5. Why Knowing What's Wrong Matters as Much as Knowing What's Right

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Thank you very much for inviting me to give this talk. I must apologize that due to a combination of being a British citizen who resides in the US, the complexities of the Indian Visa application, and my own personal timetable that I am unable to be with you in person. Nevertheless, I hope that I have something of interest to say to you today.

The position that science educators occupy is what the French term 'bricoleurs' – our job is to make sense of what the writings and work of philosophers, psychologists, sociologists, historians and policy makers imply for the practice of our discipline. We are, therefore, very much knowledge intermediaries – what some would term 'a jack of all trades' and, whilst I know what some of you are thinking, but I believe it to be incorrect. Rather, we are masters of what the French term 'didactics' – the theory and practical application of this knowledge to teaching. This is our specialism.

My task here is to illustrate how that plays out in the context of science education, and in particular, in the work that I do. Let me begin by pointing first to what I believe to be a set of three fundamental contradictions or ironies that exist in science education. The first is that school science is still predominantly a training and not an education; the second is that it has a naïve faith in its intrinsic value, when those outside it value it for its extrinsic worth; and the third, which is the one I wish to address most, is the absence of critique.

To begin with the first - school science is still dominated by the policy makers' views that it should be a pre-professional training. It does not matter where you look – be it the American report 'Rising above the Gathering Storm' (National Academy of Sciences: Committee on Science Engineering and Public Policy, 2005), or 'Europe needs more Scientists' (EC Report, 2004), or the latest report from the UK National Audit Office (2010) which puts it even more bluntly, science education is about educating the next generation of scientists. Everything else is secondary.

My fundamental challenge to this perspective on the value of a science education is that I believe science education should be an education – an education in the liberal sense of the best that is worth knowing about the major explanatory stories that science has to tell and an insight into the epistemic practices that have made science so successful. Indeed as Harry Collins has argued (Collins, 2000), science has freed us from the shackles of received wisdom as the basis of belief, promoting an Enlightenment vision of a commitment to evidence. Of course, as Collins points out, science itself can only work within a tradition where it is taught as received knowledge. What I want to explore is, what is the nature of that received knowledge that should be presented?

Let me start with a basic premise of all my work which is that the only rationale for insisting on science education for all is if such an education has something to offer *to all*. An argument which has been articulated first in *Beyond 2000: Science Education for the Future* (Millar & Osborne, 1998) and again in *Science Education in Europe: Critical Reflections* (Osborne & Dillon, 2008). Given that all of us are – or will be – consumers of scientific knowledge which informs the daily choices we make, rather than producers of scientific knowledge, an activity which will remain as the preserve of a few, science education needs to consider how educating the critical consumer is best achieved. For let us be in no doubt, the major political and moral dilemmas facing humanity – providing sufficient food, ensuring a supply of clean water, generating enough energy, controlling disease and managing climate change are all going to require an informed, educated and critically engaged public.

What is the problem with its current form, you may ask? Taught in this manner, school science has the very opposite effect of what we desire. As training, it is taught in an authoritarian manner such that it is possibly the last surviving authoritarian socio-intellectual system on the curriculum. The consequence of this was summarized well by Paul Tillich, the German theologian and existential philosopher who said 'the passion for truth is silenced by answers that have the air of undisputed authority'. Presented as a body of unequivocal, unquestioned and uncontested knowledge, it fails also to explore how we know or why we should believe in such eternal verities. Consequently the opportunities for developing any disposition to engage in critical enquiry are minimal. As Rogers (1948) points out, 'we should not assume that mere contact with science, which is so critical, will make students think critically' (p7).

For anybody with more than a passing interest in the history of science, there is the concern too that science sells itself short suffering from a form of collective amnesia about its achievements in two ways. First, it fails to point to its successes – for example smallpox was common in England less than a 100 years ago – a disease which has now been eradicated. Or likewise, a graph of the number of deaths from infectious diseases per million of the population in the UK illustrates that perhaps the claim for the single greatest scientific 'discovery' (and I use that word with hesitation as no new knowledge is ever revealed in one instant of time) was the development of penicillin. Prior to this approximately 3000 people per year per million of the population were dying of infectious diseases. Post 1945, the numbers drop off a cliff by an order of magnitude if not more.

But none of this is really my major concern. My concern is rooted in a point elegantly captured in an essay on African traditional thought by Robin Horton, written in 1967, where he compared the way young people in African villages where taught with the way our youth were taught in advanced societies leading him to the conclusion that "*grounds for accepting the models proposed by the scientist are often no different from the young African villager's ground for accepting the models propounded by one of his elders. In both cases the propounders are deferred to as the accredited agents of tradition*." (Horton, 1967)

Taught in this manner, there is no equivocation – knowledge can either be accepted or rejected. Few students come to recognize, that as Harré argued, theories are the crowning glory of science and that the practice of science consists of a process of building and testing models (Harré, 1984). Rather they see the establishment of facts as the major achievement and do not distinguish experimental findings from the ideas that they are designed to test. Experiments tell you in a straightforward manner if you are right or wrong and are not designed to test causal relations. The consequence of that is science teachers and science educators all have a strong faith in the intrinsic value of science, whereas over 50% of high school students in the UK say that their science classes are either too boring, too hard or too difficult. To borrow a term used by Bourdieu and Marxist economists – its use-value is low. The deep and second irony here is that the evidence is that students persist in science because of what Marxist economists would call the high exchange value of science education – that is the fact that the qualifications it offers can be exchanged for financially advantageous employment. Yet this is a feature which is hardly ever mentioned in school science as the exploration of possible careers that the study of science affords is virtually absent from the curriculum. Thus, we have a situation on the one hand where science is blind to its own achievements and on the other hand blind to the one form of value that society and its students do recognize. In this manner, school science sells science, and itself, short – findings which are supported by work that I and others have published (Osborne & Collins, 2000; Osborne, Simon & Collins, 2003).

My project here is to attempt to point to what I now think is the major missing element in school science – something which I think my work has been directed towards but only recently, through the half-light and dim light has become clearer. This is third irony - the absence of critique. One of the defining characteristics of science (and scientists) is a critical spirit that is central to the practice of science. Critique is essential for the construction of claims to knowledge as ideas must be defended against alternative hypotheses. Only those which survive such onslaught are considered worthy of belief. Indeed, as Ford (2008) argues, the establishment of new knowledge is dialectic between construction and critique and it is 'critique which motivates authentic construction of scientific knowledge'. Claims must be defended against critical arguments that question either the validity or reliability of the data, the warrant that justify the significance of the data to the claim, or the background theoretical assumptions. Only claims to knowledge that survive this process are considered to be reliable knowledge. The formal embodiment of this process is peer review and it is through this practice of discourse and argument that science maintains its objectivity (Longino, 1990).

The thesis of this presentation then, is as important as the construction of knowledge, it is the role of argumentation for critical review and evaluation that matters as much in student learning. Now, there will be those that will respond with the argument that it is impossible to engage in argument and critique unless you have some knowledge – a point with which, in one sense, I will totally concur. In another sense, however, I would ask what kind of knowledge? A question I ask, as many science educators have forgotten that there are essentially three forms of knowledge essential to scientific understanding. There is of course, *knowledge of content*. The major ideas and theories and the many detailed items of knowledge about the material world, we have acquired through engaging in the scientific enterprise – the nature of the Solar System, the organs of the body or the number of distinct elements and how they react. This is what we all commonly associate with scientific knowledge. However, I want to argue that there are two *other* forms of knowledge essential for understanding science. The first of these is *procedural knowledge* or what Gott and his collaborators call 'concepts of evidence' (Gott, Duggan & Roberts, 2008). This is the knowledge of such things as what is meant by a variable; the distinction between an independent and a dependent variable, or the common sources of error in measurement and their remediation. The other form of knowledge is what I would term *epistemic knowledge*. This is the knowledge, for instance, of what a theory represents in science, the features of an observation or a hypothesis and the elements of an argument. Why, I ask are these two forms of knowledge, which are such an essential feature of science and engaging in critical enquiry, such a marginal feature of most science education?

Let me illustrate their importance with two simple examples. The first of these is the standard explanation for day and night which most of you will know. Across most of the globe it is commonly taught in elementary schools.

However, a critical science educator might ask of his students, why we should believe this explanation. After all, it is the Sun which appears to move during the day not the Earth. Second, if it was spinning surely when we jumped up, we would not land on the same spot? Finally, it is spinning once a day, the speed at the Equator would be over a 1000 mph – surely we would be flung off into space? How might his or her students respond? First, they would need to establish why such arguments might be flawed. To do this, they would need knowledge of the content of science which has either been taught or they have acquired through their own experience. To rebut the first, they would need to know that motion is relative and to draw from the common experience of being deceived into thinking you are moving in a train or car when it is the adjacent train or car that is moving. To rebut the second, they would need to know that horizontal and vertical motions are independent of each other and that there is nothing to slow the person when they jump up so they will land in the same spot. To counter the third, they would have to draw on a knowledge that gravity is an extremely strong force and that even the gases that form our atmosphere have been held in place by this force since the Earth's inception. This illustrates well that it is impossible to engage in reasoning without relevant domain-specific knowledge. But what evidence could they look to establish the commonly accepted scientific answer. Indeed, I always find it fascinating to ask how many of you – presumably well-educated in science, could identify even one of the two well known pieces of evidence? I normally find when I do this exercise that it is about 5% and less than 1% who can identify two pieces of evidence.

The first piece of evidence is the Foucault Pendulum. This is a long, massive pendulum on a frictionless pivot that appears to rotate its plane of oscillation during the course of the day (Here at Stanford by 220 degrees in a day). To explain this motion, you have to engage in the epistemic activity of constructing a model of the pendulum held to Earth by its pivot but at the same time, freely moving and ask what would happen on a moving Earth. The simplest case is to imagine being either at the North Pole, where the pendulum would rotate by 360 degrees or at the Equator where there would be no rotation. This process is made easier if you have the epistemic knowledge that representational models are essential heuristics for scientific understanding.

Figure 1: **Photograph of star trails.**
(Source -- Star trails over the ESO 3.6-metre Telescope. http://www.eso.org/public/images/271109-cc/. Credit: ESO/A.Santerne. The photograph is released under the Creative Commons Attribution 3.0 Unported license.)

What other piece of evidence might you point to? This photograph is one (Figure 1). It is taken by pointing the camera at the night sky and leaving the shutter open for 8 hours. All the stars appear to rotate around one central star. There are two possible explanations – either all of those stars are rotating around that central star or, alternatively, the ground on which the camera is situated is rotating. How do we decide? By invoking another piece of epistemic knowledge known as Occam's Razor. This is the belief or value inherent to science that when confronted with competing explanations, we always value the simplest. This is a well-known piece of epistemic knowledge but something which rarely forms part of school science.

For my second example, look at this question and attempt to answer it for yourself:

Jasmine was asked to do an experiment to find how long it takes some sugar to dissolve in water

What advice should you give Jasmine to tell her how many repeated measurements she should make? (Choose one)

A	Two or three measurements are always enough
B	She should always make 5 measurements
C	If she is accurate she only needs to measure once
D	She should go on taking measurements until she knows how much they vary
E	She should go on making measurements until she gets two or more the same

Firstly, there is no simple or straightforward answer to this question. Choosing one answer is much more of a case of applying a critical eye and establishing which one of these options are definitely wrong and why. Doing so requires some procedural knowledge. For instance, that all measurement has inherent error and that a single measurement cannot be relied on, eliminates the third option.

This last example is an illustration of the major argument that I wish to make – that knowing which answer is right is dependent on knowing which answers are wrong. That capability can only be developed by engaging in critical discussion of plural alternatives – a dialectic where the process of establishing what is true is a process inference consisting of the elimination of false ideas or misconceptions rather than a process of deductive proof of what is right. The argument for why that form of reasoning matters comes from a Bayesian account of reasoning.

The distinguishing feature of Bayesian inference is that it is a probabilistic system of describing the certainty of knowledge. The degree of certainty is reflected in probabilities assigned to a given hypothesis or event. As new evidence emerges, these probabilities are updated. Sometimes the new evidence strongly favours the target hypothesis over a rival hypothesis, and sometimes it does not. Bayes' theorem describes mathematically how this balance of evidence changes the assigned probabilities. In other words, Bayes' theorem describes how the certainty of knowledge is updated given new data. In this regard, Bayesian inference shares many aspects with scientific reasoning and argumentation. Both involve evaluating uncertain hypotheses and both involve weighing new evidence against target and alternative theories. In certain ways, the very process of science can be viewed as the repeated application of Bayes' theorem as data and evidence gradually change the probabilities in the minds of scientists, 'convincing' them of the truth or falsity of a given hypothesis.

Bayesian inference also offers a means of characterizing an individual's assessment of a hypothesis. Its tenets are derived from Bayesian *probability*, which is typically used to describe random, well-defined systems. Examples of such systems include gambling outcomes, gene assortment, and many quantum phenomena. However, while Bayesian *inference* is developing as a model for scientific reasoning (Howson & Urbach, 2006), there has been little thought about its implications for education – something which I now wish to attempt.

An Intuitive Explainer

One of the problems confronting the wider adoption of Bayesian reasoning is its expression in a mathematical formalism which is somewhat opaque. In its original mathematical form, Bayes' theorem appears as follows:

$$P(h|e) = \frac{P(e|h)P(h)}{P(e)}$$

In this formula, $P(h \mid e)$ is the probability of a hypothesis h given that some evidence e is true. This is referred to as the *posterior probability* as it is the new, updated probability assessment given the evidence e. $P(e \mid h)$ is the probability of the evidence e occurring given that hypothesis h is true. This is referred to as the *likelihood* of h on e because it reflects how determinate h is to explaining e. $P(h)$ is the probability of hypothesis h being true by itself. This is called the *prior probability* since it reflects the probability of h independent of the new evidence e. Finally, $P(e)$ is the probability of evidence e being true by itself.

This abstract formulation is the typical presentation for Bayes' theorem and it is this lack of transparency that has hindered the acceptance of Bayesian inference as a framework for science educators. To address this, let me illustrate its significance on the first examples I just showed – the scientific explanation for day and night. Fortunately, Bayes' theorem can be simplified into its key conceptual components. The figure captures the essence of what Bayes' theorem postulates: *new evidence is used to update prior probabilities to what are now posterior probabilities, a change in the degree of certainty that depends on the likelihood ratio (how strongly the evidence pertains to true versus false positives).* In Bayesian epistemology, this is referred to as the Simple Principle of Conditionalization (Adams, 1965).

Whether the scientific account is to be believed has to be weighed not only in terms of what information or evidence there is that they are correct but also in terms *of what the likelihood is that they might be wrong*. To do otherwise, is to engage in faulty reasoning and logic and to misinterpret the inferences that can be drawn from any set in evidence. In this case, let us say that the balance of probabilities, as illustrated in the example is 50:50 or equally likely. The goal of good teaching is to shift the balance of probabilities. Let us say that an exemplary teacher manages to put forward strong arguments with good illustrations without addressing why the argument is flawed. Let us imagine that the balance of probabilities is now changed to 80:40 or 2 to 1.

However, a much more efficient approach would be to explore not only the evidence or arguments for *but also* the reasons why the arguments against are flawed. Whilst the arguments for and the probability associated with the arguments for remains the same, the probability associated with the arguments against is now reduced so that the balance of probabilities becomes 80:20 or 4 to 1. Such an approach should, therefore, be more pedagogically effective leading to a more secure understanding of the scientific explanation.

Applications to the Reasoning Process

This application of Bayesian notions to personal degrees of belief is sometimes called the subjectivist view (De Finetti, 1974) and has been developed by certain authors such as Howson and Urbach (2006). As a model of informal reasoning, Bayesian inference provides a useful analogue. When we are considering a theory, we tend to have some preconceived notions (i.e., prior probabilities). For instance, when we employ somebody to fix our car, we may feel that a car-repair person is trustworthy for any number of preconceived reasons such as they are friendly or they look honest. When new evidence arises, such as a friend recommending the mechanic, we are apt to update our assessment (i.e. posterior probability). That new probability, however, depends on both true and false positive considerations. If our friend is reliable and is mechanically knowledgeable, that increases the strength of our certainty. However, if our friend is shifty and owns a stake in the mechanic's shop, it has the opposite effect enhancing the evidence of false positives. In Bayesian inference, the degree that the new data supports our target hypothesis versus the alternative hypothesis is the likelihood ratio.

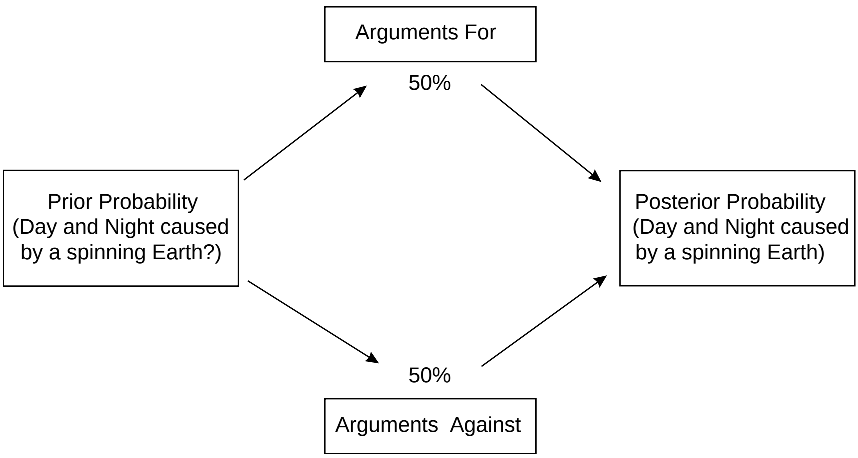

Figure 2: **Simplified Bayesian probability update model.**

Establishing the likelihood of any claim to knowledge being true, however means considering it in the light of alternatives. For instance, Watson and Crick (1953) begin their famous paper by arguing why two possible alternatives structures are wrong rather than arguing why their proposed structure is right. In doing so, they were acknowledging that human reasoning is essentially probabilistic and that an indispensable means of establishing belief in your own ideas is to demonstrate why alternative ideas are flawed.

Numerous findings in science education too have shown that providing students with correct explanations alone is inferior to explaining also why misconceptions are incorrect. For instance, Hynd and Alvermann (1986) found that physics texts that contained "refutation text" addressing common misconceptions resulted in significantly better conceptual gains. Likewise, Ames and Murray (1982) found greater learning gains among discussion groups with differing preconceptions versus those with more similar ones, even if those differences were based on incorrect premises. In short, providing information about both negative and positive cases improves conceptual learning in the sciences significantly.

These findings are consistent with Bayesian conceptions of probability updates, namely that it is not possible to develop a posterior probability without a consideration of a competing alternative hypothesis. According to this view, correct explanations only provide half of the picture. This is critical because in the Bayesian model, the strength of the true positive information does not stand alone; it is always relative to strength of the false positive alternatives (Royall, 1997). As such, students need both target and competing explanations to construct assessments of the presented material. Good teachers of science recognize this need intuitively attempting to contrast the scientific explanation with the common intuitive notions addressing why they are wrong as much as why the scientific idea is correct (Ogborn, Kress, Martins & McGillicuddy, 1996). Likewise, the French philosopher Bachelard understood this concept when he argued that 'two people must first contradict each other if they really wish to understand each other. Truth is the child of argument, not of fond affinity' (Bachelard, 1968). What both are pointing to is that it is *difference* which enables conceptual understanding because, as I would argue, from a Bayesian perspective it provides the individual with evidence both for the proposition and the falsity of the alternatives.

Similar evidence comes from the work of Johnson on the history of the development of one specific engineering product – ABS braking (Johnson, 2009). In her historical account of the development of this technology, Johnson shows how it was knowledge sharing that was essential to the process of its development. Those who did not contribute any knowledge to the community, predominantly American engineers (regardless of whether it was right or wrong) simply did not have the information necessary to make a good judgment about the Bayesian likelihood ratio, and the outcome was a loss to their European counterparts. Similar arguments can be made about Crick and Watson's development of their model for DNA. The critical pieces of information were as much evidence of why certain of their proposed structures were wrong and were as important as the evidence from Rosalind Franklin's X ray crystallography suggesting that the structure was a helix.

Finally, several studies have evaluated the capability of individuals to coordinate theory and evidence (Kanari & Millar, 2004; Koslowski, 1996; Kuhn, 1991, 1993). A particularly interesting finding in this field was a study by Koslowski (Koslowski, 1996; Koslowski, Marasia, Chelenza & Dublin, 2008). Koslowski and her co-workers found that information was more likely to be considered as evidence when a causal explanation was provided. In this study, subjects were provided two plausible explanations for some phenomenon. Data was presented that supported one explanation over the other. The authors observed that subjects were more likely to consider the data as evidence when given a causal framework that permitted its incorporation. Without this explanatory framework, subjects were more likely to disregard the data and did not change their evaluation of which hypothesis was better.

The results of this study can be interpreted with a Bayesian notion of likelihood ratio. By pointing out explicitly a possible explanatory framework, the likelihood of the data supporting the target hypothesis over the rival hypothesis increases. Without an explanatory framework which identifies why any data is salient to the hypothesis, the evidence is not so much discounted as simply not counted. Thus it is not just data that matters for updating probabilities. Providing an explanatory framework which helps the individual see why the data supports the positive hypothesis enables the subject to reassess the likelihood ratio from one where the probabilities may be evenly balanced toward the target hypothesis. Such an interpretation would predict a greater change to posterior probability in the subjects who were provided theoretical explanations versus those that were not, an effect that was indeed observed in the study.

Implications

Bayesian inference has several potential implications for classroom pedagogy. First, it adds further emphasis to the significance of findings that alternative misconceptions must be addressed if students are to gain secure understandings of scientific concepts. Teachers need to be aware that lowering the likelihood of false positives (i.e. alternative 'wrong' ideas) is as instructionally powerful as raising the likelihoods of true positives (the 'correct' idea). Secondly, if learning does indeed occur though a Bayes-like process of data weighing and integration, this reinforces constructivist notions of knowledge acquisition. From this perspective, simply providing the correct answer is not sufficient. Students must be given evidence and allowed to grapple with assessing likelihoods in order to update properly their belief assessments (i.e. posterior probabilities). Specifically, acceptance of new concepts is a function not only of how well the teacher presents the case for a new idea (i.e. strength of the likelihood ratios), but also the extent to which they address the strength of the student's misconceptions (i.e. strength of individual prior probabilities). For students with strongly held prior misconceptions, it may take multiple exposures to evidence to change these beliefs. The Bayesian model suggests this is normal, even when the learner is evaluating the evidence rationally. Therefore, even if a student does not initially accept a new concept, instruction can still be considered a success as long as the learner is more open to the idea than they were before.

Perhaps most fundamentally, this account of scientific reasoning from a Bayesian perspective offers a fundamental rationale for why argument and critique are central and core to scientific activity. If, as I have suggested, beliefs are transformed not solely by confirming evidence but by negating alternative hypotheses, there is then a central role for critique to the construction of knowledge *both* for the scientist *and* the learner of science. Or to put it another way, knowing why the wrong answer is wrong matters as much as knowing why the right answer is right.

The model that I wish to hold up for our societies to aim for is typified by the work of Ben Goldacre who writes a newspaper column in the UK Guardian newspaper called 'Bad Science' (Goldacre, 2008). Essentially what he does is use this column to explore the extent to which we should, or should not believe some of the scientific claims that are made on a daily basis. In so doing, he educates his audience about basic concepts in science and, rather like a literary or film critic, enables his audience to engage with the science *critically* to the extent that they would be happy to have a conversation about science.

The modernist conception of science may be one that sees it as a hall full of awe and wonder. However, as Beck (1992) has pointed out, our relationship with science has changed. Bhopal and a litany of other incidents has taught us that science and technology are a source of risk as well as a source of solutions. Moreover, science does not exist in some value-free space of detached objectivity. It has its own internal values and the implications of the knowledge it offers raise wider issues of value. Opening up the space to engage with such issues in the science classroom serves two functions. First it helps individuals to construct a deeper knowledge of the science itself as they are forced to grapple with scientific ideas. Second, and perhaps more importantly, it helps students to see that science is not a vast, monolithic castle of impenetrable speech but rather a cultural contribution of continuing significance whose salience requires enduring engagement. Or to paraphrase E.M.Forster – only connect! Only connect, science and critical engagement, then both will be exalted, robbed of their isolation, neither will die and both will flourish.

References

Adams, E. (1965). The logic of conditionals. *Inquiry, 8*(1), 166-197.

Ames, G. J., & Murray, F. B. (1982). When two wrongs make a right: Promoting cognitive change by social conflict. *Developmental Psychology*, *18*, 894-897.

Bachelard, G. (1968). *The philosophy of no: A philosophy of the new scientific mind.*(G. C. Waterston, Trans.). New York: Orion Press. (Original work published 1940)

Beck, U. (1992). *Risk society: Towards a new modernity.* London: Sage.

Collins, H. (2000). *On beyond 2000. Studies in science education, 35*, 169-173.

De Finetti, B. (1974). *Theory of probability: A critical introductory treatment.* Vol 1.Chichester: John Wiley & Sons.

European Commission. (2004). *Europe needs more scientists*. Report by the high level group on increasing human resources for science and technology. Brussels: European Commission.

Ford, M. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404-423.

Goldacre, B. (2008). *Bad science*. London: Harper Collins.

Gott, R., Duggan, S., & Roberts, R. (2008). *Concepts of evidence and their role in open-ended practical investigations and scientific literacy*. Durham: Durham University.

Harré, R. (1984). *The philosophies of science: An introductory survey* (2nd ed.). Oxford: Oxford University Press.

Horton, R. (1967). African traditional thought and western science. *Africa*, *37*, 157.

Howson, C., & Urbach, P. (2006). *Scientific reasoning: A Bayesian approach* (3rd ed.). Chicago: Open Court.

Hynd, C. R., & Alvermann, D. E. (1986). The role of refutation text in overcoming difficulty with science concepts. *Journal of Reading*, *29*, 440-446.

Johnson, A. (2009). *Hitting the brakes: Engineering design and the production of knowledge*. Durham: Duke University Press.

Kanari, Z., & Millar, R. (2004). Reasoning from data: How students collect and interpret data in science investigations. *Journal of Research in Science Teaching*, *41*(7), 748-769.

Koslowski, B. (1996). *Theory and evidence: The development of scientific reasoning*. Cambridge, MA: MIT Press.

Koslowski, B., Marasia, J., Chelenza, M., & Dublin, R. (2008). Information becomes evidence when an explanation can incorporate it into a causal framework. *Cognitive Development, 23*(4), 472-487.

Kuhn, D. (1991). *The skills of argument.* Cambridge: Cambridge University Press.

Kuhn, D. (1993). Science as argument: Implications for teaching and learning scientific thinking. *Science Education, 77*(3), 319-337.

Longino, H. (1990). *Science as social knowledge: Values and objectivity in scientific inquiry.* Princetown, NJ: Princetown University Press.

Millar, R., & Osborne, J. F. (Eds.). (1998). *Beyond 2000: Science education for the future*. London: King's College London.

National Academy of Sciences: Committee on Science Engineering and Public Policy. (2005). *Rising above the gathering storm: Energizing and employing America for a brighter economic future.* Washington, DC: National Academy Sciences.

National Audit Office. (2010). *Department for education – Educating the next generation of scientists.* London: National Audit Office.

Ogborn, J., Kress, G., Martins, I., & McGillicuddy, K. (1996). *Explaining science in the classroom.* Buckingham: Open University Press.

Osborne, J. & Dillon, J. (2008). *Science education in Europe: Critical reflections*. London: The Nuffield Foundation.

Osborne, J. F., & Collins, S. (2000). Pupils' and parents' views about the school science curriculum. *School Science Review, 82* (298), 23-31.

Osborne, J. F., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. *International Journal of Science Education, 25*(9), 1049–1079.

Rogers, E. M. (1948). Science in general education. In E. J. McGrath (Ed.), *Science in general education* (pp 1-23) Dubuque, Iowa: Wm.C, Brown Co.

Royall, R. M. (1997). *Statistical evidence: A likelihood paradigm.* London: Chapman & Hall.

Watson, J. D., & Crick, F. H. C. (1953). A structure for deoxyribose nucleic acid. *Nature, 171*, 737-738.

DISCUSSION

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Q1: I have a question that is related to educating children. I am going to give an example of my daughter who is 4 years of age. She had the intuitive understanding that everything needs rest, so she asked me, where is this house kept, where is this *dharti* - earth kept. I felt that I must tell her that at the moment I have no answer for you, your question is valid, but you will understand only later. So I went to her and tried to discuss, but she just didn't pay any heed to me, she was happy with the question. So the point which I am trying to make is that while developing a concept, a person may like to have a pause in between. What I am trying to say is that let students have some misconceptions, gradually they will come up with a good understanding.

JO: I think I don't disagree with you. What Bayesian statistics tells you is that the business of educators is changing the amount of probabilities. And what it also says is that we are not going to do that necessarily, particularly when there is an alternative hypothesis that people have about any particular example. If the idea is strongly entrenched, they are going to take time. People need to consider these, they need to weigh the arguments and rushing them isn't necessarily the best thing to do. The mistake in science education is - not more questions, not what can you explain, about a particular kind of phenomenon, like why a puddle disappears, but what I'd like to see more is the case where students are asked to explain why some thing is wrong. So you get examination questions for instance - here is an idea or hypothesis put forward to explain let's say the cause of day and night. The example we are using - explain why this answer is wrong or why this hypothesis is wrong. Because I think that would encourage the teaching of science from where it is transmitted and where teachers lay out what is the standard in scientific explanation to one where they actually think how they develop a skill in students, not only to explain why the right answer is right but also to use that knowledge to justify why other answers are wrong. That is why I think with the example of day and night, a student is explaining why a lot of things are wrong. I am not sure if that answers your question but I don't disagree with your basic premise of time. It needs time to change your ideas.

Q2: Thank you for your informative lecture. I agree, those ironies exist and we need to remove them. In order to do that I feel there are two critical aspects - one is teacher education and the other education of parents. Because, teacher plays an important role and he or she would decide what is to be assessed or evaluated which determines what is to be remembered and what is to be reproduced. So do you have any specific suggestions to educate the parents and teachers so that these ironies are removed?

JO: About parents, it is much more difficult and problematic. In education one needs to be an optimist and I still remain an optimist. I think the key to what happens in the class is strangely enough, not curriculum but assessment. And teachers read the intentions of the curriculum, not so much from the curriculum documents but from the examination questions that students are going to have to answer. If we can transform or change the examination questions so they require more critical thought and engagement then you will see a slow recognition by the teachers that they need to teach a different set of competencies and skills. Now you might say why am I optimistic, after all we have been assessing science for the past, around 50-100 years and predominantly most assessment is low-level recall. Well what is coming on the horizon is much more computer based assessment, and I think that is interesting because there are many more forms of questions asked when questions are represented on computers - these can be dynamic, and they can be simulations. You can also ask for or have an extended answer-questions on computers. Here in America, the college learning assessment system is developed by my colleague Richard Shavelson who has developed a computer based system that has a good reliability. Although I think this would go about trying to change our construction or conception of what science education is. In the sense of these large scale assessments like PISA or TIMMS, there is a need of frameworks that drive their assessment. Changing that conception I think is significant. But really what matters more is changing the assessment.

Changing parents' conception is a much harder task and you can see this not so much being played out in the context of science education but played out in the context of mathematics education where any changes in the curriculum are met with large resistance from many parents. Here what one has to point out is that parents want a student to enjoy school. If you ask many parents about their own experiences of school science – it's not very positive. So my advice is that you can use this to say – did you enjoy your science in school? What we are trying to do is now trying to improve the quality of experience. This may not be easy, but I think this kind of experience where you have to explore ideas will engage more students with science. I think it would work because what they find very difficult about science is that it seems to them there is nothing that they can offer, or engage with. It's either take it or leave it. But once you start to speak about ideas which have to be evaluated and argued for and ideas where you have to change your thinking then I think it will change students' conceptions to some extent. Student engagement would lead to students who are happier and students who are happier make parents who are happier. And the course would change and that's what I would look to.

Q3: I completely accept your argument that critical engagement is essential in the classroom. However, I think all of us are also aware that it is very difficult with the kind of teachers that we have. So, don't you think that it is much more easier to do though it sounds equally difficult but I think it is easier if you bring in History of Science (HoS) in the classroom. By bringing in both bad as well as good examples of science in the process, critical engagement becomes much more easy. The teacher is expected to actively engage in the discussion which is much more difficult than bringing in HoS, so what do you say about that?

JO: I am a great enthusiast of HoS because I think there are so many examples over there. The example I am using in my talk is an example from HoS. I mean there is much more to it than simply trying to present it because the arguments for the Copernican idea were played out over a long period of time. I see what really is very interesting is that in the HoS, the Copernican idea was accepted long ago before there was any empirical evidence. But there is a kind of warning I want to give you about HoS. One has to think very carefully about how to incorporate these kinds of examples. In my personal view, we much rather prefer history as something to be looked at, the kind of debates that happened and why. So to some extent that is what I tried to do with the example, just picked out what were the arguments for, and arguments against, and to look for examples of that nature. Michael Matthews in his book, gives some very good examples. I think about the argument about Toricelli's vacuum, it's not the kind of tool that is going to be taught and repaired by teachers. So there is a problem with teaching HoS. Basically, history taught by science teachers was bad history and science taught by history teachers was bad science. One has to pick examples of history that are not too difficult. But if you attempt to teach historically in-depth, then there is a danger that students will think those people were stupid or silly. Of course those people were not stupid or silly, they were in the cultural context of the time and they were limited by the resources they actually had. So, I still think, we are very enthusiastic about HoS for some of the reasons that I gave in this talk.

Q4: I cannot think of a single example where Occam's razor failed. But I was just wondering whether one could make an argument, could one not argue that it is procedural knowledge rather than epistemic.

JO: I don't know what the argument would be. My response would be that it is really an issue of values. There is always a notion of reductionism, which is that we always tend to look for simplicity and elegance, and solutions which are not simple are treated with doubt and disdain. I mean, in some sense, there is a reason historically that the Ptolemaic account fell apart, it just looked more complex and nobody really wanted to believe that actually the universe was that complicated. The virtue of the Copernican account was that it was simple. To some extent, it wasn't any better or worse in making predictions about the motions of planets. So I do think because it is a value, I would classify it as epistemic knowledge and not procedural knowledge. Given two competing views and there being not much to choose between them necessarily, what you resort to, is on the basis of procedural knowledge. But there is another argument that I need to make -- any authentic kind of scientific reasoning calls for at least two dimensions of knowledge - procedural and epistemic. In reality you also need both kinds of knowledge whether classified as procedural or epistemic.

Q5: You made this very important statement that the Copernican model was accepted long before the evidence for it was there, and you know both of the evidences that you gave against. The Foucault pendulum was not available when the Copernican model was accepted. So what worries me about this is that your formulation in terms of hypotheses and evidence is completely, entirely verbal whereas an understanding of day and night has, I think, a strong visuo-spatial and embodied aspect to it. And if one wants to get across arguments of this kind, I believe it cannot be done entirely through a verbal argument. We have been working in this area – astronomy and children's' understanding of day and night and its pedagogy. We have used gestures and diagrams in order to make these arguments and explanations plausible to students. So the plausibility does not come out of logical arguments, it comes out of seeing it visually or experiencing it with your body. So, I would say that some of this knowledge is not explicit, it's embodied and after all it is a matter of personal conviction that one has which is not always expressible in words. I was wondering if this modelling fits in your Bayesian framework, and where do you put it, because it is neither hypotheses nor evidence.

JO: I think my argument is presented verbally because that is how I am presenting here and now in that sense. But if you want to start to capture an understanding of the Copernican account you need to engage in what I call the practice of modeling and that modeling can be models where you draw diagrams or watch computer simulations. One of the things I do when I teach elementary students is, I work out an explanation with this model - one of you is the sun, one of you is the earth. If you were using a Copernican explanation that would be very different than where you would be using the geocentric explanation. Actually in some senses you have to enact, move in that kind of way. If I have given the impression that all arguments are verbal, that's a mistake because scientists make their arguments out of models, representations and visualizations. I mean contemporary chemistry high school very much relies on building models and in some sense, manipulating these models and thinking what might happen and what are the alternatives. Modeling or the teaching of modeling is a very important practice. If you build a model then you run the model and convince yourself that actually the argument is plausible. It becomes evidence and the model in some senses is the evidence to convince oneself - I have seen how it works, yes it is true. I did not have time in this talk to mention one of the pieces of work I am currently involved in as a member of the National Academies who are trying to write a set of framework of common core standards in American science education wherein emerges an idea that science should be taught through offering to students opportunities to engage in a set of practices, one of which is modelling of the kind that you were talking about and not set of arguments and critiques.

Q6: I am not quite sure, if I understand that the world goes around the sun, what difference does that actually make to my world? There is an interest issue in what phenomena we actually choose to deal with. For young people, if you were to pick a set of phenomena to do the arguments for, arguments against, that is critical and that's the challenge from your perspective and I just want to know what perspective you pick.

JO: I will resort to physics, I think one needs to understand that people have difficulty with Newton's third law because basically it is articulated in a way - forces are equal and opposite - and because then you think the logic is about the forces being equal or not equal and opposite then force is equal to zero and then why do things move? So you have to give experiences that enable people to see where the flaw in a particular argument is.

You know, I think basically the phenomenon is kind of a contrary hypothesis, standard misconceptions that people have and these are the ones that you really got to spend a lot of time exploring - why there are misconceptions otherwise they will remain misconceptions. I have taught Newton's third law, one norm is to state that it doesn't make sense to me, this is a bit radical, but I think it is really a point where people might engage. There is an instance where a teacher who used to teach about man landing on the moon found that every year some of the students said they do not believe it and that it is all conspiracy. They had to argue why or how it is a conspiracy.

Q7: I want to go back to your question on History of science. While there is global awareness of Needham's data on Chinese science, I want to shift the focus to fairly rigorous amount of work done in history of science in India. In Delhi, the National Academy of Sciences published the works of history of science in India. This has raised interesting discussions. Do you think in a non-western context, or western context, histories whether correct or wrong, should be included in the discourse. There is evidence of blood circulation theory much before Harvey. The evidence of Copernicus, Tycho Brahe, have been preceded in the Kerala region by a system of mathematics that was about hundred years earlier. When you come to those questions some of them are very tightly documented. How does one go ahead?

JO: That is a good point. My instant response to you is that it is a complex question. I can give some bits of the answers and I am not sure how much they weigh out. I think it is tremendously important that all education systems are in some sense bodies of knowledge that societies themselves help to form the identity of the next generation. In that context, history of what people or that culture have done in the past is tremendously important. So if you have science education, say for instance, in India or China which totally neglects what anybody in that culture has done as contribution to science, or somehow nobody in that culture ever engaged with that activity, then I think that is a mistake. The question is how do you incorporate these kinds of elements into your science education as well as, all those standard canonical science which has been a product of western society as science. I do not think that is very easy but I do think that making the case for little bit more history of science in a curriculum where you require students in education to at least engage in one or two case studies is important. I do think that in textbooks we should explicitly make reference to how science was undertaken in that society.

At the same time I cannot answer what is it that led to science being at the forefront in western societies. I do think it is very much a contingent accident. It just happened to be that society in that period of time was unique to share the kind of endeavours going on. You also need a sensibility that you need to show the contingent nature that is why I mean there is a very interesting story. Harvey studied circulation of blood in heart. He was English but worked in Italy where all the interesting work was happening in the 16^{th} and 17^{th} century. So there is something about the cultural context going on and how do you do that and I do not have easy answers. Although I think I would want in any kind of science education to require students to undertake extended studies by one or two examples of HoS which would have been scientific in that society. I think what you are pointing to me is that we are each a product of our cultural environment. I am very much a product of western environment and thought about western science. Here what is happening is that some-things are not well documented. In some sense it is the responsibility of the community to rehabilitate that and show that this activity has been going on and if necessary an element of it could be a feature of the science curriculum.