Science as Process or Dogma? The Case of the Peppered Moth

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A Waldorf high school science teacher stands before a wonderful and yet difficult task. We need to be at home in modern scientific research in the fields in which we are teaching, but we also need to transcend the narrow confines of the theory-driven, reductionist approach so widespread in science and science teaching today. Much of what we learn about science today has a dogmatic character - we learn about theories as if they were hard facts and not ways of interpreting the phenomena. Where textbooks and the Discovery channel offer answers, a Waldorf science teacher should be raising questions. We need to penetrate to the facts, to the actual scientific process. This is by no means easy.

In the following essay I describe a famous example from evolutionary biology that I gradually realized was much more complicated and problematic than my textbook knowledge. I now cringe at the thought that I had been passing this example on to my students. I came to see how this example can show the pitfalls and promises of so much science teaching today. I hope this essay will stimulate other science teachers to think more critically about the examples they use in the classroom to "prove" a point. I also hope non-scientists will benefit through the journey and gain a clearer, and more critical view of how science works. I offer one more prefacing remark: Waldorf schools are sometimes criticized for being soft on science or, even worse, for teaching pseudo-science. Such criticism may be valid in individual cases, but it cannot be directed at the Goethean, phenomenological methodology, which lies (or rather should lie) at the heart of Waldorf science teaching. This essay can at very least show that a Goethean approach - in which one views participation on the part of the scientist as a central part of science - leads to a critical and reflective view of science that protects both student and teacher from dogmatism. And dogmatism should be the enemy of every science teacher. To help students view and experience science as a living process, and not as a teaching or an edifice of "facts" is, in my view, a far truer embodiment of the scientific spirit than much of what one finds today around the globe in classrooms and textbooks.

The Story of the Peppered Moth

The peppered moth is used in high school and college biology courses, as well as in many textbooks, to illustrate evolution via natural selection. The story goes like this:

> The "peppered moth," *Biston betularia,* occurs in light and dark (melanic) forms, both of which are shown in Figure [1]. The normal ("original") form is a light, peppered color. A specimen of the dark type was first captured in 1848, near Manchester, England, just 11 years before the publication of the *Origin of Species*. In the years thereafter, in various parts of England, the relative frequency of the dark form was observed to increase until today, in some regions, only dark forms are found. Why the change?
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> The answer is almost self-evident from the photographs shown in Figure [1]. In A we see a tree trunk of the sort found in rural England far from industrial centers: lichens covering the oak tree give it a variegated surface against which the lightly peppered moth is hard to see; the black form stands out prominently. By contrast, on trees growing in industrial areas, the lichens are killed and the trunk is blackened by soot; on such a tree it is the black moth that is protectively colored, the light moth standing out "like a sore thumb." Birds that prey on the moths have been observed and photographed catching moths, and it has been proved that they bring about differential mortality favoring the survival of the light forms in unpolluted woods and the dark forms in industrially blackened woods. (Hardin, 1966, p. 183)

Figure 1. Light and dark forms of the peppered moth were photographed against the lichen-covered trunk of a tree in an unpolluted area of England. The light form is hard to see, the dark form is very conspicuous (from Kettlewell, 1959).

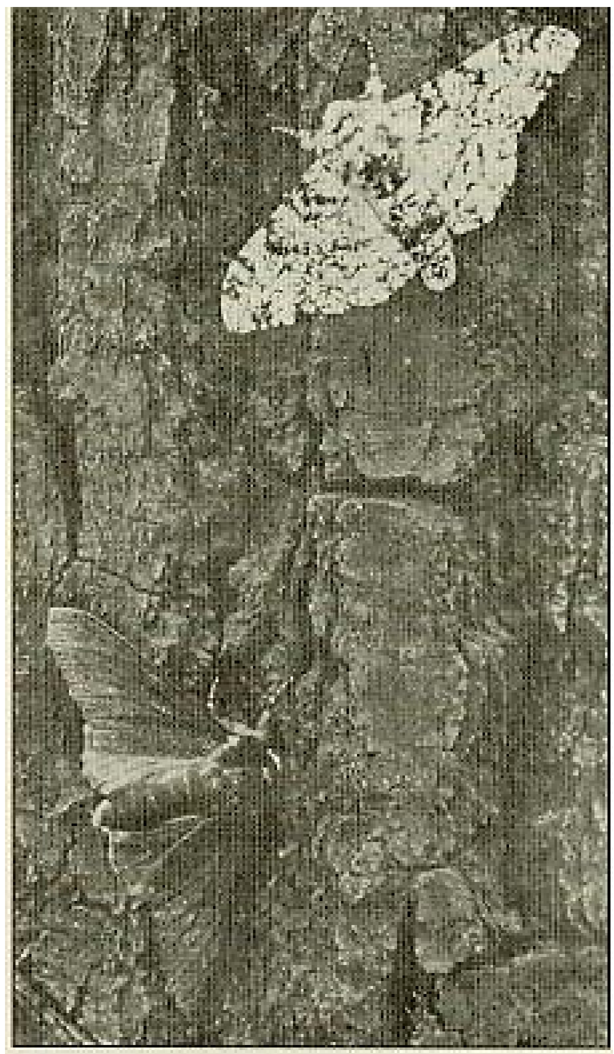

Figure 2. The same two forms as in Figure 1, but photographed against the trunk of an oak tree blackened by the polluted air of Birmingham, England. In this case the dark form is hard to see, while the light form is conspicuous (from Kettlewell, 1959).

This text was published in 1966. Newer accounts give a similar version of this classic story.

Sometimes textbooks update the story: Since the 1960s clean air acts in Great Britain and the United States have led to markedly improved air quality around industrial centers and the numbers of dark moths have fallen significantly in the forests near such centers in Great Britain, while the light moth is again becoming more prevalent. The evolutionary trend is reversing. A striking case of parallel evolution has been found in the forests near Detroit, which had over 90% dark moths in 1960, but in 1994 only 20%.

This type of evolution has been called industrial melanism. (Melanin is the pigment that makes the wings dark). It exemplifies the Darwinian view of evolution: A species displays phenotypic variation (light and dark forms) on which natural selection can operate. In this case, birds selectively feed on conspicuous moths, and because the background coloring changes, the moth population evolves. “Had Darwin observed industrial melanism he would have seen evolution occurring not in thousands of years but in thousands of days—well within his lifetime. He would have witnessed the consummation and confirmation of his life’s work” (Kettlewell, 1959, p. 33).

Waking up

In the early 1980s I began teaching about peppered moth evolution in a university preparatory, high school biology course in Germany. Using this example I could clearly develop the concepts of mutation and directed natural selection as factors of evolution, concepts required in the state-regulated curriculum. Since I was only teaching the peppered moth as an example to make certain concepts clear, and could spend only a short time with this theme, I used textbook descriptions and other secondary sources. Essentially, I taught the story described above, including some of the results of H.B.D. Kettlewell’s experiments, which I will discuss below.

In 1986 I came across a short report on new research concerning the peppered moth. The report gave me an awakening jolt. The last sentence stated that Cyril Clarke, a British scientist, had investigated the peppered moth for 25 years and found only *two* specimens during daylight in their natural habitat. What is going on here, I asked myself. I have been showing students photographs of the moths on tree trunks, telling them about birds selectively picking off the conspicuous moths, etc. And now someone who has researched the moth for 25 years reports having seen only two moths. I immediately ordered Clarke’s article (Clarke et al., 1985) and my study of the primary literature began. In recent years an increasing number of scientists have expressed their doubts about the classic story. A much richer, riddle-laden picture has emerged. (For critical reviews of peppered moth research see: Lambert et al., 1986; Majerus; 1998; Sargent et al., 1998, Wells, 1998.)

Where is the Peppered Moth?

As strange as it may seem, no one knows where the peppered moth lives during the day. Clarke’s sighting of two moths in 25 years is more than other authors can claim. How, then, have the moths been studied? Researchers enter the forests at night and turn on bright lamps that attract nocturnal insects. In this way they capture the moths. They also set up so-called assembling traps housing virgin females that release pheromones into the air, attracting males into the traps. The males only fly into the assembling traps at night; they are never caught during the day. Since one rarely, if ever, sees these moths during the day, it is assumed they are resting somewhere in the forest, becoming active at night.

If the moths aren’t observed during the day, where do the beautiful photographs of the moths on trees come from? In general, authors don’t report the conditions under which the photos were made. I have found references only in an article by Lees and Creed (1975). They describe how the moths are killed, glued to the tree surfaces, and then photographed. Most photos in textbooks are reprints from Kettlewell’s work (like the ones shown above); he does not state how they were made. Since the light and dark forms are so ingeniously placed to show camouflage or lack of it, I suspect he might have used dead specimens and/or arranged the moths accordingly. Readers will normally (and perhaps naively) assume, unless otherwise informed, that they are looking at a natural phenomenon. The impressive image of camouflage in the peppered moth sticks in the mind, especially when the image is accompanied by a text like the one quoted above, which gives no hint that we are looking at an artificially-constructed situation. And as the textbook states, the explanation of industrial melanism appears in view of such images almost "self-evident." This self-evident explanation dissolves when we learn that researchers don't find the moth during the day and that the pictures are composed by the researchers themselves.

Kettlewell (1955, p. 323) stated:

> "Yet after more than twenty-five years of observation and constant enquiry, I have found no single instance in this country [Great Britain] in which anyone has witnessed a bird detecting and eating a moth belonging to a protectively coloured (or cryptic) species while sitting motionless on its correct background."

Kettlewell knew Great Britain was a land of good observers, with many bird watchers and ornithologists. What he doesn't state is that some moth species—like the peppered moth—are almost never seen at all during the day. If one glosses over this fact, it is much easier to have a simple explanation, but what one is explaining is not the natural situation itself. Cyril Clarke summarizes: "They might be resting anywhere. The latest story is that they rest on the leaves in the top of trees, but it's not really known. The answer is that, either way, they're very good at hiding" (quoted in Kaesuk Yoon, 1996).

Kettlewell's Experiments

In the 1950s Kettlewell, who was a biologist at Oxford, undertook a series of impressive experiments to see if he could observe experimentally what nature might be doing in a more hidden way (see Kettlewell 1955, 1956, 1959, 1973). Kettlewell bred moths in the laboratory in order to have large enough numbers for experiments, especially females, which rarely ever flew into the light traps at night. He then marked the moths on the underside of the wings for later identification. The light and dark forms of the moths were then released early in the morning into unpolluted and polluted forests. He later recaptured some of the moths in the light and assembling traps. Kettlewell summarizes the results of two such mark-release-recapture experiments (1959, p. 29):

> In an unpolluted forest we released 984 moths: 488 dark and 496 light. We recaptured 34 dark and 62 light, indicating that in these woods the light form had a clear advantage over the dark. We then repeated the experiment in the polluted Birmingham woods, releasing 630 moths: 493 dark and 137 light. The result of the first experiment was completely reversed; we recaptured proportionately twice as many of the dark form as of the light.

There is a clear correlation: In polluted forests more dark moths are recaptured and in unpolluted forests more light moths are recaptured. But the experiments do not reveal whether *birds* are feeding on the moths. Kettlewell investigated this question by performing other experiments. In collaboration with the well known Dutch ethologist, Niko Tinbergen, Kettlewell released moths (not for recapture) onto tree trunks, where the moths remained stationary (Kettlewell 1956, p. 294).

The scientists hid and observed birds feeding on the moths; Tinbergen even filmed the process. Generally, the more conspicuous moths—those on the "wrong" background according to our human standard—were taken first, and after all the conspicuous moths were eaten, their numbers were replenished. Camouflaged moths were also eaten, but not as many.

In an aviary similar observations were made (Kettlewell 1955, pp. 328 ff.): Kettlewell observed that the birds—a pair of Great Tits—took no moths within the first two hours, but then within an hour they had eaten most of the conspicuous moths and a few of the camouflaged ones. The second time the experiment was performed all the moths were taken much more quickly, within one half of an hour of being released. "It was suggestive that the tits were becoming specialists on *betularia* [the peppered moth], and subsequently they were seen to be searching each tree trunk eagerly one at a time immediately after admission, thereby defeating the purpose of the experiment."

Kettlewell brings results of the mark-release-recapture experiments together with those of the bird predation experiments and concludes: "the effects of natural selection on industrial melanics for crypsis in such areas can no longer be disputed," and "birds act as selective agents as postulated by evolutionary theory" (Kettlewell 1956, pp. 341f.)

Kettlewell believed his experiments prove that the evolution of the peppered moth is caused by selective predation by birds. But how compelling is this conclusion? Consider, for example, the results of his aviary experiments. He observed that the two birds were much quicker at taking moths after they had had experience in doing so. They found the camouflaged moths as well. If one takes *this* experimental evidence and imagines it transferred into a natural habitat, wouldn't it be reasonable to think that as the dark peppered moth began to initially spread (for some unknown reason), the birds might have begun to recognize them as well? This conclusion is just as sound, but also just as speculative as Kettlewell's, which states that since the birds feed on the conspicuous (light) form first, its numbers have decreased while the dark form has increased its numbers.

More to Melanism than Meets the Eye

This phrase is taken from the title of a review article on peppered moth research written in 1982 (Jones, 1982). As the title indicates—and further research has shown—the picture of peppered moth evolution among researchers in the field has become much less straightforward.

The reduction in the lichen covering of trees, due to air pollution, in forests around industrial centers has been viewed as a primary factor in the evolution of the peppered moth, since fewer lichen would make the light form more conspicuous and the dark form better camouflaged. In forests near Liverpool the proportion of dark moths was over 90% in 1959, while in 1984 there were only 61% dark moths; the population of light moths has been making a dramatic comeback (Clarke et al., 1985). The air pollution has decreased in this time, falling steadily from 1962 to 1974 and has remained since then at a constant low value. Although green species of lichen have repopulated trees, the light species of lichen, upon which the light peppered moth is so well camouflaged, is *still absent* in the forests. Similarly, in forests near Detroit, the light moths increased from under 10% of the population in 1960 to over 80% in 1994, even though the lichen flora has not changed perceptibly in this period (Grant et al., 1996). Grant et al. therefore "suggest that the role of lichens has been inappropriately emphasized in the chronicles about the evolution of melanism in the peppered moth." Clearly, if the lichen abundance has not changed, then it is very difficult to understand how selective predation by birds could be the primary factor in the evolution of the moth forms.

Other features that contribute to the dissolution of the clear-cut textbook story. Lees and Creed (1975) report on research they performed in rural eastern England. With certain variations, they basically repeated Kettlewell's experiments. In these forests there was little atmospheric pollution and the bark of the trees was "relatively light." When they glued dark and light moths onto trees, human observers found the light form better camouflaged than the dark form. They came back to the trees at regular intervals and counted how many specimens of each type of moth was still present and how many had disappeared, presumably having been eaten by birds. The results fit well with the observation of conspicuousness: more of the better camouflaged light moths remained longer on the trees than the more conspicuous dark moths. When, however, Lees and Creed captured wild moths in traps, there were about 80% dark moths and 20% light moths—exactly the reverse of what would be expected on the basis of the experiments. If resting moths are hunted by birds during the day, then the light form would seem to be at a selective advantage. Yet the forests seem to be populated by many more dark moths than light moths. Others have made similar contradictory findings (Bishop, 1972). "We conclude therefore that either the predation experiments and tests of conspicuousness to humans are misleading, or some factor or factors in addition to selective predation are responsible for maintaining high melanic frequencies" (Lees and Creed, 1975, p. 76).

Textbooks continue to portray a straightforward picture of peppered moth evolution (for a felicitous exception see below). But the reality is much more complex—and more interesting. If one is looking for solid "proof," then the peppered moth has turned out to be a poor example.

Seeing What We Believe?

Stephen Jay Gould and Richard Lewontin, two foremost contemporary evolutionary scientists, are highly critical of the "adaptationist programme," as they call it, and one of their reasons is "its unwillingness to consider alternatives to adaptive stories" (Gould and Lewontin, 1979, p. 581). This "unwillingness" stems from a pre-formed idea that has the quality of a conviction. The idea that selective predation by birds is the primary causative factor in the evolution of the peppered moth becomes a fairly rigid paradigmatic framework under which the facts are subsumed. If Kettlewell hadn't been so convinced of the truth of bird predation causing peppered moth evolution, he might have left more room for alternative explanations.

In this example we can see how strongly a theoretical framework informs the interpretation of the facts. When scientists have, as Lynn Margulis puts it, "an uncritical acceptance of the mesmerizing concept of adaptation," there is a real danger of seeing what one believes (Margulis and Sagan, 1997, p. 272). If this happens, then we get the oversimplified portrayals, like the textbook description quoted above, that turn science into dogma. It is not very difficult to show that natural selection is at work when one tacitly weaves the theory into the description of the phenomena. What you put in, you can get out again. Rudolf Steiner saw this as a fundamental danger within science: "The basic error of many scientific strivings today is that they believe they are reporting pure experience, while actually they are only reading out of experience the concepts that they already placed into it" (Steiner, 1988, p. 31, *my translation*). These words were written in 1886, unfortunately they have not ceased to be true.

If we are truly interested in understanding the phenomena and not mirroring our ideas in them, then we must become more aware of our thinking in order to make it a more adequate and adaptable instrument of understanding. A basic, but important realization can be that in performing an experiment we are creating a simple and relatively transparent situation, which is, of course, *not* identical with the more complex system of interactions involved in any given natural phenomenon. We should be extremely wary of drawing conclusions that go beyond the experimental situation itself. Kettlewell's field experiments show that birds feed on moths released onto trees in the early morning. But since the moths are not normally found on lower tree trunks during the day, Kettlewell has created (as all experiments do) an artificial situation. We need to recognize this and not simply conclude: in nature birds feed selectively on moths in the manner Kettlewell has shown. We need to hold back the conclusions in order to free our thinking to consider other alternative explanations and also to realize what we do not yet know.

Instead of viewing experiments as a way to prove or disprove an idea, we come to see them as a way of interacting with phenomena. (For a lucid discussion of the nature of experimentation and the perils involved in making conclusions about experiments, see Goethe's seminal essay *The Experiment as Mediator between Object and Subject* (Goethe, 1995, pp. 11-17)) Experiments help us to clarify our ideas, to see new phenomena, to formulate new questions, and to look with new eyes into nature.

All experiments are guided by ideas. Without the concepts of natural selection and selective predation, most of the research concerning the peppered moth may well never have been performed. These ideas have guided and focused the research, and helped scientists to formulate specific questions and discover new phenomena. Problems arise when we no longer handle a concept as an instrument to see more, but as something to be substantiated by nature. When we begin to selectively view the phenomena, only seeing what seems to confirm our theory, then concepts that initially sharpened our attention begin to make us blind. If, in contrast, we can use hypotheses as a way to get started, well knowing that they need to be left behind when we confront the phenomena, then we begin to practice a flexibility of thought that leads us further into the complex richness of the phenomena, and not into a monolithic theoretical construct. The peppered moth becomes, in this way, more and more like a deep question, rather than a mere instance of a general theory.

Implications for Science Education

In recent years I taught the complicated picture of the peppered moth to high school seniors at the

Hawthorne Valley School in upstate New York. This is an independent Waldorf School and its curriculum is not state regulated. The students were fascinated by the peppered moth, and the contrast between the simple story and the complex reality. We spent more time on this example than one usually would, because I wanted them to see how science actually proceeds as a process of discovery and transformation.

Teaching in this historical, case-study approach demands more classroom time and also more research on the part of the teacher than providing general overviews of material. But it enlivens science as a process. We learn how scientists make observations, formulate ideas and questions, and test their hypotheses through experiments. We see how contradictions arise, how concepts become rigid, and then—often in the face of resistance—how they are modified or even dropped. Students begin to think of science as a process occurring in an historical context. What could be a more appropriate way to learn about the science of *life*, biology?

By proceeding in this way, students gain knowledge, but their knowledge is dynamic, not static information. They develop capacities and ways of approaching phenomena that they can apply in various life situations. Young people are—if we have not corrupted them too much—open-minded and interested in the world. Certainly it makes sense for them to learn science (and of course other disciplines) not as codified knowledge to be memorized, but as a way of interacting with nature that leads to insights and to ever-new questions.

A significant problem in the way science is taught, popularized, and in general filtered down into the minds of children is that students are filled with scientific dogmas: They "know" that in evolution the fittest survive, they "know" that the brain is a computer, they "know" that the heart is a pump, they "know" that genes determine heredity. One task of secondary and undergraduate science courses could be to dissolve such dogmatic "knowledge"—which in reality is only acquired opinion—by showing science to be a process. (I have attempted to present genetics in this way; see Holdrege, 1996.) In a given course one can do this for only a limited number of examples, but it is much more stimulating for students than imbibing large amounts of non-contextual information, which, in the end, can be taken only dogmatically. Teaching science as process would mean either reducing the use of textbooks or they would have to become compendia of case studies. In perusing textbook presentations of the peppered moth, I was delighted to find *one* book (a high school Biology text) with a short description of the peppered moth in the section on evolution, but under the heading "Biology in process" (Towle, 1989, pp. 228f.). The author describes Kettlewell's work briefly and then goes on to state that recent experiments raise doubts about the selective predation explanation. He thus calls attention to the unresolved questions.

The American Association for the Advancement of Science has published *Benchmarks for Science Literacy.* It is part of the *Project 2061* (the year in which Halley's comet will return; the project began in 1985, the last time Halley's was here), which has the purpose "to help transform the nation's school system so that all students become well educated in science, mathematics, and technology" (back cover). Concerning scientific inquiry, the text states that high school students should learn that "no matter how well one theory fits observations, a new theory might fit them just as well or better, or might fit a wider range of observations. In science, the testing, revising, and occasional discarding of theories, new and old, never ends"(p. 8). Most of the book, however, stands in contrast to this description of science as a process. In the main body of the book one finds for all grade levels the "benchmarks" for what should be known in a given field at that age level. In this way the book emphasizes content, not process. For example, by the end of twelfth grade students should know that "the theory of natural selection provides a scientific explanation for the history of life on earth as depicted in the fossil record and in the similarities evident within the diversity of existing organisms" (p. 125).

Once we have learned that one of the most cited examples of natural selection turns out to be very unclear, doesn't this statement seem dogmatic? If we are teaching dogma, it is important to know that natural selection *is* an explanation; if we are interested in giving a sense for the nature of the scientific endeavor, then it is much more essential to know how the concept is used, what it reveals, and what it doesn't reveal. Without intending it, this book gives a very good picture of a codified view of the nature of things. The conservative slant is discernible when the authors say "it is important not to overdo the 'science always changes' theme, since the main body of scientific knowledge is very stable and grows by being corrected slowly and having its boundaries extended gradually" (p. 5). If this "stable" body of knowledge entails the myriad phenomena scientists discover, then I can agree with this statement. (Changing theories haven't changed the fact that insects have six legs.) But if scientific theories and models have, then I think we should stimulate our students to continually question what tends toward a cemented standpoint. We should stimulate continual scientific revolution. Just as in the Middle Ages it seemed to many a self-evident fact that the earth was the center of the universe, most certainly many of the "scientific truths" (that is, theories) of today will become historical belief systems in the eyes of future humanity.

Back to the Phenomena

Once we break out of the strictures of fixed explanatory patterns, we can turn more openly to the natural phenomena themselves. If nothing else, the history of peppered moth research shows the need for very basic natural history, without which experiments and theories are anchorless. Many essential questions can only be answered by direct observation—as difficult as that may be in many situations.

Clearly, we need to know more about the life history of the peppered moth. Where does it rest during the day? What are its natural predators? How far can it fly? How long do the moths live? Similarly, a greater knowledge is needed about the egg, larval, and pupal stages.

At the same time alternative interpretations for melanism in the peppered moth need to be actively pursued. Might melanism have completely other functions than camouflage, like increasing warmth absorption or structural stability in the wing? Or is perhaps melanism in the adult a secondary effect of differences in the larval stages? Some research suggests, for example, that larvae of differing genetic types may not have the same viability (Creed et al., 1980). Theodore Sargent of the University of Massachusetts, working with a different species of nocturnal moth, has found evidence that plants the larvae feed on may induce or repress the expression of melanism in adult moths (Sargent et al., 1990).

There are certainly many other possible interpretations of melanism in the peppered moth. I doubt that any one explanation will turn out to be *the* right one, since in the long run all biological phenomena show themselves to be interconnected with an array of factors. We should probably also expect that in different localities at different times different explanations may be necessary. This is certainly not a comfortable situation if we a looking for *the* cause of industrial melanism, but why should reality be concerned about our predilection for mono-causality?

One difficulty in our approach to the peppered moth is that we have studied it only as an example of evolution. We have not yet set out to understand the moth in its own right. From the outset we have considered the moth from a limited perspective. It was interesting that a student of mine questioned whether the peppered moth really is such a good example of evolution. He took, for a moment, the standpoint of the species, and not the framework I had set by introducing the peppered moth as a good example of evolution. He said: what the peppered moth is really showing us is how a species, by having different forms, is more flexible and able to survive as one species; the populations and varieties of the species fluctuate, but the species as a whole continues to thrive. This student was implicitly raising the question of the validity of using micro, intraspecific changes as a model for macroevolution.

In the same course in which I taught about the peppered moth—entitled "Zoology and Evolution"—we spent a good deal of time studying two animals, the elephant and the sloth. Going into quite a bit of detail, we learned how these animals are integrated wholes in which all features and functions hang together and interrelate. Every part of the sloth has "sloth" written all over it (Holdrege, 1998). When we then came to the peppered moth and studied it in the light of evolution, I realized—as a contrast—that we weren't really giving the moth itself adequate treatment (which I also haven't done in this essay). The moth had been to a certain degree reduced to an example, which would be comparable to looking at the sloth only as an example of adaptation to arboreal life. Certainly, the moth became more and more of a riddle even within the evolutionary perspective, but it is important to be aware of the limitations of understanding implicit in how one formulates a theme. Since limiting is also a way of focusing and finding an entryway into a theme, we can't just abandon points of view. But what we can do is to take different approaches in different contexts to show that there are various avenues of understanding, each with its strengths, but also limitations. This exercise of mental flexibility and mobility can bring us nearer to the flexible nature of life itself.

Conclusion

For decades the peppered moth has been a standard classroom and textbook example ofevolution. Millions of students have learned this "living proof" of natural selection. The story they have been, and are, being told is most likely false, or to put it more mildly, filled with half-truths. This is not because teachers and writers are intentionally lying, or hiding and bending facts, but because the example is only brought to prove a point, so that complications appear extraneous to the argument (if not to the truth). Moreover, the idea of natural selection has become so ingrained in modern mind that it can become like a pair of spectacles that one doesn't remove anymore. Concepts then become axiomatic and science ends up being promulgated in a dogmatic form. As a correlate, the complex and rich phenomena of nature degenerate, as it were, into mere instances of overriding principles. Instead of illuminating, the idea becomes, in Goethe's words, a "lethal generality" (Goethe, 1995, p. 61).

This tendency toward solidification is not what keeps science alive. Vitality in science comes from researchers doubting conclusions, making new observations and constructing new experiments, from scientists thinking original ideas that break through the constrictions of dominant paradigms. Science teaching need not only serve the codified "body of knowledge." It can also serve ongoing exploration and the continual renewal of ideas. Since there is "more to melanism than meets the eye," peppered moth research can be an excellent teacher of the living scientific process.

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