Inaugural Lecture given by Professor Jonathan Osborne

King's College London

Thursday, April 29th

It is a honour to be invited to give such a lecture and I have to start by thanking so many of you for coming to hear what I have to say – something which, in itself, is almost as much of an honour. For those of you who are unfamiliar with the format of an inaugural lecture, it is supposed to be comprehensible to the educated layperson. So, rest assured, even if your knowledge of science is sketchy or missing large parts, I shall not attempt to baffle you with science. Indeed, in contrast, my mission is to attempt to show you that there is much in science, which is not only readily comprehensible, but also significant to the issues that confront you in your daily life.

My title for this lecture is 'Science Education for All: Radical vision or hopeless fantasy?' [OHT1] My case essentially is based around one question – how does the public judge what is good science? In essence, what skills, knowledge and expertise are necessary to develop a sense of scientific connoisseurship that enables the lay person to discriminate the good from the bad in the context of science? 'Why? you may ask, 'might that might be necessary?' Let me illustrate with two examples captured from my life in the past month. The first comes from no less august an organ than the East Oxford Green Party newsletter with a column reporting the activities of their European MEP. The column begins with a statement of concern about the threat posed by these [OHT2] mobile telephone masts which now litter the landscape. [OHT3]

'Ban **radioactive** TETRA masts – Caroline [the green party Euro MP] has called for a region wide moratorium on building 'Tetra Masts' until questions about the safety of their radiation emissions have been answered'.

Making the judgement that this is bad science is simply dependent on a knowledge that the radiation emitted by radioactive sources is produced by a different mechanism to that produced by a mobile telephone mast. One, a radioactive source, is unequivocally dangerous in excessive doses whilst the hazard posed by the mobile telephone mast is indeterminate and unknown, if it exists at all. I can only say that I hope that the residents of East Oxford are not living in mortal fear.

My second example, a more serious one, is a report on BBC2 about daily life in South Africa for black Africans, engendered by the recent elections. Amongst the many stories was one focussing on the chronic level of violence and that one of the reasons for the high incidences of rape is that there is a belief amongst elements of the African community that having sex with a virgin can cure HIV. Actions that are taken on the basis of such poorly warranted beliefs are not something that I wish to discuss here but this example, in particular, illustrates how even a little reliable scientific knowledge – what I wish to characterise as 'good science' can radically change people's lives.

More fundamentally, what these stories illustrate is the first of the principles that has driven me and so many others engaged in education – essentially a commitment to the notion that knowledge is liberating. For as Jefferson so aptly put it – those who are ignorant and free never have been and never will be.

What these stories illustrate is that the ability to determine bad science from good science *is* dependent on some basic conceptual knowledge. This in turn engenders two questions: [OHT4]

1. How much conceptual knowledge?
1. What other kinds of knowledge are necessary?

In some senses, the trivial answer to the first question is anything. The person who knows some science will always be advantaged compared to the person who knows none when faced with scientific dilemmas. And undoubtedly, there is a debate to be had here about the amount and the detail of the conceptual knowledge in either the formal curriculum, or in the wider informal sphere. My focus of interest, however, is the second of these questions as this is the locus of the argument I wish to advance tonight.

To make my argument I must begin by attempting to define, at least briefly, the contemporary scientific landscape in which science education is situated.

In doing so, I acknowledge that this is not an impartial account. I happen to be still one of science's true believers – by that I mean that I believe that the scientific endeavour has been the major influence on our culture offering us enormous material advances in our standard of living. In fact, I would go even further if I had time and argue that science is *the* major achievement of Western European culture. When you consider that a little over 400 years ago Giordano Bruno was burned alive at the stake in the Campo del Fiore in Rome for preaching that the Earth went around the Sun, you begin to have a sense of the magnitude of the journey that contemporary civilisation has made. Fortunately, Bruno is now feted with his own statue on the spot where he was burnt and even the Vatican, albeit 359 years later have publicly admitted that Galileo was correct.

And, lest we forget, to give two examples of how the wonder of yesterday becomes the commonplace of today, this used to be the effects of smallpox even as recently as 1923 [OHT5], an incurable disease whose horrendous effects have now been eradicated. Likewise, thanks to penicillin, discovered fortuitously a mere 6 stops on the Bakerloo line from here, deaths from infectious diseases have been reduced by a factor of 37 as this graph shows [OHT6]. To the more mathematically minded, a rough calculation would suggest that in this country alone, antibiotics have saved 4.8 million lives. Worldwide the number must be at least an order of magnitude greater.

What science offers us culturally is two things that excite– one is the potential to create your own knowledge – the opportunity to liberate yourself from the shackles of received wisdom. Even young children realise this as, when asked what they like about science, they will say 'science gives you the opportunity to do experiments and find out things.'

An excellent illustration of this excitement comes from the following extract from the Horizon video portraying the discovery of DNA. A video which I urge people to beg, borrow or steal – a fascinating story in its own right but a wonderful insight into the scientific community. Here, in this clip which has been borrowed many times as you will see from the quality, we see James Watson spelling out to his sister, at a conference in 1950 in Naples, the glittering prize that lay within his grasp and attempting to get her to befriend Maurice Wilkins, one of the two people after whom this building is named and an emeritus professor of physics here at Kings.

[Show clip 1 OHT7]

Unfortunately for James Watson she failed in the task she was assigned. But more importantly perhaps, this clip also reveals the second feature that excites about science – that sense of awe and wonder at the material world – in this case that every cell contains the information necessary to replicate a whole human being – 'our little bit of immortality'. A sense of awe and wonder that is captured for some by the idea that every human being contains 50 miles of blood vessels or that there are as many stars in the Universe as there are grains of sand on all the beaches in the world.

It is undoubtedly one of the tragedies of contemporary life that, not only here but in the United States, that in formulating a national curriculum, essentially out of a genuine desire to insist that all experience such knowledge and insights, we have lost sight of what really matters. For there seems to exist in education some kind of uncertainty principle. For those of you who do not know of Heisenberg's uncertainty principle what Heisenberg revealed is – that at the microscopic level there is a fundamental indeterminacy in the Universe – the more accurately you measure the position of an object, the less certain you are of its velocity. In education, the correlate of this is that the more we attempt to define what should be taught, and to measure it, the more we lose sight of what its core values are – a statement which is true not only of science but also of mathematics and English.

Watson and Crick's achievement was to achieve closure – the moment captured in this second clip when he realises that the isomorphism of the base pairing in DNA offers a means of self replication– the moment in Watson's own words when they ‘winged into the Eagle [the local pub] and announced that they had discovered the secret of life [OHT 8].

At that moment something whose structure had been indeterminate – glimpsed, so to speak, through a glass darkly, suddenly became determinate and known. Their story illustrates another feature about science – that is its ultimate aim is closure and certainty – closure and certainty in a manner that the humanities fundamentally fail to offer. For, in the case of humanities no matter how good an account you may read, for instance, about the 2cnd World War, it is always open to reinterpretation or re-evaluation of the evidence. From the perspective of the historian, our understanding of the world may increase but, because it involves humans and the complexity of human actions, there is agreement about little more than the facts.

However, science’s potential for closure engenders two problems. First, the sciences attract those whose seek such an absolutist epistemology– the idea that knowledge is based on assertions which can be checked and shown to be either false or true. For individuals such as myself science, at least in adolescence, offered an island of certainty in a sea of doubt. For science, this is unfortunate as it actually requires those who take a critical, evaluative stance where reality is viewed as not directly knowable and critical thinking is valued as a means of judging differing claims to knowledge.

Second, the notion of closure or uncertainty is problematic for science itself. For whilst the ultimate goal of science may be closure, the path to closure is strewn with controversy and uncertainty. Yet this is not the impression that the future public gets from their formal science education. This misrepresentation of the scientific enterprise by school science is deeply problematic – a problem whose nature is has been succinctly articulated by Sir Herman Bondi, formerly a professor of mathematics here, and one time scientific adviser to the UK government. [OHT 9]

'When on some issue different scientists hold differing views, journalists speak of of "this extraordinary scientific controversy". When I tell them that controversy is normal in science and is indeed the lifeblood of scientific advance, they find it hard to believe me. The public tend to think that at least some of the scientists involved in

such a controversy must be venal or incompetent or both. These views arise partly from the conflict between the popular view that scientists are 'objective and dispassionate' and the normality of active arguments, yet people are unwilling to abandon their view. Moreover, the piece of science most people are familiar with is the Newtonian description of the solar system. The rigid predictability of this is taken as a model of what all science should be like. When this expectation is not fulfilled, there is disappointment.'

Transforming this impression means that school science must raise the epistemic question of 'how we know' as a recurrent theme – to demonstrate that path to certainty goes through the foothills of uncertainty. Asking the question of 'how do you know' of the general populace and, for that matter, teachers themselves, reveals the shallow foundations on which so much of our knowledge rests. For instance, how do we know that day and night are caused by a spinning Earth? This so-called trivial piece of knowledge is such a commonplace that it is taught to primary school pupils. Why, you might ask should they believe it? After all, there are good arguments to refute it.

If the Earth was spinning, you should not land on the same spot.
If it is spinning, once a day, the speed at the equator is over 1000 miles an hour which should fling most people rapidly into space.
And, surely, at that speed, there should be the most enormous wind as the earth runs ahead of the atmosphere which drags behind.

Looked at like that, I would hope you would agree, that the accepted scientific explanation seems less self-evident. Now lest I lead you to doubt the Copernican world-view, I should show you the counter–evidence. The first direct observable evidence came from the demonstration in 1851 by the Frenchman Foucault here [OHT10] at the Pantheon in Paris of a massive pendulum. When watched over a number of hours, as this diagram illustrates, the plane in which the pendulum swings appears to move during the course of a day [OHT11]. The explanation is not that the pendulum was moving but, rather, the Earth beneath it. The second piece of evidence come from this photograph taken by a camera pointed at the Pole star with its shutter left open for 8 hours[OHT12].

There are two competing explanations for this photograph. Either the camera is turning, or all the stars are turning around a single star. How do we decide? We can't. However, we can apply a principle first advanced by a 14th Century monk William of Occam which is that when confronted by two competing explanations – pick the simplest. In this case, the camera sitting on a turning Earth explains it all. If we were to pick the second explanation, we would have to explain why all the stars appear to rotate around one single star. What, for instance, is so special about that star? Thus, even in primary science, it is possible to expose one of the values that lies at the heart of science.

The scientific explanation stands because (a) it is impossible to refute such evidence and (b) we can justify why the arguments for a moving Sun are wrong. This illustrates two features of science – that scientific ideas are those that stand the test of time and, second, that knowing why the wrong idea is wrong is as important as knowing why the right idea is right. Scientific literacy depends as much on the ability to refute and recognise poor scientific arguments as much as it does on the ability to reproduce the correct scientific view. This is why my work and others has been centrally concerned with exploring how such ideas can be presented so that students can begin to appreciate that argument *is* a normal feature of science.

There is, however, another reason for why addressing the question of how we know is so important. For me an argument that was elegantly articulated nearly 40 year ago by Horton who argued that unless we address such questions:

'the grounds for accepting the models proposed by the scientist are often no different from the young African villager's grounds for accepting the models propounded by one of his elders. In both cases the propounders are deferred to as the accredited agents of tradition.....For all the apparent up-to-dateness of the content of his world-view, the modern Western layman is rarely more 'open' or scientific in his outlook than is the traditional African villager.'

Science may have been responsible for the dawn of the enlightenment but it would seem that it has yet to reach its classroom.

Moreover, the need to educate individuals to resolve uncertainty, to evaluate scientific argument, is made ever more pressing by the kind of scientific dilemma posed by science for the contemporary citizen. Let me illustrate this with two recent examples.

The Case of Lead in the Environment

Should we be concerned about lead? The data that would support the assertion that we should comes from a long series of studies on the neurotoxicity of lead. The results of the most recent are presented in Fig 1. A noticeable feature of is that it suggests that none of the studies on their own have provided a definitive result – in each case the 95% confidence interval intersects with the vertical axis which would show a null result. That meant that, in 1995 there was at least a 5% chance that each positive result was a random artefact. When the data from the four separate studies were pooled, however, and meta-analysed, the larger effective sample size produced a distinctly more robust conclusion. The line that represents the combined results from all four of the studies provides clear cut evidence that an increase in lead levels from 10 to 20 μg/dL results in a deficit of approximately 2 IQ points, and that there is less than a 5% chance that the conclusion had been reached accidentally.

In the case of lead, therefore, the evidence indicates that a detailed knowledge of the ways in which representations of lead toxicity have been constructed enables us to appreciate that that particular area of scientific knowledge has become increasingly reliable and precise; and many of the assertions made by regulatory scientific institutions have become increasingly secure. While that conclusion may fall short of that required to produce total certainty or consensus, the evidence is strong enough to satisfy all but the most perverse and recalcitrant members of the scientific community. In short, – a judgement warranted by 'good's science.

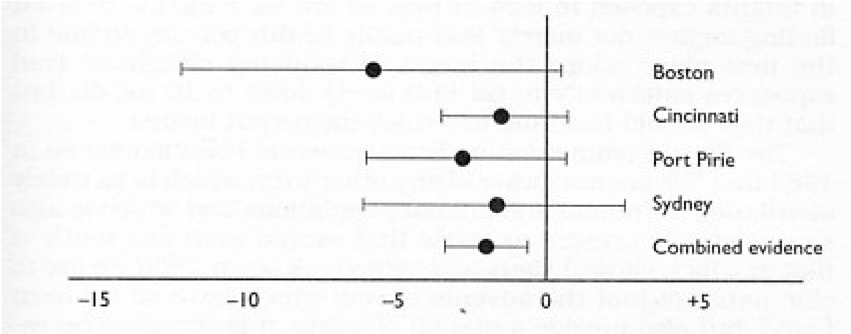

Fig 1: Estimated mean change in IQ for an increase in blood lead level from 0.48 to 0.96 μmol/litre (10 to 20 μg/dl) in prospective studies [OHT13].

Participating in the argument about the environmental impact of lead requires sufficient knowledge to interpret the information I have presented graphically, particularly in this case, the meaning associated with error bars. It also requires some understanding of how the level of certainty surrounding scientific evidence is typically characterised. To put this more prosaically, in the words of the latest Governor of California Arnold Schwartznegger – 'you can't bootstrap without boots'.

Now contrast the case of lead with another example – saccharin – where research begun in the 1970s with rats suggested that there was a possible link with incidences of bladder cancer. A bold attempt was made in the late 1970s by a US National Academy Sciences panel to estimate the upper and lower bounds of the risk that saccharin might pose to the US population. [OHT 14]. The panel estimated that if, on average, the population of the USA were to continue to ingest some 120 milligrams of saccharin daily for a period of 70 years (which corresponded to the average level of consumption in the USA in the early 1980s), it was unlikely that fewer than 0.22 extra deaths from bladder cancer would occur throughout the entire US population over that period, while, on the other hand, it was unlikely that more than 1,144,000 extra deaths would be caused. In other words, estimates of the potential carcinogenicity of saccharin for humans are characterised by uncertainty of **six** orders of magnitude. Yet, despite such conspicuous uncertainties, advisory bodies have continued to set Acceptable Daily Intakes to the first decimal place. Such judgements are not so much false as poorly warranted. In short, a case of poor science.

The Context of Contemporary Science Education

Now, let me turn to see where science education, my own specialism, finds itself situated in contemporary society. Science education wrestles with a tension which no other curriculum subject suffers. In a very fundamental sense, the subject is still a training for the next generation of scientists, engineers, doctors, vets and technicians rather than an education for all. Its function is essentially a pre-professional training for the scientist-to-be or, to resurrect a somewhat archaic word in the English vocabulary that summarises that elegantly in one word, its function is essentially propaedeutic. Much of the current concern about the state of science education, including the report published by the House of Commons Science and Technology committee which I acted as an adviser to, is driven by a deep sense of unease about whether we will produce sufficient scientists and technologists to sustain our economic competitiveness.

The problem is exacerbated by the fact that science does progress in a cumulative way in a manner which art does not - so its discourse inescapably deviates increasingly from that of everyday life. The contemporary scientific paper bears about as much resemblance to that published 200 years ago as chalk does to cheese. Learning the discourse of science thus requires a long apprenticeship which must begin in school if the neophyte student is to acquire the conceptual understanding required for its contemporary practice. The trouble is that this can only be achieved, as our research has found, by frogmarching young students across the scientific landscape such that there is no time to stand and stare – to consider how we arrived where we are, and the achievement that represents. This, for example, was one students' typical comments on her experience of school science from some research we conducted 3 or 4 years ago: [OHT14]

Keiran: *It's all crammed in, and you either take it all in or it goes in one ear and out the other. You catch bits of it, then it gets confusing, then you put the wrong bits together and, if you don't understand it, the teachers can't really understand why you haven't grasped it.*

The tension for school science is that the training needs of science are best achieved by an authoritative and authoritarian introduction to a body of unequivocal and unquestioned knowledge. In short, it is one of the great ironies that a subject which, more than anything, has been responsible for making us all sceptical enquirers does so little to promote such a view in its own classrooms.

However, in contrast to the needs of the future scientist, the need of the future public, as I tried to illustrate with my previous examples, are best met by a rational examination of what counts as good science – developing the critical abilities to resolve the uncertainty inherent to science-in-the-making.

Unfortunately, the consequence of this tension is that the science curriculum serves neither of these purposes very well.

So in that context – what kind of education is needed?

Some would argue, and indeed they do argue, that it is unrealistic to expect science education to accrue additional educational goals. It is not difficult to make such a case. Let me present it – at least the shorthand form.

First, there is the issue that science is hard. The attempt to represent science as simply applied commonsense is undoubtedly a failed project. Commonsense tells you, for example, that: [OHT 15]

The Sun goes round the Earth
Plants get their food from the ground
You need a steady force to sustain a steady motion
Aeroplanes have no means of support
Heavier objects fall faster

Science tells you the opposite of all these ideas. Challenging and changing notions which are the product of everyday experience is no mean feat. Indeed the last of these ideas was a basic tenet of Aristotelian physics and took over 1500 years before challenged by Galileo.

Second is the issue that learning science does not require the learning of a single language but many. Science is now communicated using a multi-semiotic language of: [OHT 16-19]

Words: And here it is worth remembering that there is evidence that the average GCSE course introduces more new words to its student than the average course in a modern foreign language.
Diagrams [show slide for each of these]
Symbols and Models
Mathematics – here, for instance are the equations, derived by James Clerk Maxwell, the third King's professor I shall mention tonight, that describe the behaviour of radio waves, light, and the microwaves that operate your mobile phone
Charts and Graphs

The appropriate use of each of these forms has to be taught explicitly and their correct use learnt. Even then, the task is learning how to use these forms synthetically to communicate economically with others in the field.

Then there is the fact that scientists deal with three worlds:

1) At the basic level they produce description of macroscopic phenomena – the world around us;
2) then there are things which are too large to imagine or too small to be seen and only accessible via instrumentation;
3) finally, there are theoretical entities which are not even accessible to instrumentation such as some of the ideas of string theory.

Now, all of the interesting stuff in science happens in the second and third of these. And you can't go far there without resorting to a model or a representation of what might be happening out there in the real world. What, for instance, causes a rainbow?

Constructing appropriate models to answer such a question requires the introductions of variables which are causally related and have to be mentally manipulated. Most of this requires higher order abstract thought. Now, whatever, you believe about Piaget, and I do believe he has something important to say about the genesis of the rational mind, such science requires abstract thinking and is cognitively demanding. Given that the work of my colleague Philip Adey would suggest that only 30% of the population attain such capabilities by age 16, surely your sceptic would say, teaching such science to all is only a hopeless fantasy?

Finally, they will argue, that such a diet is unattractive to the vast majority. Such an apprenticeship requires discipline, commitment and application – virtues which most are lacking. For instance, here is a comment taken from the same research that reflects a dissatisfaction between science-as-taught and science-as-practised. [OHT 20]

The blast furnace, so when are you going to use a blast furnace? I mean, why do you need to know about it? You're not going to come across it ever. I mean look at the technology today, we've gone onto cloning, I mean it's a bit away off from the blast furnace now, so why do you need to know it?

This student has a point. Why? Any such science course is generally a treatment of the basic concepts or major stepping stones of the century. What, for instance, would you think the major scientific discoveries of the last century were if you were asked such a question? [Ask question of audience then show results beneath]

	%
DNA	27
Splitting the Atom	21
Silicon Chip/Microchip	21
Space	19
Penicillin	18
Plastics/Polymers	15
Genetic Engineering	14
Computers	13

'The stepping stones of the Century'

And how would you expect students to answer such a question? [Show results after pause].

	%
Personal Computers	39
TV	24
Laser Technology	23
Space/Science Fiction	17
Video	16
Telephone	14
Motor Cars	7

‘The world around me’

Clearly, students arrive with the expectation that they are going to learn about the material world and are offered a very different fare instead which contributes to their sense of disappointment.

What is the problem with this argument?

At this point, you might be beginning to believe that I had made a good case for science being taught to some kind of Platonic elite – that any attempt to teach it the majority is doomed, best exemplified by the story about Dirac who, on being asked what he meant by the beauty of a mathematical theory of physics, replied that if the questioner was a mathematician then he did not need to be told, but were he not a mathematician then nothing would be able to convince him of it.

Those of you who know me will know that I do not believe in such arguments and think that they rest on a fundamental contradiction which goes unacknowledged.

My argument is twofold. First, any education in science must be a balance of four goals:

Conceptual – that is knowledge and understanding.
Cognitive – that is teaching people how to think and reason in science
Epistemic – addressing the question of how we know and how certain we can be

Social – that is ensuring that the experience is engaging, generating a sense of awe and wonder, fostering student curiosity about the material world, and providing opportunities for learning how to work with one another.

To place the overwhelming emphasis on the first of these four goals is exactly why students emerge with such a distorted view of science. It is as if we decided to teach about English literature through the medium of Chaucer and Shakespeare. And just as there is more to literature than this, so there is more to science.

The second part of my objection to such arguments are that they are fundamentally anti-democratic. We cannot, on the one hand subscribe to the notion of a democracy in which everyone has a legitimate right to participate and, at the same time, operate elitist practices which leave the majority of the population without the intellectual wherewithal to critique expertise and exercise that right. George Santayana made the oft-quoted remark that those who forget the lessons of history are condemned to repeat the mistakes of the past. Some of the mistakes of the past, in which the scientific community were at least implicated, lest you forget, were – open testing of nuclear weapons, thalidomide, BSE. These examples show that scientists and technologists can be as blind as the next human being when it comes to make decisions about the application of science and its possible effects. It is my belief that a more critical sceptical public might reduce our potential to make such mistakes. It is also my belief that scientists that better understood the limits of science might be less prone to making such errors.

Whilst I would concede that in today's society, the goal of intellectual independence is a myth, the reduction of intellectual dependence is not. For science students this means that - yes they should acquire beliefs about science; yes, they should experience some of the awe and wonder associated with the insights that science offers of the material world, but that they should also have the opportunity to acquire those beliefs after seeing and judging for themselves the sufficiency of the evidence. To present science without any concern for the meaning and justification of what is said, is to treat students with disrespect. Why? Because students have a right to expect from their teachers reasons for what teachers wish them to believe – as possessing beliefs that one is unable to justify is poor currency when one needs beliefs that can reliably guide action.

Confronted with any dilemma of a scientific or socio-scientific nature, the first question that the individual must ask is ‘Is so-and-so rightly regarded as an expert? How is the nonscientist to answer this question without relying on other scientists? How is the expertise of those other scientists to be judged? Would the nonscientist know which scientists' judgement would be relevant? Would the nonscientist know what questions to ask the other scientists, and then, how do they assess the answers to any questions they were asked?

If we continue to neglect the epistemic and cognitive goals of science we leave individuals with none of the critical faculties to answer such questions. This leaves them with two choices – either to accept whatever is heard or to reject what is heard – both of which are fundamentally irrational in that they are positions that have no warrant.

The crucial issue for most people, in any case when confronted by a political or moral dilemma on which science impinges, is deciding what is good science – that is to what extent are decisions made on the basis of scientific evidence justifiably warranted. So, should I get my child vaccinated by the MMR vaccine? Does driving a car or eating foreign vegetables contribute to global warming? Surely you might say the expert is the best person placed to judge what constitutes good science? However, would the same kind of thinking apply in arts – that the only person suitable to judge the worth of a book is the educated and informed critic. I think not – the function of a good language education is to give students the intellectual capital to help them adjudicate what constitutes good writing. Likewise, the function of a good science education is to achieve the same thing in the context of science.

Exactly which of the cognitive and epistemic aspects of science should form the basis of any education about science was the focus of a recent piece of research that we conducted as part of an ESRC funded project. In that case, we had to listen to the opinions of others as to what counted. As I now have the platform let me, in my closing arguments, make the case for the importance of a few elements that might broadly fall under the umbrella of epistemic goals.

First, it is important to understand that judgements about the validity and reliability of scientific knowledge are achieved through a process of peer review. That this is the scientific communities system of self-regulation and, that whilst it is not infallible, it is the product of a moral community whose internal structure is based on a network of trust and faith that in all matters the individual will act honestly recording observations accurately. Notably, the community manages to develop this value despite an education where you learn that the objective is to fiddle your result to match the agreed outcome.

Second, I think there is a need to educate people about risk. Risk has always been an inherent aspect of our society but in an era where people will sue at the drop of a hat, there is a false expectation that somehow risk can be eliminated. The issue here is risk management and the dilemma is most aptly posed by John Adams example of how to reduce road deaths to virtually zero. Adams radical suggestion is that if we seriously wish to cut road accidents, we should remove the seat belts from our cars and place instead a large sharp spike at the centre of the steering wheel. Such a suggestion brings home many of the issues associated with risk. For instance, the fact that we underestimate familiar risks – in this case driving a car particularly when we are cosseted by air bags and safety belts neglecting the risks to others, and that human adaptation to risk is a matter of perception. Further empirical evidence about our inability to make reliable judgements about risk comes from the following table, where if I was to ask you to make a judgement about which of these activities posed the greatest risk of dieing by age 40, I would guarantee that over half the room would get it wrong. Thus, in the spirit of science, let me put my hypothesis to an empirical test by asking you all to judge which you think is the most likely way of dieing by age 40 and we will see whether I am right. [Show list then show results]

Risk	**Rating**	**Probability**
All natural causes at age 40	2	1 in 850
An accident in the home	7	1 in 43, 500
An accident on the railway	10	1 in 500, 000

An accident on the road	4	1 in 8000
Being hit by lightening	11	1 in 10,000,000
Radiation/nuclear industry	8	1 in 57, 000
Homicide/Murder	9	1 in 100, 000
Influenza	3	1 in 5000
Leukaemia	5	1 in 12, 500
Playing football	6	1 in 25, 000
Smoking 10 cigarettes a day	1	1 in 200

More to the point any such set of figures as these immediately bring into question how we measure risk. All of these are based on mortalities and give no measure of other potential dangers associated with any activities. In addition, there is a distinction to be drawn between situations where the risks are identifiable, and to a certain extent measurable, and uncertainty where the risks are not even known such as the debate surrounding the human version of BSE and its transmission through the food chain. Fine, you may ask, but what has this to do with science and, in particular, school science? The answer in my view is everything. As much as you may wish to preserve a hermetic seal between contemporary science and school science, it is simply impossible. Advances in science and technology are what continually pose not only the ethical and moral dilemmas for our society but what I wish to call 'dilemmas of risk'. Let me reiterate that our young people are at the beginning of their lives – they are excited by what is to come not what has been; their vision is prospective not retrospective. For them, issues of risk are what permeate the cultural milieu of being a responsible and political adult – they do want a theatre in which to consider such issues. Here again, it is the voice of the student drawn from our research which best articulates this desire:

Tania: If you, like, give suggestions to discuss these issues they just ignore it and go –'No it's written in the syllabus that you've got to do this'. And it's just kind of fixed upon the syllabus and you're like, 'Well can't we just find a gap for it?' And they're, like, 'No'.

And since science and technology are responsible for raising these issues, science and technology education must take responsibility for providing some of the conceptual apparatus necessary to come to better critical judgements about their implications.

The third component that I would argue for is developing a sense of the uncertainty of science – that it, and its resolution, are a normative feature. It is here that I feel that zeitgeist of science education fails most significantly. Fixated as we are on consensual well-established knowledge, a product of the exact sciences, we have looked at this issue through the wrong end of the telescope. Let me give you one simple example. You can go into any year 7 science classroom and find a group of children all measuring the boiling point of water or for that matter the melting point of ice. Most of them will probably already know the answer – 100C. So why are they doing it, you may ask? A good question and one to which there are often not very good answers. What they will actually get for a variety of reasons, not least of which most of them are incompetent at using a thermometer, is a whole set of readings - 98, 103, 101 even possibly a 100C. The issue for the science teacher should not be 'Which one is right?' but a) Why do they vary? ; b) in a context where variation is a natural feature of measurement how do we come to a consensus about an agreed answer; and c) how can we reduce our uncertainty and express that in a quantifiable manner. To do otherwise is to present science as what it is not – the deliverer of fixed and absolute certainties.

So to conclude, my answer to my question in my title is not that such an education is a radical vision, rather that, for those of us committed to representing a more accurate picture of science as it is, and to providing our future citizens with some of the capabilities necessary to participate in contemporary society, it is a moral necessity. That science education for all is only justified if it can break free of the cultural sclerosis that binds science education to its traditional roots as a training for future scientists. In this form, it offers only a distorted vision of one of our most important cultural practices. Transforming that vision, is the project of the work that I have been privileged to undertake with colleagues both here and elsewhere, and which will remain the project of my work to come. Thank you for listening.