Teaching and Learning about Evolution and Natural Selection: Problems and Solutions

Karen Haydock and MC Arunan
Homi Bhabha Centre for Science Education
VN Purav Marg, Mankhurd, Mumbai 400088
haydock@gmail.com, mcarunan@gmail.com

epiSTEME-5 International conference to review research on Science, TEchnology and Mathematics Education, Proceedings, Homi Bhabha Centre for Science Education, 2013, pp. 106-112

We have analysed the difficulties in teaching and learning about evolution and natural selection. We have done this by reviewing textbooks and teaching methods, collecting data through questionnaires, and working with students and teachers individually, in classrooms, and in workshops in a few major cities of India. We conclude that students as well as teachers commonly have great difficulties understanding evolution and natural selection and using and integrating their understanding to analyse and evaluate problems in biology. We have found that the reasons for these difficulties are: (1) Evolution by natural selection is inherently difficult to understand because biology is complex; (2) Natural selection conflicts with our ways of thinking about the world, in particular with our tendency to think teleologically and our tendency towards idealistic or dualistic rather than materialistic ways of thinking; and (3) We may be lacking in sufficient scientific temper. We have developed teaching methods in order to assess and redress the problems we have identified.

INTRODUCTION

The problem of how to teach and learn about evolution in India is quite different from the situation elsewhere. In the west, particularly in USA, there has been substantial research to find the reasons why various people do not think evolution occurs. Researchers have found that the main causes are: (1) lack of understanding of evolution, natural selection, and the evidence for evolution, (2) lack of understanding of the nature of science, and (3) religious, political and social reasons (Allmon, 2011, Richards, 2008, Matthews, 2009, and references therein).

Although no one has conducted a survey or analysis of the general population in India, it is obvious, given the current state of education and literacy, that most people probably have never heard of evolution by natural selection. Since less than 5% of the population speak English and less than 10% of the population has access to the internet, this also limits contact with the subject (Satchidanandan, 2012, Wallraff, 2000). Perhaps the general population also does not have a good understanding of the nature of science.

We have found that even in elite institutions, students as well as teachers commonly have great difficulties understanding evolution and natural selection, and they also have difficulties using and integrating their understanding to analyse and evaluate problems in biology. We have found that this is related to their lack of understanding of the nature of science. In this report we will discuss these problems, the evidence, and analyse the

reasons for the problems. We will then discuss the teaching methods that we are evolving in order to address these problems. Finally, we will discuss the possible reasons for the teleological thinking which makes it hard to understand evolution by natural selection.

METHODS AND PROCEDURES

The methods we have used to study how biology teachers and students teach, learn, and think about evolution have been mainly qualitative case studies conducted in workshops and classrooms from 2007 to the present with students and teachers from a few dozen schools and colleges in Mumbai, Delhi, Pune, Hyderabad, Indore and areas near these cities. Most of the students and teachers with whom we have interacted have been based at elite English medium institutions.

Our analysis also relies on feedback and discussions at seminars, in email groups, and from published articles, for example from a large number of emails received in response to an article in The Hindu newspaper to commemorate the 200th birthday of Charles Darwin (Haydock, 2009). We do not claim that these results have a more general or quantitative significance.

What problems do students and teachers have in understanding evolution?

The students we have been working with have studied in schools in which evolution is included in the syllabus in Class X, and then in more depth in Class XII (except for students in the arts or commerce streams, who do not study evolution after Class X). In some cases evolution is mentioned as early as Class VII. Some of the students' problems in understanding evolution stem from the way they are taught, which is almost exclusively listening to lectures, reading textbooks, and memorising. These methods do not tend to motivate active involvement in learning. Another problem is due to the content that students are exposed to through teachers and textbooks (Haydock, 2012 unpublished). This often leads students to assume that evolution is teleological - i.e. that it occurs intentionally, for a purpose.

Problems in students' and teachers' understanding

We have used True/False tests to find out whether teachers and students hold some common misconceptions related to evolution and natural selection. When we administer these tests at the beginning of our evolution workshops, we find that biology students as well as teachers frequently think that evolution depends on the inheritance of acquired characteristics, that we have never observed evolution occurring because it is a very slow process, that organisms evolve with the purpose of becoming better suited to their environment, and that evolution is the survival of the fittest, meaning that animals with more muscles will survive and weaker ones will not survive.

This indicates serious problems regarding acquired characteristics, the timescale of evolution, and teleology. Although we have mainly studied teachers of Classes I to XII, based on informal conversations we suspect that even university lecturers may hold some of the same misconceptions.

On the other hand, we have not come across any biology student or teacher who says that they do not believe that evolution by natural selection occurs. Very rarely do they say that there is any conflict between a belief in evolution by natural selection and any religious beliefs that they hold.

We were surprised to find that confusions persist even about artificial selection. For example, one week after completing a session on artificial and natural selection (using plants in the mustard family as examples), we asked a group of BSc Biology students to write answers to the following: "(a) Explain in your own words how some kind of plant in the mustard family might have evolved through artificial selection; and (b) What is evolution by artificial selection?" Based on their oral responses it had seemed that the class had a fairly good understanding of artificial selection, but many of their individual written responses were unclear and insufficiently detailed. Here are some responses which indicate misconceptions and confusions:

> Student 1: (a) The kinds of plant species liked by humans in a locality would have been consumed by them more than other kinds (with undesirable traits). These uneaten other kinds, were the only ones majorly left to produce seeds and form the next generation. Over a period of time, these other kinds with specific traits represented the whole population of mustard. The mustard plant could then be said to be evolved in the direction of that trait. (b) Evolution where selection is done by humans.

This student has recalled some aspects of artificial selection, but has made a logical error in telling how farmers could produce a population with undesired rather than desired characteristics.

Following is how a Class VII student answered the same questions after a similar session on artificial and natural selection.

> Student 2: (a) The ancient man grew the wild mustard and saw some undeveloped, highly packed flowers and tasted it, they found that it was very tasty then they took some seed from that plant and cultivated the undeveloped tightly packed flower and by generation to generation they done the same thing intentionally to see what they will get and got a cauliflower; (b) Artificial selection is done by a human beign for some intention.

Student 2 seemed to have a fairly good understanding, except it is not clear whether she realised that a population of cauliflowers is produced, not just one cauliflower plant. Interestingly, the intentionality is rather tentative. Note that the farmers were never referred to as 'men' in the session, but gender bias appeared in the answer. This led to a discussion of statistics which show that most farmers in India are women, not men.

Some students realised that variation is necessary, and that variation can be due to environmental factors, but failed to understand that unless there is a heritable aspect to the selected traits there can be no evolution. This interdependence between genetic and environmental factors makes it inherently difficult to understand the mechanisms of evolution. It involves a dialectical logic to which most of us are not accustomed. Following are examples of this from a Class VII student and two BSc students:

> Student 3: (a) Some kind of plant in mustard family might have evolved with the changes in the condition while sowing the seed. I think the seed grown in the sunny day may grow faster as compared to the seed that would be sown in a shady or a rainy day. If the farmer would keep the plant for more days, the roots may grow longer and wide, which may lead to grow a raddish. In the same way for the cauliflower or the cabbage the leaves may be grown for a longer time during the generation which may lead to the growth of a cabbage and cauliflower.
>
> Student 4: (a) I think the temperature and climatic conditions may be the reason in variation of the same mustard family and this was the new type of leaves and roots of the same mustard evolved; (b) The selection manipulated by man for his

own purpose artificially is artificial selection.

> Student 5: (a) During artificial selection the caring and watering would be in a limit so the plant would not extend to root but save itself from winds it would shorten the height of shoot becoming cauliflower or cabbage. (b) Evolution by artificial selection is the changes caused in a species due to the intentional or unintentional intervention of another species.

Although artificial selection is by definition teleological because it relies on people selecting variants for a purpose, Student 5 has extended the teleology to include the intentions of other species and even the intentions of the plants which are evolving. Some non-human species may be able to plan and act intentionally to some extent, but it is certainly an exaggeration to think that a plant or a micro-organism can intentionally evolve.

The students' and teachers' understanding of natural selection was even more problematic. The biggest problem was the teleology which kept creeping into the answers. For example here is how a few BSc students answered the questions, "(c) Explain in your own words how some kind of plant in the mustard family might have evolved through natural selection; and (d) What is evolution by natural selection?"

> Student 6: (c) If we go according to Darwin's Natural selection theory, then i will think about "survival of the fittest". But even if a plant of mustard family is able to survive, then it is possible that they can be eaten by some predators or some ants. So, I think the only way that the mustard family plant can survive, is by protecting or preventing itself from any type floods or ants and insects, is by developing a defense mechanism. (d) Evolution which takes place naturally without interpretation of living organisms [sic]

> Student 7: (c) Natural forces - calamities/wind, rain, etc, bugs, birds might prefer a particular plant type OR they stronger plants survive the calamities while weaker may perish. The survived ones grow, reproduce & eventually evolve; (d) Nature's forces (Environmetal cond^{n}, animals, etc) select a variety which can sustain in prevailing conditions i.e. grow & reproduce in it. Thus it get evolved.

Solutions: How to address the problems in teaching evolution and natural selection?

In order to address the problems we encounter, we have spent the last three years continuously developing, testing, comparing, and modifying a number of different approaches to teach students and teachers about evolution. Originally we focussed more on doing activities and having discussions in order to understand a broad range of evidence that evolution occurs. Participants did not have much difficulty in understanding and being able to remember and discuss the evidence. In some cases the participants already had a fairly good understanding of the evidence before the workshop or classes began.

However, we found that even at the end of our sessions, many participants still held on to a number of misconceptions and were not able to verbalise a good understanding of the mechanisms of evolution - in particular natural selection. Therefore, we have lately focussed our workshops entirely on understanding evolution by natural selection. As much as possible we use constructivist approaches in which the participants are led through a series of activities and data analysis to construct an understanding of natural selection. **Table 1** summarises the approach that we have developed, in its most recent form.

No.	Activity
1	Observe and draw an individual mustard plant (a species from the Brassicaceae family). Discuss what you learn by the process of drawing and what questions come to your mind as you draw.
2	In groups of 6, compare the 6 different mustard plants you have, and compile a list of similarities and differences. Discuss the similarities and differences and the possible reasons for the similarities and differences.
3	Read and discuss the beginning of the picture book, "What Comes from Wild Mustard?" (Haydock, 2012) in which the development of wild mustard is shown in pictures.
4	Observe some mustard plants at various stages of development, and describe the process of development.
5	Discuss what is science and plan an experiment that can be done to find out whether the size of a mustard seedpod may be due to the seeds. Discuss possible results and conclusions from such experiments.
6	Continue reading and discussing the book, in which the production of different types of crops from the mustard family (Brassicaceae) by artificial selection are shown
7	Write answers to the question, "Suppose there were no people. Could a similar thing happen without people? Without intention?"
8	Read and discuss the rest of the picture book, in which some possible ways that mustard could evolve by natural selection are shown.
9	Participants write and discuss, "What is the difference between evolution by artificial selection and evolution by natural selection?" Teleology is discussed at length.
10	Simulate the evolution of a population of beetles by natural selection; the participants model birds (predators) selecting beetles (coloured moong) for several generations. Results are graphed, questions are answered and discussed.
11	Discussion on confusions, misconceptions and difficulties regarding evolution by natural selection and final assessment.
12	Discussion on further questions, evidence, and research concerning evolution by artificial selection, including: (a) a discussion of whether our ancestors who developed crops such as cabbage, cauliflower, and radish were doing science; and (b) a discussion of modern methods of plant breeding and the social questions they raise; (c) Who decides?
13	In the end, the following definition of evolution by natural selection is presented and discussed: (a) There is variation between the individual organisms that make up any population; (b) This variation occurs partly because there are random mutations in the genome (differences in the DNA) of individual organisms. These mutations can be passed to offspring; (c) Throughout the individuals' lives, their genomes interact with their environments to cause variations in traits. (The environment of a genome includes the molecular biology in the cell, other cells, other individuals, populations, species, as well as the abiotic environment.); (d) Individuals with certain variants of the traits may survive and reproduce more than individuals with other variants; (e) Therefore the population evolves.

Table 1: Summary of our approach to teach about evolution by natural selection, developed over the course of this study. Activities are shown in chronological order.

Most students are not in the habit of planning and doing experiments in class, and they often do not have a good understanding of the scientific method. This becomes apparent when we ask them to plan a carry out an experiment. They are not in the habit of questioning and critically analysing what they read and what they are told, and looking for evidence based on observing physical reality. This leads to problems in understanding evolution and natural selection. This is why we found it necessary to include activities, experiments, and discussions on variation and similarity, "What is Science?" and artificial selection before discussing natural selection. We have used the same basic approach for students and teachers at all levels from Classes VII to BSc, adjusting the terminology and details as needed. We have assessed the understandings of students and teachers initially and throughout these sessions.

We found that it was beneficial to discuss artificial selection before natural selection, stressing that it occurs by design, and then see if any students could construct a hypothetical scenario by which a similar thing could happen without people and without intention. Younger students who had not previously studied evolution seemed to be better at constructing such a scenario. One Class VII student immediately said, "Maybe a monkey could do it!" Other answers indicated a surprising amount of success in our teaching method, for example:

> "It could be possible that wild mustard gave rise to mooli without farmers. The process could have happened naturally or accidentally. It could also have happened due to animals. Some animals must have eaten the seed and the seeds may have stuck to the animals skin. The animal was used as a way of dispersal of seed to long distance. Hence, the undeveloped flowers may have not been eaten and would have reproduced during long periods or the undeveloped flower may have got unusual conditions by which it turned to different types of mustard plants."
>
> "The plants which have undeveloped flowers would have accedently be fallen because of the storm and would have been transported to different places and because of rain it would start growing."

In our experience, it is very important to stress the differences between artificial and natural selection, to explicitly discuss teleology, and to avoid using phrases and terms such as, “adaptation”, “survival of the fittest”, or “struggle for survival”. During our workshops, the participants themselves start objecting when someone makes a needlessly teleological statement like, "The plant's roots try to find water", or "The plant knows..” (Such a discussion among BSc students led to the question of whether plants have "atma". It was pointed out that there was no physical evidence for this. Still, one student insisted that he knows plants have "atma" on the basis of his intuitive inner beliefs - and that authorities have told him.)

Why do people think teleologically?

Why is it that teleological thinking in biology is so widespread? Some say that teleology is intuitive, and that is why even young children have a natural tendency to think teleologically (Kelemen, 1999; Kampourakis et al, 2011). But perhaps this is being unnecessarily determinist. More likely, teleology springs from our rational efforts to understand and explain our world. In order to explain the unknown, we make analogies with what we know - and one of the areas we know best and are most concerned about is ourselves. This rational tendency towards egoism is one factor that contributes to our tendency to think teleologically. One of the defining characteristics of humans is our ability to plan and do things intentionally. We understand other organisms, other processes, and other things by comparing them to ourselves and our own behaviours and processes. Therefore, by analogy we suppose that other organisms also do things

intentionally. This is not intuition, because it is based on reasoning, although the reasoning may not always be very conscious or explicit.

Another factor that may contribute to our tendency to make teleological explanations is that such explanations are simpler. It is simpler to think that animals got wings in order to fly than to think that in a population of mostly wingless animals some individuals just happened to have heritable wings, and then they found that they could use wings to fly, and then the ones with wings survived and reproduced better than the ones without wings. Reality is complicated, interconnected, and difficult to understand.

Our work confirms that the non-teleological process of evolution due to natural selection is more difficult to understand than the teleological process of evolution due to artificial selection, with which we are more familiar. Uneducated farmers understand evolution by artificial selection because this is the process that they use to develop crops and domesticated animals. So it is easy for a farmer to suppose that other physical processes are also teleological. As we have seen, many Class VII children in our workshops manage to understand how artificial selection works. By simple analogy some students then suppose that a plant wants to produce thorns so that cows will not eat it, just as a farmer wants to produce plants with larger fruit so that she can eat it.

Another reason why people think teleologically is that in India, as in many other parts of the world, people tend to have an idealist way of thinking about the world, thinking that abstract ideas, spirits, 'atma', or some kind of god or gods are basic causes of physical reality. Some even go to the extent of believing that the physical world is only a figment of our imagination. Thus, idealists will tend to look for non-material causes. They will be more likely to think teleologically, expecting that things are the way they are because they were designed for some purpose rather than because they are the result of a physical process. Why do people have idealist ways of thinking about the world? Perhaps it is a dominant form of cultural indoctrination, which helps to keep order in the social system because it encourages faith in authority rather than questioning authority.

This is in contrast to a materialist way of thinking about the world, in which matter is basic and ideas are considered to be the products of physical processes. The natural sciences require a materialist way of thinking since they are concerned with finding material causes for physical reality.

Of course, many people are dualists, believing that there are two separate, non-interacting worlds - one of physical reality, and the other of ideas or spirits. A dualist may be able to understand that evolution occurs due to the physical process of natural selection, while still adhering to non-material explanations for other processes. Conflicts may arise when trying to distinguish between whether a physical process is due to material or non-material cause.

For example, it is not uncommon for Hindu fundamentalists, and even those who are not so fundamentalist, to pride themselves in claiming that Hinduism is 'scientific' and rational. Not only do they believe that evolution has occurred, they also believe that the ancient Hindu sages already knew about biological evolution - and they also knew much more:

> "The standard sequence of biological species that modern biologists have inferred from the fossil records spanning long stretches of time, is accepted as a “lower-level truth” already known to ancient Hindu sages who are said to have “surpassed” it in favor of the “higher” truth of spiritual evolution." (Meera Nanda, 2010)

This view was expressed by numerous people in emails received in response to the Hindu article (Haydock, 2009).. Here are two examples:

> “What the bio-scientists today call Gene factor, is the jiva-atman in the Indian belief system. Life-giving cell atman is trans- migratory among different physical forms - monkeys, snakes, birds, bees, animals and humans - and even trees.”
>
> "well I am not scholar of Hinduism but one of sacred writing in Bhagwat geeta it has been described that what had happened and what is happening and what will happen is happening for good.(jo hua who achha hua jo ho raha hai who bhi ache kay liye ho raha hai aur jo hoga who bhi ache kay liye hoga)…I take this Jo hoga (happening) as Darwins theory"

They are actually not understanding what is biological evolution or what is natural selection, or what is science. They are using pseudo-science in order to prove the validity of religious beliefs that are based on faith, rather than on observing physical reality, questioning, analysing, and experimenting. It is interesting to note the contrast with western non-scientists who use religious beliefs to 'disprove' science. In neither case is a scientific method being understood or followed.

Here is another example, this time by an idealist engineer teaching at a major university:

> "Early on in the quest for science, we teach the students to study the functions and limitations of the instruments used, so as to gauge the reliability of the observations.
>
> But the curriculum most often falls on its nose with a thud: Has the student ever been taught to introspect and know the functioning and limitations of one's own intruments of perception?
>
> Western system of scientific enquiry is completely flawed. Should we turn a blind eye to the infinite knowledge and wisdom garnered by the sages of yore and infused into our traditions and philosophy; and ape the johny come of late western system??!!!!
>
> Be one to awaken the sense perceptions of the young and eager and lead them on to true knowledge."

This kind of thinking may appeal to a post-modernist relativist who believes that scientific and non-scientific explanations are equally valid and a scientific method should not be used to investigate the infinite knowledge of the sages of yore. We find this kind of thinking creeping into the thinking of some educationists:

> "I find that students sometimes accuse teachers who propose that science is the only way of knowing, the only legitimate tool for answering any question, of scientism—inappropriately privileging science and scientific methods above all else. The criticisms of these students seem to be appropriate." (Smith, 2010)

We think this is an odd position for a science educator to take. We would expect that a science educator will use scientific methods.

Educationists need to be aware of the differences between indoctrination and education. Both indoctrination and education result in changes in beliefs - various kinds of beliefs. But the process of indoctrination is based on accepting authority, whereas science education is based on learning through questioning authority and observing physical reality. However, we should not deceive ourselves by thinking that science education can be objective. Teachers as well as students do have particular points of view and ideologies, depending on their backgrounds, past experiences, circumstances, and environments (Matthews, 2009). It will be better to be aware of our points of view and the reasons for them.

This is not to say that a teacher should insist that students should not be religious. If we use a scientific method to analyse why people are religious, we will see that there are good reasons for religion:

> Religion is, indeed, the self-consciousness and self-esteem of man who has either not yet won through to himself, or has already lost himself again. But man is no abstract being squatting outside the world. Man is the world of man—state, society. This state and this society produce religion, which is an inverted consciousness of the world, because they are an inverted world. Religion is the general theory of this world, ... its moral sanction, its solemn complement, and its universal basis of consolation and justification.
>
> Religious suffering is, at one and the same time, the expression of real suffering and a protest against real suffering. Religion is the sigh of the oppressed creature, the heart of a heartless world, and the soul of soulless conditions. It is the opium of the people.
>
> The abolition of religion as the illusory happiness of the people is the demand for their real happiness. To call on them to give up their illusions about their condition is to call on them to give up a condition that requires illusions. (Marx, 1844)

Our goal as science educators is to increase scientific temper. We teach and learn about evolution and natural selection not just in order to examine and understand life, but also in order to change our world. Even if we find that religious fundamentalists are interfering with the teaching and learning about evolution and natural selection, we cannot demand that our students completely abandon religion. Religion may be very necessary for them at present.

It is interesting that although late in his life Charles Darwin was not religious, he took a position which is not conflicting with the ideas expressed in the above quote.

“It seems to me (rightly or wrongly) that direct arguments against Christianity and Theism hardly have any effect on the public; and that freedom of thought will best be promoted by that gradual enlightenment of human understanding which follows the progress of science. I have therefore always avoided writing about religion and have confined myself to science.” (Darwin, 1880)

Note that this approach is quite different from the approach of Smith, who seems to be afraid to be too scientific and afraid to "privilege ... scientific methods above all else". Should educators teach how through intuition, introspection, or faith in authority we can know more than we can find out through science? It will be better if educators aim for education rather than indoctrination. We suggest that the words of both Darwin and Marx can guide us in our approach to leaching and learning about evolution and natural selection.

References

Allman, W.D. (2011) Why don’t people think evolution is true? Implications for teaching, in and out of the classroom, Evolution Education Outreach (4) 648-665

Beckett, B. & Gallagher, R.M. (1989) Co-ordinated Science: Biology, Oxford University Press .

Darwin, C. (1860). Letter to C. Lyell, 6 June, 1860; assessed from *www.darwinproject.ac.uk/entry-2822* on 1 May 2012.

Haydock, K.. (2009). What difference did Darwin make?. *The Hindu,15 February 2009, Magazine section, p. 1*

Haydock, K. (2012). What Comes from Wild Mustard? in press.

Haydock, K. (2012). An analysis of the teaching of evolution in school textbooks in India, unpublished.

Kampourakis, K., Pavlidi, V., Papadopoulou, M., & Palaiokrassa, E. (2011) Children's Teleological Intuitions: What Kind of Explanations Do 7–8 Year Olds Give for the Features of Organisms, Artifacts and Natural Objects? Res. Sci. Educ.

Kelemen, D. (1999). The scope of teleological thinking in preschool children, Cognition 70, 242-272

Matthews, M. (2009) Science, Worldviews and Education: An Introduction; Sc. & Educ 18: 641-666

Marx, K. (1844) A Contribution to the Critique of Hegel's Philosophy of Right, Introduction

Meera Nanda, (2010) Madame Blavatsky's Children: Modern Hindu Encounters with Darwinism, in Handbook of Religion and the Authority of Science, ed J>R> Lewis & O. Hammer, 279-344

NCERT [National Council of Educational Research and Training]. (2006). Science: Textbook for Class X. New Delhi..

NCERT [National Council of Educational Research and Training]. (2006). Biology: Textbook for Class XII. New Delhi..

Richards, R.A. (2008) Philosophical challenges in teaching evolution, Evolution Education Outreach (1) 158-164

Satchidanandan, K. (2012) Indianising English, Frontline 29, 19

Smith, M.U. (2010) Current Status of Research in Teaching and Learning Evolution: I. Philosophical/Epistemological Issues, Sci & Educ (2010) 19:523–538

Wallraff, B. (2000) What global language, The Atlantic Monthly 286 (5) 52-66