Nature of Science & How Not to Teach Science as Dogma

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BLURB: This article is an attempt to arrive at a broad understanding of what the nature of Science is, and what its implications are for science education, how science is taught today and what the shortcomings are.

Broadly, school science, and what is found in textbooks, has the following characteristics: (which I shall go into in some detail further on)
1. the appearance of some scientists as 'gods' who gave knowledge to common mortals
2. the experiments that are done are normally verification experiments
3. many of the experiments are not do-able, they are item-numbers

Starting with the first point – science textbooks usually list some 'great' people who had access to the secrets of the universe – Curie, Watson & Crick, Rutherford, Mendel, Boyle, Hooke, Newton, Darwin. The obverse of this is that some people are made figures of fun – Lamarck for one. The circumstances that gave rise to different theories, the data the scientists had access to, the equipment available at that time, these are never gone into. Knowledge is created in a certain social context, all knowledge, not just scientific knowledge, and often reveals its relevance only in that specific context. Also, this creation of demi-gods necessiates that the very human failings these scientists were prone to are glossed over. This leads students to believe that adding to scientific knowledge is beyond them, that Science is a finished body of knowledge, all of it contributed by these great beings.

School science does not expose us to the process by which this knowledge has been generated. We have not been given the data on which this knowledge has been based. We have not been told the proofs for this nor do we know what questions were asked, what doubts were raised. We are just given various answers. As an aside, I would like to add that school science also gives answers without the kids having any idea of what the question is.

Answers make sense when we have been grappling with a problem, some contradiction that does not fit in with our prior knowledge. Once a question arises in our mind, we strive to find a solution. When the students are given answers to questions that have not occured to them, the knowledge does not fit in organically with their schemas, their belief systems. So we have students and even adults who have very robust alternate conceptions. But alternate concepts, and how to deal with them is not the issue here, so I will not go into it. Hopefully, we can take it up some other time.

Anyhow, one of the major aims of science education is to encourage the spirit of critical enquiry, and it cannot be done if Science continues to be taught the way it is. We do not try to find out things for ourselves, we are only allowed to replicate certain experiments. Take for example the pendulum experiment. When we do the experiment in school, we already know that (within the limits of experimental error), the material, thickness of the string does not make a difference, the material and mass of the bob does not make a difference, the initial displacement of the bob makes no difference. We know that the time-period is proportional to the length (of the pendulum) and nothing else. We also know the value of g (acceleration due to gravity) that we are supposed to get from this experiment.

This has resulted in practicals being reduced to a ritual in most school systems. Many boards have got rid of practicals till class X, so they don't have to deal with such existential questions, and they can sleep in peace. But where experiments are done, even at the college level, whether it is a titration, or finding the frequency of a tuning fork, the whole process is a farce.

Let me explain why I am calling this a farce. Have you ever tried to demonstrate the first law of reflection? Do it honestly, draw the incident ray at 40°, place the mirror properly, align the pins, and then measure the angle of reflection. Do this for three more angles, in how many cases will you get the two angles exactly equal? When we actually do any experiment, take any reading, make any measurement, a whole lot of errors happen. Some of it is due to carelessness on our part and we can reduce this by taking due precautions. But some of the errors are due to problems inherent in the instrument, its limitations; and this will always be there. Then there is a whole range of variation in nature. Thus, if the students were to sincerely do the experiments, there would be as much variation in their records as there are in their faces and names. But instead of drawing the amoeba they see under the microscope, all of them copy the diagram given in one textbook and we sign the record without batting an eye-lid. Instead of reporting the value of g obtained from their readings, they cook up the readings to reflect the expected value. So they do not even learn any experimental skills, never learn how to actually minimise errors. For this is an important reason for all students carrying out the standard experiments, they learn how to handle various instruments, the careful handling of glass-ware, learn experimental skills and what precautions to take with each. Only then will they be in a position to use these skills when faced with a novel situation or problem.

We need to acknowledge the messy nature of data generated by the real world. There are random errors, errors due to limitations of the equiment, errors due to the limitations of our senses, background noise. Science (or scientists) still manages to make some fantastic claims, how?

In fact, measurement is a whole science in itself. If you were to get all the students in a class to measure the length of their class-room, you would be amazed at the variation that is reported. Same is true of any experimental reading. Measure the time taken for 20 oscillations with a pendulum which has a length of 50 cm. You get some reading. Get your friend to repeat the experiment, repeat it yourself, you will get three different readings. There will be some time lag in starting and stopping the stop-watch (there will be the response time too – you see the oscillation being completed, then you still take a split second to press the button of the stop watch, all of you might be having stop-watches in your mobile phones, see how fast you can start the timer and stop it – this is your response time). This error will be more or less built into any reading that you take. One way to reduce the error due to this is to take the reading for 20 oscillations, not 1. It would be even better if we take the reading for 50 oscillations.

How does anyone make any measurement then? Methods have been worked out to reduce random and systematic errors, and any truly scientific study always reports the error inherent in their readings. Graphs will show the extent of variation in data with error bars.

Then there are the experiments and activities suggested in the textbooks to illustrate the concepts covered. The problem with many of these activities is that they don't work, or they don't work in the manner described, or they are showing the effect of some other phenomenon. Take for example, the activity given in primary school to show that air is matter, that it has mass. You weigh two balloons on the two pans of a balance, make sure they balance and then fill one balloon with air and show that this balloon is now heavier than the empty balloon. This activity ignores all the complications of buoyancy. Imagine trying to find out the mass of water in a bucket when it is immersed inside a tub of water. The difference in mass in the case of the filled and empty balloons is very slight, and might not show up on ordinary balances. And the difference is not due to one balloon being filled with air, but because this air is under pressure, that is, the 450 mL (say) of air in the balloon is under pressure and contains more molecules than 450 mL of air outside. Imagine filling this balloon with hydrogen gas, this balloon would then float and you would not be able to weigh it – er? does that mean that hydrogen has negative mass?!!

Another example is that of graphite and solutions of salts conducting electricity. If you use a 1.5 volt cell and connect it to a torch-bulb using wires of any metal, the bulb will glow. But if this same circuit includes a length of graphite (a pencil lead) or a salt solution, connected absolutely properly, the bulb will not glow. The conductivities of both graphite and salt solutions are very low as compared to any metal, so you will need to apply a much higher voltage to make the bulb glow in this case.

Why then have these experiments in the textbook? It is as if the textbook writers are paying lip-service to the experimental basis of science. They have a concept to convey to the students, and they dress it up with an activity which supposedly illustrates that concept in action. You find contradictions like this on a careful reading of textbooks, and if you try out the activities according to the instructions given because textbook writing is a joke in this country. There is no attempt to verify anything – neither the information given nor the activities. Two small anecdotes about this carelessness. One is about the amount of iron in spinach or paalak. The original study had reported an error, there was a problem with the placement of the decimal point, this seemed to show that spinach is a great source of iron, and we have Popeye the sailor becoming instantly stronger after eating spinach. That mistake has now been corrected in the primary literature, but our textbooks still perpetuate the old mistake. Similarly, we are told that the browning seen in sliced apples is because of their iron content – sorry, no!

The other is about finding an appropriate actiity to demonstrate the concept you want to convey. When the Eklavya team was working on a module on Heat & Temperature for high school, we wanted to show how the specific heat of a substance affected the rate at which its temperature would increase on being supplied with heat. We thought this was easy, we took the same mass of water and mustard oil (since we were trying this out in Indore, mustard oil was what was easily available) in two test-tubes and immersed them in a water-bath. We then monitored how the temperature of both changed at equal intervals of time. According to the figures we had looked up, the specific heat of the mustard oil was about 1/2 or 1/4 that of water and we thought it a safe enough margin to give us the result that we expected – the temperature of the oil should increase faster than that of water.

But, surprise, surprise! the temperature of water was going up faster than that of the oil. It took us quite some time to figure out that this was because the mustard oil was so viscous that the convection currents set up were slower, much slower. We had wanted to use cooking oil since it was likely to be easily available. We then tried out various other liquids to see what would work, we wanted something which was easily available, and at the same time had a specific heat sufficiently different from water so that the variation in the rate at which temperature increased would not be swamped by experimental errors. If we had started by saying take water and chloroform to do this experiment, it would be quite likely that the activity would not get done because of a lack of materials.

Hence, whenever Eklavya is part of any textbook writing exercise, we try to ensure two things, one that the experiments work as we describe them, and two that the materials for the activity will be available in the average school. When I was part of the NCERT team working on the science textbooks for classes IX and X, we had this teacher on our team who tried out all the activities in the Chemistry chapters with her students. In Chhattisgarh, we check with the teachers on the team and find out what chemicals are likely to be available in the school laboratory and then only plan the activity. Sure, you might be able to show some wonderful result with silver nitrate, but if silver nitrate is too expensive for 95% of the schools to buy, what is the point in talking about it?

Another small story as an aside – we keep reading about Rutherford and his gold foil experiment. It was only when we were working on this topic in Chhattisgarh and reading up about it that we found that Rutherford (or rather, his students) had tested thin sheets or foils of many different metals. How do you think the data would change when a silver foil is used instead of a gold foil? Since this is an experiment which is not understood by most students, discussing it in some greater detail, the different things that were tried, might lead to some of the confusions getting cleared.

And now back to our topic. After all this (content and experiments) is taken care of, there still needs to be space for open-ended investigations in the science classroom. Projects today ought to give space for this, but sadly, project-work is also a ritual in most places. Otherwise, the time given over to project-work could be used by the students to find out how the process of science can be used to find out answers to different questions, maybe some questions of their own.

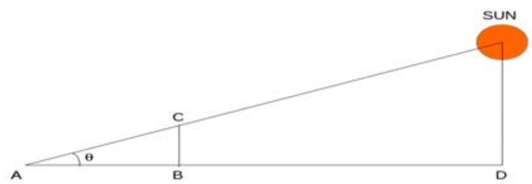
We try this out regularly in our teacher-trainings. This is a week-long residential affair, so in addition to regular sessions in which we deal with concepts which are part of the regular syllabus, we devote a lot of time to getting teachers to work on questions to which they would like to find out the answers. We start by asking everyone to list questions that have occured to them. Then we chose those problems which 1) can be worked on during the course of a week (for example, one question this year was how long wheat grains would remain viable – that is, germinate, this could not have been studied in a week) and 2) does not require fancy equipment like an electron microscope. I will give you a few examples of the kind of questions we worked on – 1) how little soap and water do we need to really clean clothes? 2) why don't we get clear ice, how can we get clear ice? 3) if we take a glass with some water and cover the top with a piece of stiff paper and turn it upside down, the paper sticks to the glass and the water does not fall out, why? (and we were able to show that the facile explanation using air pressure is not sufficient) 4) does twisting strings together make for a stronger rope? why? 5) can we find out the amount of iron and vitamin C in different foods? 6) how can we check the claim that the density of water is maximum at 4 °C?

It is not as if all these investigations lead to satisfactory answers. But the learnings from the process of exploration are immense, and almost all of the participants plan out a series of experiments to test the hypotheses that the team has generated, and learn to fine-tune their experiments. The teams learn from their mistakes, and learn not just about the phenomena that they are investigating, but also gain a first-hand experience of the process of Science.

Similarly, unless we teach Science as Science in schools – the process and not just the product, we will have to live with the consequences. I have already discussed the problems of accepting anything blindly, does coffee cause cancer? do cell-phones cause cancer? are vaccines safe? what is the importance of anecdotes on deciding issues like this? does event B following event A mean that A causes B? how do we find what causes B? There is a 'fact' being spread around in Madhya Pradesh that tulsi and banyan (peepal) are holy and they produce oxygen at night. How can anyone who has learnt about photosynthesis (which we tell kids about in middle school itself) not question this statement? We need to be able to recognise superstitions and pseudo-science for what they are.

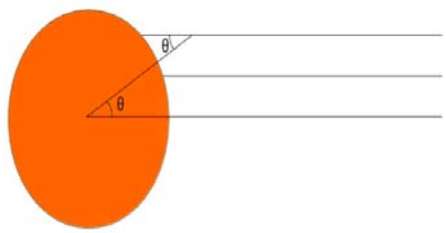
This tells us about one more essential feature of Science – every thing hangs together. Science does not concoct different explanations for different phenomena, nor are theories based on one stray observation. I shall use a very old story to explain what I mean by this. For a long time, people believed that the earth was flat. And at this time, there was an observation by some Greeks that when an image of the Sun was visible inside a deep well on a particular day in Siene (supposed to be modern Aswan), poles or pillars cast a shadow of a certain length in Alexandria. That is, the Sun was overhead in Siene, but not Alexandria. This observation, along with the known distance between Siene and Alexandria was used to calculate the distance to the Sun using simple geometry.

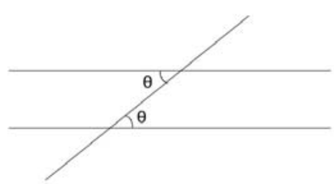
That is, ABC and AD and the Sun are two similar triangles that have a common vertex. Here BC is the post which is casting the shadow of length AB; and AD or BD is the distance between Alexandria and Siene. And since AB / BC is proportional to AD by DE (where E is the Sun); and AB, BC and AD are all known (can be measured), we can arrive at the distance between the earth and the Sun.



About two hundred years later (which was more than two thousand years ago), Erastothenes used this same observation – that on the particular day that vertical objects cast no shadow in Siene, shadows were of a certain length in Alexandria, to conclude that this showed that the earth was spherical and calculated the circumference of the earth (his calculation was remarkably accurate, by the way, only about 10% different from the value accepted today).

He also used simple geometry to do this calculation, the properties of parallel lines. He said the Sun was a source of light far away and this gave us parallel rays of light (there are many ways to show that, for terrestrial scales, the sun's rays are essentially parallel). These parallel rays cast no shadow in Siene while a post of a given height cast a shadow of a certain length in Alexandria. The angle θ could be found out, and this was the same angle made by the arc represented by the distance between Alexandria and Siene made at the centre of the earth. So if θ is known, and the distance between Alexandria and Siene is known, the circumference of the earth can be calculated using the unitary method.





So here we have the same observation being used to calculate two different things, that is, essentially, there are two different theories – that is, either the earth is flat (in which case, the distance to the Sun can be obtained) or the earth is spherical (in that case, the size of the earth, its circumference, can be calculated). How do we choose between the two? This is not done in an arbitrary manner, depending on whatever makes us feel good because the observations of the shadows in themselves can prove neither. We look for additional observations which lend weight to either of these two theories. Eratosthenes used three additional observations to conclude that the earth is spherical.

The first was from astronomy, travellers found that when they travelled north or south, though the constellations followed behind each other in the same sequence east-west, they moved to the south when one travelled north and to the north when one went south. That is, the constellations which were overhead in one's hometown moved towards the southern horizon when one went north, and towards the northern horizon when one moved more and more south.

The second was the experience of looking out for ships. When one watched a ship appear on the horizon and move towards the shore, it didn't just grow bigger, it was observed that the mast appeared first and then the lower portions of the ship. Likewise, when a ship sailed away from a port, the lower portions appeared to sink into the sea and the last portion of the ship to be seen was always the highest point – the mast or the flag. People on the ship also noted that the highest points on the shore became visible first – hills, tops of trees, towers and then only the beach. This was found to be true no matter in which direction the ship was sailing off – north, south, east or west. This can be observed in the hills too, for example, when one travels towards the Himalayas, first the tall snow-capped mountain ranges appear on the horizon, and only when one is much closer do the foot-hills (which are not even half as high) become visible.

Thirdly, there were numerous observations of lunar eclipses. The shape of the shadow on the moon was always an arc of a circle. It was known that the only solid shape whose shadow was consistently a circle, whatever the direction of the light and whatever angle the screen was placed, was a sphere.

From all these, Eratosthenes concluded that the earth was a sphere, and the flat-earth theory went out of the window.

Thus, in Science, we give more weightage to a theory that can bring together diverse observations and can make the most novel and unexpected predictions. For example, to explain the revolution of the earth around the Sun, we have Newton's explanation using gravity and we have Einstein's explanation that massive objects cause space itself to bend. Einstein's theory had an interesting consequence, if space was curved, then light should travel along this curve instead of in a straight line. Eddington managed to take photographs during a solar eclipse which showed the light from stars which were behind the Sun and this lent weight to Einstein's theory and led to its acceptance amongst the wider scientific community.

But we will continue to be swayed by piece-meal arguments and pseudo-scientific claims if we do not learn what Science actually is. The mish-mash of facts and concepts force-fed to us in schools teaches us nothing about what Science really is, nor do we learn how to use the process of Science to find out things for ourselves or assess the claims made by someone else. Hence, this is a heartfelt plea to everyone out there to bring about a drastic change in the way Science is taught in schools.