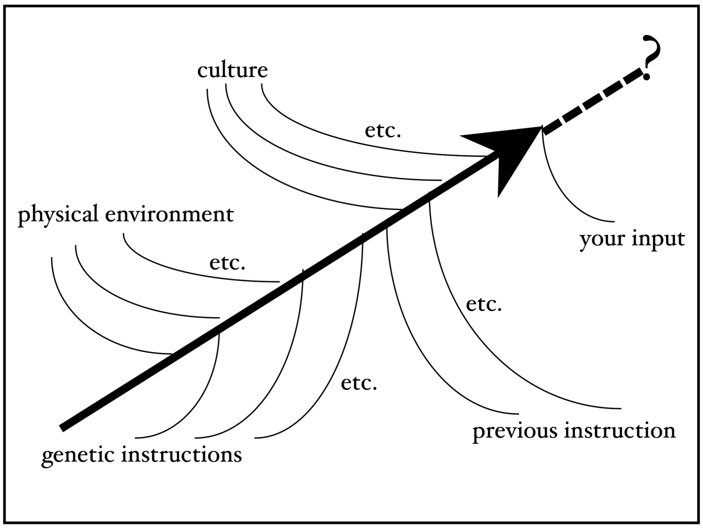


Figure xx.4: The teacher is just one more source in the learner's ongoing iterative knowledge construction project

The different sources have variable reliability, and are all interpreted in terms of what we understand to date: an accepted misinterpretation may later be corrected, or may simply be the basis of further misinterpretations of related learning. 'Sandra' logically deduced that the stars were much smaller than the sun; because she knew they were much closer; because she knew astronauts had passed them on the way to the moon (Taber, 2010a). The starting point for this chain of logic was a false premise, apparently a misinterpretation of footage she had seen of the view through spacecraft viewing ports.

Building upon the learner's creativity

It has been suggested that constructivist teaching schemes (Driver & Oldham, 1986) that begin by asking pupils to suggest ideas to explain phenomena are likely to encourage the development of alternative conceptions. Perhaps that is sometimes the case; but, if so, that's a sad indictment on the way ideas are treated in science lessons.

In science, ideas are seen as possibilities for imagining the world, not absolute accounts of what must be. That must become the case too in science lessons.

This brief consideration of creativity in science and learning has suggested a number of important propositions

- creativity – forming new ideas - is a major part of science
- learning is intrinsically a creative process
- students create all sorts of ideas about the world

This might suggest that we should be able to build creativity into science education. That would be good not only because creative scientists are valuable in society, but because creative learning is engaging and so motivating (Csikszentmihalyi, 1988).

Going by the wide range of alternative conceptions reported in the literature, every classroom offers a potential wealth of alternatives ideas to be explored and tested in science lessons. Yet it has also been widely argued that students do not seem to be very good at subjecting their ideas to critical examination and testing – understandably, perhaps, as this involves overcoming the natural tendency to trust the cognitive apparatus we usually rely upon to make sense of and act meaningfully in the world, and adopting, for argument's sake, a different perspective. Consequently constructivist approaches to teaching may be seen as encouraging an intellectual free-for-all that is high on imagination but lacking disciplined analysis.

Perhaps this is often so, but if my account of how school science must appear to students reflects common experience, then we have little reason to expect anything different. Shifts between alternative, inconsistent accounts that seem to be based on little more than 'which description works here' do not encourage the critical attitude. 'Inquiry' into the effects of the variables students are already expected to have learnt about does little to teach open-minded approaches to experimentation and evidence. Practical work that requires students to draw generalised conclusions of universal applicability by testing single examples drawn from broad classes are not designed to give insight into the context of justification of scientific ideas.

Teachers demonstrate much creativity in getting across some flavour of abstract scientific ideas, for example using metaphor – such as atoms that share electrons - or more explicit analogy –particles which, like people, huddle up in the cold, and spread out when things are getting hot. These creative processes reflect the approaches used by scientists (what if the nucleus is like a liquid drop?; what would happen if I could sit on a beam of light?), but students will not appreciate that if the metaphors and analogies are presented *as if* realistic accounts of the world,

Courting the handmaiden

Bringing together these considerations about creativity in science and science teaching; the creativity inherent in learning; and the tendency for students to assume science and science teaching is meant literally and realistically; suggests some directions for improving science education.

Science teachers need to celebrate the creative aspects of science – the context of discovery. They should emphasise how scientific models are thinking tools created by scientists for exploring our understanding of phenomena; how teaching models are speculative attempts to 'make the unfamiliar familiar' by suggesting that 'in some ways it's a bit like something you already know about'; and in particular how scientists always have to trust imagination as *a source* of ideas that may lead to discovery. However, it is equally important that the creative act is always tempered by critical reflection. Scientific models have limitations; teaching models and analogies may be misleading; and all of us have to select carefully from among the many imaginative possibilities we can generate if we seek ideas that help us understand rather than just fantasise.

Science should not be taught as if a 'rhetoric of conclusions', but rather as the offspring of as a marriage between the creative impulse and the logical evaluation of ideas against evidence. There will be tensions in the marriage between the expansive potential of imagination, and the restrictive constraints of logical analysis. However, creativity has to be understood as an equal partner, and not just as a light distraction to break up the serious scientific work. The logic of justification depends upon the source of discovery for its material. We can give ourselves permission to let the imagination reign free, as long as we know how to then evaluate what we create.

So there are two aspects to the recommendations being suggested here. Firstly, it is vital for science education that we are more explicit about the nature of the ideas we discuss in science classrooms: whether well-established and widely verified scientific principles; scientific models of limited application; the teacher’s creative attempts to make abstract ideas concrete, relevant or familiar; or the students’ own creative attempts to make sense of experience and teaching. All such ideas, whatever the source – scientist, teacher or student – are due respect as creative products worthy of consideration. However, all such idea, regardless of source, must be tested against evidence, and their application justified. Inevitably most of the students’ ideas will need to be at least modified – just as scientists’ ideas usually evolve, and have to survive competitive selection, before they become public. But that does not negate the importance of the creation of those ideas. Science does not proceed without new ideas to test; and learning does not proceed without new potential ways of understanding to explore.

So once we can overcome the notion of science being about ‘facts’ and teach it as primarily about ideas - thinking tools, that are often interim and suboptimal – we will be in a position to encourage students to see science as about a process of generating and then testing ideas. *Then* we can shift science education away from being understood as learning a catalogue of previously discovered facts, to being at its heart a process of exploring and evaluating ideas that inevitably have to be created anew in each learner. This certainly does not underplay the context of justification, but suggests that justification only makes sense in the context of the imaginative discovery of possibilities. Then we can acknowledge and celebrate the centrality of the creative process in the science classroom: not just as the handmaiden to logic, but as its true partner, without which science is not complete.

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