

Things you should not believe in science

Students should be encouraged to believe that the scientific approach provides a powerful means of generating useful knowledge, whilst being actively encouraged not to believe in the science they are taught.

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Abstract: This article considers the relationship between belief and learning science. It is argued that belief in science (as a process) needs to be distinguished from belief in particular scientific ideas and knowledge claims. Scientific knowledge is theoretical and provisional - something to be adopted for its utility, not as articles of faith. The scientific attitude is to always be sceptical and retain a critical attitude to what we think we know. Belief in scientific knowledge is not only inappropriate in terms of scientific values, but can also be unhelpful from an educational perspective. The science teacher should actually encourage students not to believe in the various theories, models, and other products of scientific work presented in class. This approach can avoid conflicts with students' personal beliefs, support scientific literacy, and better prepare future scientists.

Do we want learners to believe in science?

This article considers two questions that are important for science teaching:

- *What do scientists believe?*
- *What should science teachers encourage their students to believe?*

Inherent in the second question is a third: *Do we want students to believe in the science that they are taught in school?* These are considered important questions, because they relate to two key challenges that science teachers face. One of these challenges concerns the particular situation where students consider that some of the scientific ideas they meet in school are contrary to their own strongly committed personal beliefs. This only tends to happen in a small number of topics, and then only with certain students, but is potentially a serious issue when it arises. This raises the question of how science teachers should respond when canonical scientific ideas they are charged with teaching are considered not only incorrect, but sometimes offensive (e.g. heretical), by students.

The most noted example probably concerns the teaching of evolution by natural selection (Reiss, 2008). Natural selection is a core idea in modern biology, such that virtually all active areas of biological science adopt an evolutionary framework. A version of biology which denies or excludes this perspective could not today be considered as authentic science, and certainly that a school biology which ignored natural selection, rather than placing it as a central theme, would provide a deficient and inadequate education in the subject. Yet in many countries there are some students, and in some communities most students, who would completely reject any form of macroevolution, where new classes of living things evolve, as not only wrong, but as an abhorrent idea. This clearly creates a potential problem for curriculum planners, textbook authors, and examination boards in that they may easily upset and offend some students and their families. Assuming the groups who determine curriculum decide not to compromise the science, then the problem shifts to the classroom teacher who actually has to present the ideas directly to students. It is perhaps not surprising, even if it is certainly regrettable, that sometimes teachers may choose to avoid conflict by underplaying or even omitting material that could lead to conflict (Long, 2011).

Although evolution of living things has been the most obvious area where this problem arises, other scientific ideas relating to the formation of the universe and/or the solar system, and the geology of the planet, are also potential points of conflict. In some societies there may also be other areas of science - such as the germ theory of disease - which whilst uncontroversial in most parts of the world, are at odds with local belief systems (White, 2015). So there is here a general issue of how as teachers we should approach the teaching of scientific ideas which may be contrary to the committed beliefs of our students.

The second challenge concerns an issue less likely to cause tension, because it is likely that teaching which does not address it will pass unnoticed by students. This is the challenge of offering students a view of the nature of science which is authentic in acknowledging the limitations of science, without undermining the worth of science itself. In effect, how can we teach that science does not have a method that leads to certain knowledge, and yet still encourage students to have confidence in the power of science as a key source of reliable knowledge? How do we present scientific knowledge in the light of the slogan 'Scientific certainty is (almost certainly) dead - long live science!'

This second challenge is not restricted to particular topics, but applies across our teaching of science. At its heart is another question - *Does it matter if school science gives the impression that science has an infallible means of producing absolute knowledge?* It could certainly be argued that most of what we teach in school science is necessarily a simplification, and needs to be refined when students move on to study science at higher levels, so perhaps teaching science as having a method for producing definite knowledge is just another simplification judged to match the

capabilities and needs of relatively novice learners (Taber, 2008). This is a reasonable point, but I will argue here there are very good reasons for rejecting such an approach.

Knowledge and belief

Before proceeding it is useful to consider what we mean by the term 'belief', and indeed the related term 'knowledge'. When in Wonderland, Alice was told that words can mean whatever we want them to mean. In a sense this is true - anyone can use any word to mean anything: but if language is to support effective communication it is sensible to seek to ensure we share understandings of key terms.

In everyday language we might use a term like 'believe' in a fairly loose sense. When someone is said to believe something this may be intended to imply some point on a continuum which at one pole there is an absolute unshakable commitment and at opposite pole a romanced idea that at that moment captivates us and seems likely (or desirable). 'Beliefs' of the latter kind may soon be put aside on reflection, or simply forgotten as the stream of consciousness progresses.

This is an issue that arises in science teaching when we consider the nature of student's alternative conceptions. A great many different such conceptions have been recognised in research, but they are not all of the same status or relevance to classroom learning (Taber, 2014). Before studying physics classes students commonly 'believe' that any moving object must be subject to a net force. Perhaps this 'belief' is near the committed end of our spectrum, as after being taught otherwise, students often still commonly suggest that any moving object must be subject to a net force. Before secondary school, most students have few very specific beliefs about atoms - apart perhaps from that they are very small. Sadly, after studying secondary school chemistry many students have come to believe that all atoms want to have a full outer shell of electrons, and that they will consequently act (react) to get the electrons they need. Advanced chemistry teaching, including offering much evidence to show the absurdity of this principle, does not readily disrupt this belief: advanced students (including science graduates) will often suggest that a chemical reaction occurs so that atoms can obtain stable electron configurations - even when they are given the reaction equation showing the reactants are of the form of stable molecules.

Yet there are many very different conceptions that could be called beliefs, but which are not so tenacious. Many children believe that all metals are magnetic (i.e., ferromagnetic). This is usually readily addressed by testing a range of examples. Students commonly believe that mushrooms are plants, a categorisation that is common in everyday usage. Even after being taught otherwise some students will habitually tend to think and talk of mushrooms as plants, yet will be perfectly able to accept that - in terms of biological classification - fungi are a distinct type of living things. Arguably they still retain their earlier conception, but now complemented by the scientific alternative, and no longer justifying the label of a belief.

We might consider some hypothetical student who believes both that all metals are magnetic, and that human beings were specially and directly created by a deity, yet it is unlikely that these 'beliefs' have similar levels of commitment. Most children have little invested in their notions of the classification of toadstools or the properties of metals. A student may believe that all metals are solids, but readily abandon that belief on observing mercury or being shown videos of liquid iron being cast. Not a great deal depends upon holding true to the original idea.

The issue with our first challenge is that some students hold a worldview which is shared with their family and community, which is core to their identity, and which involves very strong commitment to specific ideas contrary to science: e.g, the earth was formed no more than 10 000 years ago, each group of animals and plants were separately created fully developed, and that natural processes can lead to variation within groups, but cannot allow one creature to evolve into a fundamentally different kind of creature. These commitments may be linked to ideas about moral behaviour, and

indeed the possibility of an afterlife. Someone who suspects that accepting natural selection will alienate them from their family and friends, and potentially exclude them from eternity in paradise, is not in a strong position to look dispassionately at the arguments for the scientific perspective. In this particular case it should also be pointed out that macroevolution is not consistent with most people's everyday experience of the world; the timescale over which evolution has worked is vast compared with human experience; and that a full understanding of evolution involves synthesising a number of abstract ideas and principles.

The evidence for natural selection is vast, but draws on a range of scientific fields where a full understanding of the evidence often requires strong background knowledge. Moreover there is plenty of supposed 'evidence' against the scientific account in circulation (e.g. on the worldwide web), some of which immediately looks flawed to the science teacher (if not the novice), but some of which is quite sophisticated.

Knowledge is another term which is potentially problematic. At one time knowledge meant those beliefs people held with good justifications, and which were indeed true. Clearly adopting such a notion of knowledge means we can only judge someone's ideas as genuine knowledge if we know they are true - so if we can adopt a 'God's eye' view and suggest what is definitely the case. As scientists we should have reservations there.

Knowledge in science

The ability of science to develop knowledge of the world has been subject to considerable critique, and in the 21st Century it is widely accepted that:

- scientific knowledge should not be considered as definitive and absolute, but rather as provisional
- established scientific ideas should remain open to reconsideration in the light of new evidence or a new perspective for interrogating the available data
- there is no single scientific method
- all scientific methods admit the possibility of error
- scientific knowledge should be understood to be of the form of theories and models, not absolute accounts of how things are

It is now accepted that drawing general conclusions without examining all possible relevant cases (induction) is logically flawed (you should not conclude all swans are white, unless you have checked all swans), and that when science proceeds this way it relies on theoretical assumptions (we 'know' that all water ice in the universe is H_2O based on our theories of substances and molecules). Experiments that support hypotheses never exclude other potential hypotheses (perhaps not yet imagined) which would lead to the same conclusions. Experiments which fail to support hypotheses do not strictly refute the idea underlying the hypothesis as there might have been an error in carrying out the research, a logical flaw in the research design, or the failure might be in the theory of instrumentation (perhaps we do not fully understand how this type of electron microscope, or gravity wave detector, really works - or perhaps the calculations behind the Fourier transform have not been programmed correctly).

This is certainly not to suggest that science has little worth or that scientific knowledge should not be taken seriously. We have to accept that science offers an imperfect means of understanding the natural world, but it is still the most trustworthy and powerful means we have. Comparing the imperfections of science against the potential of guesswork, sheer optimism, tea leaves, tarot cards, the patterns in entrails of sacrificed animals, or political ideology, there is little doubt of the merits of science. Science produces incredibly powerful knowledge that helps us understand the world, and act in it based on - usually - reliable predictions. It is just not perfect. Sometimes we know our knowledge is limited (our models of climate change), or of limited range of application (the ideal gas law), and sometimes ideas seem settled for a long time before they are found to

break down under newly considered conditions (Newtonian physics). It was known for a long time that Mercury did not behave as Newton's laws suggested it should, but those laws were still incredibly powerful in most respects. Even when relativity supposedly superseded the Newtonian worldview (and Mercury's orbit came to fit the theory), the outdated physics was good enough to get Apollo missions to the moon and back.

Being honest about what we teach in science

This is one reason why there is no shame in teaching Newtonian mechanics in school (as long as we acknowledge it is not a definitive account) - it remains very useful, even if we have to accept that it is not a complete and absolute description of an aspect of nature. Often school science necessarily compromises on scientific knowledge. It is pedagogically sensible to represent complex and sophisticated scientific knowledge in a form suitable for students who are still developing their cognitive abilities and who hold limited background knowledge and limited experience of many of the phenomena science seeks to explain. The specification teachers are asked to work with is therefore often a considerable simplification of the science. Moreover, teachers have to find ways to make the unfamiliar familiar, and this may include further simplification, various kinds of models, the use of cartoons, metaphor, analogy, simile, anthropomorphism, narrative, and so forth. There are then three levels of separation between what students commonly experience in school science classes and the actual nature of the world:

- scientific knowledge comprises incomplete and (in principle) provisional, theoretical, accounts of aspects of nature
- the school curriculum usually offers selective and simplified accounts of scientific theories and models
- the teacher employs various forms of teaching model to mediate between students' current experience and understanding, and the target knowledge set out in the curriculum.

This of course explains why few, if any, children enter secondary school thinking that atoms want to fill their shells with electrons, yet most seem to believe this is the scientific account at the end of compulsory science education. Our attempts to simplify and communicate the abstract ideas often seem to go wrong here, but finding solutions to the Schrödinger equation is simply not an option for the average 14 year old.

Just as many scientific theories and models are not suitable for presenting in their full glory to school students, there is much scholarship about the nature of science that is complex and sophisticated, and which is not suitable for presenting directly to most school age learners. Yet just as we can seek optimal simplifications of scientific ideas - balancing authenticity with accessibility - so we can look to do the same in teaching about the nature of science (Taber, 2008).

Avoiding idealistic notions of science

To face the challenges outlined above, it is essential to make sure that our students understand the provisional nature of scientific knowledge. The strongest case probably concerns the wider aim of science education that applies to all students (even if they have no interest in studying further science). We want students to be 'scientifically literate' so that they can engage in the culture of modern society, and in particular to be empowered to act in the civic sphere. In a democratic society we need people (voters) to engage with debates about gene therapy, climate change, nuclear power, and so forth; as well as to be able to make informed decisions about their own consumption, behaviour in relation to health, and actions that impinge upon the environment. Yet science in society is usually contended, with different theoretical perspectives, different interpretations, and even different 'facts' being offered. Different scientists may therefore take different views about the way things are or what should be done. The science teacher knows that

is pretty typical in science. Yet school science tends to ignore all this and just present selected scientific ideas that have become established as if they were certain knowledge, having been 'proved'.

A second consideration relates to the particular challenge of those who hold strongly held personal beliefs inconsistent with current scientific thinking. It is very unlikely that scientists will abandon natural selection any time soon, or revise the age of the universe downwards by many orders of magnitude. However, if this theoretical knowledge is presented as absolute, as what scientists believe, then scientific beliefs are set up against students' personal beliefs so some form of conflict is inevitable. If scientific ideas are always presented as theoretical ideas, imagined by scientists to best explain currently available evidence, but open to revision, this can avoid direct conflict. A student who thinks evolution is an intrinsically evil idea used by the devil to lead good people astray is inevitably going to be uncomfortable when this material is presented in the classroom but there is a big difference between being told:

- this is what scientists have shown (proved) is the way things are

and

- this is the idea most scientists think makes best sense of the evidence found so far

The important difference is the stance taken by the teacher, which is not:

- it is my job to persuade you to believe this

but rather

- it is my job to help you understand the scientific theory, and appreciate why scientists are currently applying this way of thinking

The latter approach asks the student to take a 'meta' perspective: not to accept an idea, but try to understand it. This is analogous to understanding why a friend likes a different football team, or a different pop star, which can be done without changing their own preferences. This requires some sophistication of thinking - but then in history classes students will be expected to understand why Hitler came to power, or the causes of the French revolution, without becoming Nazi sympathisers, or wanting to send aristocrats to the guillotine.

Preparing future scientists

A final consideration is the anxiety caused by teaching limited and partial models, and especially simplified teaching models, to those students who do want to follow careers in science. If students have successfully learnt that 'work done is force times distance', only to later be told they now have to think in terms of displacement and apply a trigonometric function, it can be a little disheartening. Chemistry perhaps takes the prize for teaching such semi-truths: oxidation is the addition of oxygen, strong acids have pH1, neutralisation produces neutral products, stable compounds obey the octet rule, elements are metals or non-metals, non-metals combine with covalent bonding, the Cl⁻ ion has a full outer electron shell ... I recall the anguish of one hard-working student coming to terms with the realisation that the shell model of the atom that he had conscientiously learnt for his end of school examinations now had to be replaced by one with s, p and d orbitals. (A model, incidentally, which although widely applied, is probably only strictly valid for the hydrogen atom and hydrogenic ions.)

Many of these problems disappear if we teach scientific knowledge explicitly as theories, models, generalisations, typologies, and so forth, throughout school science. Time and effort put into

exploring the status of scientific knowledge can avoid problems later. If students believe that what they are taught in science is absolute they will learn it that way. If they are told there are two types of chemical bond and receive this as an eternal and absolute fact about the natural world, then when they meet metallic, and polar, and hydrogen, bonds they are likely to misconceive them as variations on, or types of, covalent and ionic bond (as commonly happens) (Taber, 2013).

Ultimately if we want students to study further science and seek to become scientists, then we need to prepare them for what is involved in science. Learning some science will certainly help, but appreciating the nature of science as a process, the theoretical nature of the products of science, and the nature of the conceptual work of scientists is likely to be even more valuable preparation. After all, it will be easier later on to learn some specific science that was missed in school, than to fundamentally reorientate their notion of what scientists are seeking to do. Getting across the excitement of science, the role of imagination in science, and the potential of any young scientist to challenge the current orthodoxy in their field, is surely more important than learning many of the specific cut-down scientific ideas prescribed in the curriculum. There is a danger that for many school students the values of science seem to be associated with accepting authority, and regurgitating knowledge statements verbatim without contaminating them with any personal creative insights or flourishes.

Scientific values

This would be tragic, as the essence of science is surely the core values that underpin the scientific attitude. This comprises such features as:

- be critical of your own way of thinking and understanding
- be open to consider alternatives, and be prepared to change your mind
- always consider the evidence carefully before coming to a conclusion
- always try to imagine different ways of making sense of the data available

If school science achieved nothing other than encouraging young people to adopt such principles it would make a very useful contribution to society. Sadly, too often the science that is taught is presented dogmatically, so that students have little option than to just learn what they are taught on the authority of the teacher, the curriculum, and the examination specification. What is learnt is not authentic science, but bowdlerised and gutted versions of some scientific knowledge claims stripped of their provisos and ranges of convenience, and largely decontextualised from the grounds on which they were justified. This is seldom the teacher's fault, as often the amount of material to be 'covered' does not admit a critical examination of the evidence and arguments for ideas, and - unforgivably - what is wanted in examinations may be a precise form of words rather than evidence of a personal understanding of the ideas the words are meant to represent. As is often the case, what may be readily assessed objectively may not be what it would be most valuable to assess.

Conclusions

The scientific attitude helps develop knowledge that can be considered objective as it derives from a self-critical process that seeks to consider alternatives, test ideas, and give due weight to all relevant evidence. This knowledge is still provisional because even the most careful humans cannot fully avoid bias (Nickerson, 1998), and scientists can only collect finite evidence to test the possibilities they can imagine, so there is always scope for both new evidence and the imagining of other possibilities. These features produce a form of knowledge that is critical to the success of modern technologically advanced and economically developed societies. An important role for science education is to help young people understand the nature of the scientific process, and why science - albeit only ever able to offer theoretical knowledge that might need to be refined or

replaced at some point - is such a powerful tool for advancing our understanding of the world. In that sense, teachers should encourage our students to believe in science: not as infallible or perfect, but certainly as the best approach we have for generating useful objective knowledge of the world.

However, teachers should not encourage their students to believe in the knowledge that science produces, as belief is not appropriate for theoretical knowledge (Taber, 2017). Belief in a concept, a theory, a principle, a model - rather than the utility or relative merits of that concept, theory, principle, or model - is antithetical to the nature of the very science that produced it. Belief is unquestioning and accepting: a stance suitable for religious faith but not for scientific understanding.

Teachers should actively encourage students not to believe in scientific knowledge claims, but rather to accept them as useful tools, developed from a strong rationale, but open to being refined, complemented, or even substituted. This can reduce tension when teaching scientific theories or models that some students feel they must on consciously reject as contrary to deeply held beliefs. They will still be uncomfortable being taught such ideas, but being told that, like all scientific ideas, they should be examined critically, is surely better than having them presented as definite knowledge with the authority of science. Treating all scientific knowledge as theoretical and current best understandings open to review also prepares all students for science in society when different versions of scientific knowledge are presented in the public domain. Finally, seeing all scientific ideas as useful but imperfect or limited conceptual tools, helps learners appreciate why they might need an inclusive toolkit of such tools (Taber, 1995) - so they do not feel they have wasted time learning a false model or definition (of acid, oxidation, atomic structure, or whatever) that then has to be replaced by something different. Given all this, the wise science teacher will actively encourage students not to believe in the scientific ideas they are taught. They should be encouraged to appreciate, to understand, to apply, even to value these conceptual tools. Belief, however, is not an appropriate response in science.

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