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Kettlewell's Missing Evidence, A Study in Black and White

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The classic case of Kettlewell and the peppered moths, which includes significant details omitted from standard textbook accounts, serves as an occasion to reflect on the role of simplification in science teaching.

Even non-biologists know the peppered moth, *Biston betularia*, and how it evolved in the polluted forests during Britain's industrial revolution. The images of the moths against different backgrounds—black against mottled white and mottled white against black (Figure 1)—are themselves a visual argument for natural selection (Tufte 1997, Robins 1992). (Any half-witted predatory bird would notice the difference.) The lesson for "survival of the fittest" is vividly clear, even without words. No wonder these iconic images "pepper" biology textbooks. One non-majors text even includes the same paired images *twice* (Starr 1994, pp. 7, 202). Non-science students readily recall these images long after leaving the classroom, a tribute to their potency—and to their importance for understanding science education more generally.

Consider the history of these paired images. The peppered moths gained renown through H.B.D. Kettlewell, who investigated the survival rates of the moths in the contrasting forests of Birmingham and Dorset (ostensibly portrayed in Figure 1). Kettlewell presented his studies, including the now familiar images, to a lay audience in *Scientific American*. Reprints became a stock feature in science classrooms. In

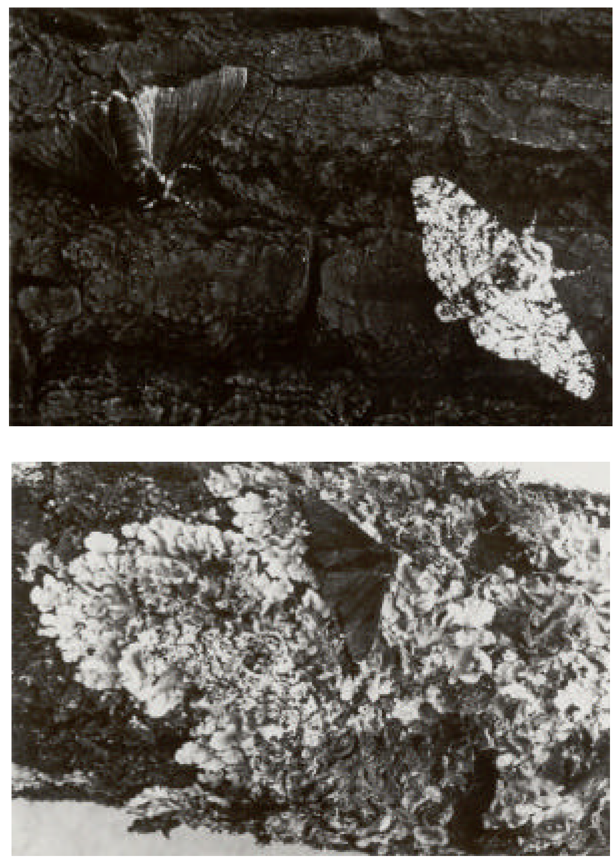

Figure 1. The peppered moth (*Biston betularia*), staged on model backgrounds of lichen and soot-covered tree trunks.

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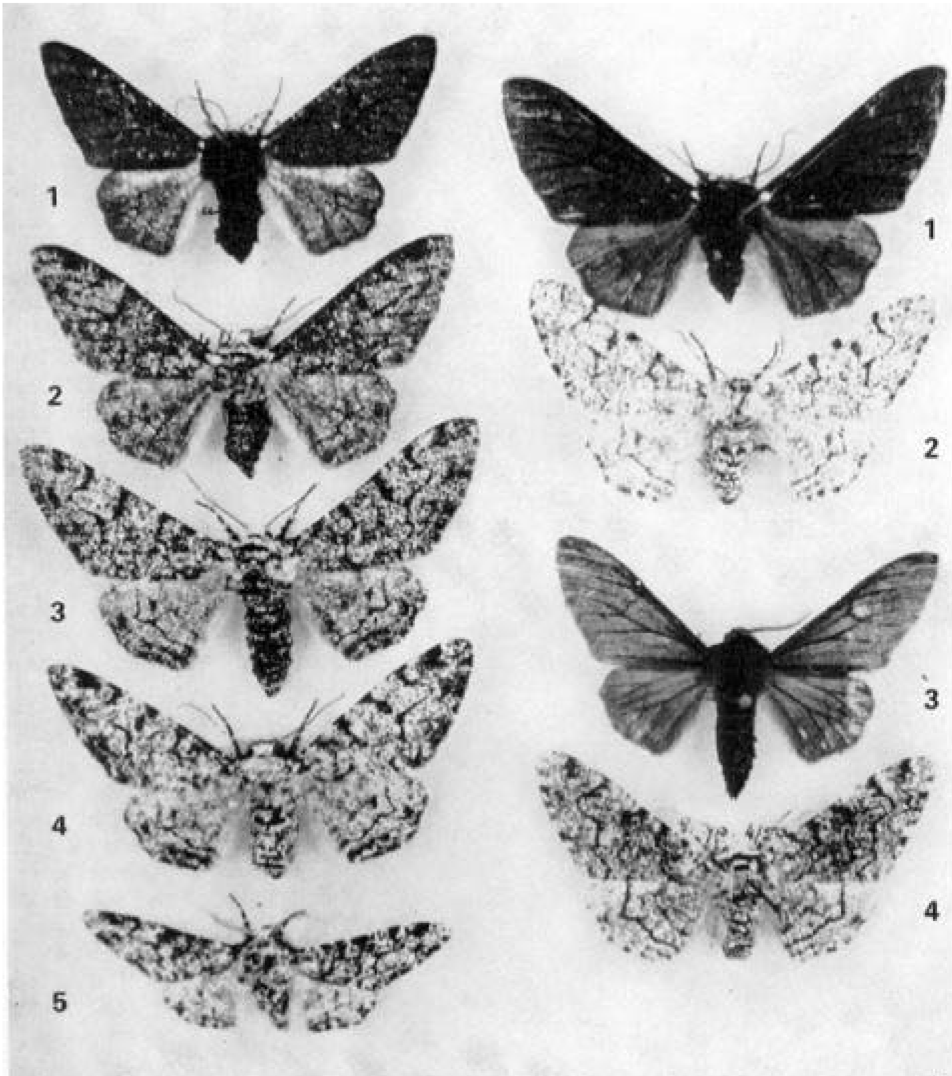

Figure 2. Various forms of the peppered moth: *insularia* (left, #1-5), *carbonaria* (right, #1) and *typica* (right, #2). *Insularia* is normally omitted from textbook accounts. (From Kettlewell 1973, Plate 9.1; reproduced by permission, Oxford University Press).

this 1959 article, a centennial tribute to the publication of *The Origin of Species*, Kettlewell underscored that Darwin's evidence for natural selection, while persuasive, had been only circumstantial. The peppered moths and other cases of industrial melanism, on the other hand, dramatically demonstrated evolution in action. They were, Kettlewell argued in his title, "Darwin's Missing Evidence."

Consider next the image (Figure 2) that appears in Kettlewell's monograph, *The Evolution of Melanism* (1973, plate 9.1). On the top right are the two familiar forms of *B. betularia*: *typica* (#2), the once common "peppered" form, and *carbonaria* (#1), the nearly black form that proliferated later. Arrayed on the left, however, are five other specimens of the same species, all intermediate in darkness: a third form, known as *insularia*. Here, one can witness the whole series of light and dark between the two extremes. How would they fare in different environments compared to the others? How does this change our "image" of natural selection? Why does the popular story, promoted in part by Kettlewell, exclude them? We might call the *insularia* moths "*Kettlewell's* missing evidence."

In what follows, I discuss the hidden facts in the classic Kettlewell case to invite reflection on what I perceive as a broad problem, the tendency to teach only simple concepts in introductory and general education courses. I am concerned, in particular, with the consequences for scientific literacy and K-12 science education.

REDUCING NATURE TO BLACK AND WHITE

Kettlewell was well aware of the *insularia* forms. Indeed, in his now famous field studies, he tallied the survival rates of all three forms (Kettlewell 1955, 1956). In addition, for two decades he catalogued the relative frequency of the three forms in various locations around Britain (Figure 3). The incidence of *insularia* was sometimes as high as 40% or more, especially in southern Wales and the Isle of Man (Kettlewell 1973, pp. 134-36; also Lawrence Cook, personal communication). *Insularia* is no minor player. Though Kettlewell documented *insularia* in his scientific publications, the form became eclipsed in subsequent renditions of his work. For example, Figure 3 is redrawn in the *Scientific American* article (1959, p. 51), but the main text fails to refer to *insularia*. Textbooks, too, sometimes reproduce this diagram, but usually without any grey section in the pie-charts (treating *insularia* as a wholly melanic form). The dust jacket of Kettlewell's monograph (1973), similarly, sports a simplified image (akin to Figure 1) which, like the textbook versions today, omit *insularia*. By hiding real complexity, the now canonical presentation of the peppered moth reduces nature to black and white.

Finding accounts of Kettlewell's evidence incomplete does not mean, of course, that the results no longer support natural selection in the wild (Endler 1986). However, in the classroom the simplified image can mislead students in ways that teachers never intend. The black-and-white image shapes how non-biologists think about evolution. It affects metaphors about nature and, hence, perceptions about what is "natural" in human culture. Unschooled individuals already tend to conceive natural selection in stark terms. Survival is life-or-death. The struggle for existence has two categories only: the fit and the unfit. Competition has winners and losers. The simplified peppered moth case, especially when presented as a benchmark example, merely reinforces this harsh stereotype. There seems to be, after all, only two types of moths. And only two types of environments (moreover, each is portrayed as homogeneous). The choice, posed visually to the student as a vicarious predator, is fairly "black-and-white." A more textured view of selection, with *differential* survival and *differential* reproduction in sometimes *heterogeneous* environments, rarely even emerges as a possibility. Nature is cast in black and white simplicity. The challenge for the teacher (in this and other cases) is how to avoid promoting such implicit messages.

Culturally, this stark either-or framework has powerful overtones. Images of competition and "survival of the fittest" pervade our society, from the Super Bowl and school athletics to the job market, political elections and national economies. As a "natural" scenario, the peppered moth case implicitly guides our thinking. A win-lose model of competition is subtly written into the moth images, and is

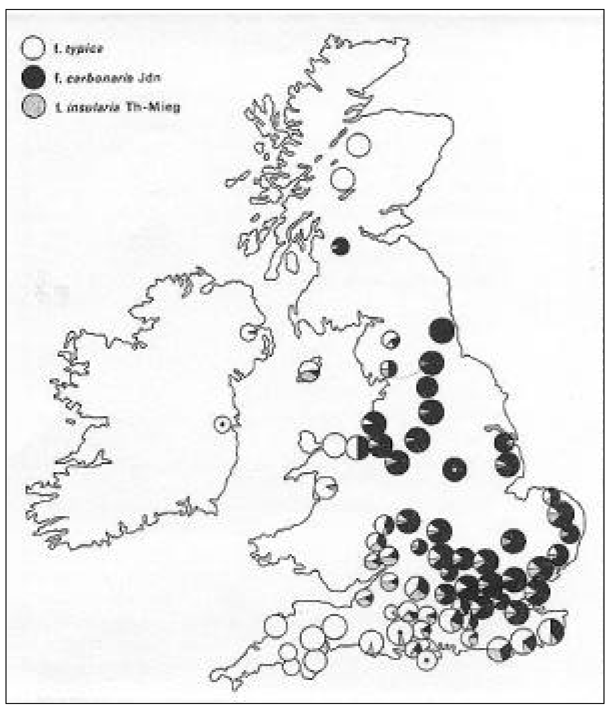

Figure 3. Frequency map of the three forms of *Biston betularia* (Kettlewell 1973, p. 135; reproduced by permission, Oxford University Press).

indirectly legitimized by them. They confirm visually (not logically) that natural selection functions through clear, dualistic choices. The average student thinks: "Can humans escape the fundamental 'laws' of nature?" Few persons embrace Social Darwinism outright. Still, the ideological iconography strongly affects how we perceive the world, and what we find "natural" or "normal," and thus deem "acceptable" or unchangeable. (I invite the skeptical reader to poll introductory students: "Is competition 'the way of the world'? Is that how nature works? Is that therefore how human society works?") The simplified version of the peppered moth is not idle or modest. It helps reinforce notions of either-or, win-lose competition on the basketball court, in business dealings, in the halls of Congress and in other aspects of our culture. How does the careful teacher avoid the implications of simplified nature?

The misleading imagery is echoed when the peppered moths are treated genetically. With just two forms—one dark, one light—one assumes that one allele is dominant, the other recessive, as dictated by the traditional Mendelian model (and as portrayed in many texts, in accordance with Kettlewell's description [1959, p. 51]). This assumption also fits conveniently into basic models of population genetics, which are frequently taught using the peppered moth case as an example. Unfortunately, the diversity of moth forms (Figure 2) immediately implies greater complexity. Kettlewell imagined multiple alleles (1973, pp. 106-7); other experts now suspect polygenic inheritance. We cannot really say that the expression of one allele wholly eclipses any other. In this case, one simple interpretation that is false leads to another that is also false. The genetics of peppered moths is not black-and-white, either. Indeed, the case is only one of many simplifications that help support the further mistake that Mendelian dominance itself is fundamental (Allchin 2000). This case thus illustrates a general challenge about teaching a simplistic account of nature at the introductory level.

REDUCING SCIENCE TO BLACK AND WHITE

The problem of simplicity does not occur with images of nature alone. Consider the history of Kettlewell's studies of *Biston betularia.* Some biology texts honor this classic work by going beyond the concepts, first, by naming the scientist, and second, by celebrating the elegant design of his experiments. In short narratives of this type, students ostensibly learn about the *process* of science. In this case, textbooks may describe Kettlewell's mark-release-recapture technique and/or the key comparison of complementary environments. Some even include tables or graphs of the original published data. However, these "textbook histories" are greatly streamlined. Like the image of the moths themselves (Figure 1), they leave out important information—with profound effect.

For example, some textbooks highlight Kettlewell's exemplary scientific practice in using two contrasting environments to show the effects of natural selection. In the dark polluted woods near Birmingham, the melanistic forms (*carbonaria*) were recaptured twice as frequently. On the other hand, in the lichen-covered woods of rural Dorset, the speckled forms (*typica*) were twice as likely to survive. The coupled investigations exemplify a colossal controlled experiment, using the single variable of selective environment. That's the familiar textbook story. As Hagen (1993, 1996, 1999) has observed, however, originally Kettlewell (1955) presented only data from Birmingham. At first, he made no reference whatsoever to Dorset. Nor did he give any hint that his study was incomplete or preliminary, or that readers could expect forthcoming complementary data. Why? If the Dorset data was so crucial, was the first study flawed? What does Kettlewell's "missing" evidence mean in this instance?

Historian Joel Hagen (1993) offers several possible scenarios why Kettlewell might have published the Birmingham results alone. Originally, perhaps, Kettlewell did not see the "control" as important. This seems likely, given subsequent criticism of his work, his personal correspondence and the apparent timing of his plans to add Dorset the following year. In this case, the need to address criticism would have motivated Kettlewell's extended study, not an initial perception of the need for clarity. That is, he did not conceive the entire experiment in a single flash of insight. Rather, he patched together two separate studies. This scenario transforms the stereotypical image of great scientists working in "Eureka!"-like moments into one involving less extraordinary modes of thinking and working. This is critical for public understanding of science.

In another scenario, Kettlewell could not afford to run both full scale experiments simultaneously. The release-recapture method is labor intensive and he was working alone (he had no funds to hire field assistants). Travel between the two sites would have been problematic. Later, Kettlewell enlisted his wife and son, for instance, to help conduct the research. Or perhaps Kettlewell began with a pilot study, which yielded unusually favorable results. Might he instead have rushed to publish simply to establish his priority? One of the hidden tasks in a recapture study is raising the hundreds of organisms for release—and having them all ready at the appropriate time of year. This would have meant breeding moths in cages and sorting each form—not as simple a task as one might imagine. Was Kettlewell limited by sheer logistics? All these possible alternatives help reveal the complexities of doing science—labor, cost, ambition, developing reliable technique, maintaining lab organisms and responding to peer criticism. They show that the process of science is not so "black-and-white" as the textbook stories typically imply.

Textbooks also tutor students to see Kettlewell's studies as well designed, definitive and (hence) beyond all doubt. This earns them their classic status. At the same time, teachers often identify skepticism as a hallmark of science. Are Kettlewell's conclusions open to analysis or criticism? Philosopher David Rudge (1999) offers an example. He focuses on Kettlewell's central claims about bird predation. At the time, many doubted whether birds preyed on peppered moths at all. Comparing polluted and unpolluted woods, Rudge contends, did not address the key issue. Rather, Kettlewell made various ancillary observations to ensure that his recapture rates reflected predation, not some other environmental factor. Kettlewell checked possible bias in the traps, for example, and monitored migration from the study area. He enlisted ethologist Niko Tinbergen to film birds eating the moths in the wild. Texts rarely discuss these tests, Rudge notes. To further isolate differential predation as the chief causal factor, Kettlewell would need to have controlled for the presence (or absence) of birds, even if it required an unimaginably large exclusion enclosure. Yet other alternative explanations seem not ruled out by Kettlewell. For instance, were the two sites parallel in all relevant respects? Why were nearly twice as many moths recaptured in Birmingham as in Dorset? Did the release of a large number of moths alter predation rates? Can we safely generalize from the limited studies to real nature? When viewed more closely, the path to secure conclusions is more complex. The textbook narrative reduces the experimental reasoning, too, to black and white. Ultimately, a simple account distorts the process of science and perpetuates misleading stereotypes about scientific genius and experimental evidence.

Finally, the popularization of Kettlewell's work raises interesting questions about the ethics of reducing science to black and white as it moves from professional to lay contexts. Currently, omitting or hiding significant data in scientific circles violates norms of research conduct. But what are the relevant norms for interpreting science for the public or for other scientists outside the field? Did Kettlewell have ethical duties to discuss *insularia* in his own popular (and now widely read) *Scientific American* article? Or is this precisely where professionals are responsible for judging how to simplify scientific lessons for non-experts? Parallel ethical questions arise in education: to what degree should teachers simplify the process of science for students? What, indeed, would be the alternative?

REDUCING SCHOOL SCIENCE TO BLACK AND WHITE

Much as the images of the peppered moths typically serve as a visual epitome of evolution, the Kettlewell case can serve as an epitome of common approaches to science education. Toward appreciating the dilemma it poses, let me first distinguish between "real science," as performed by research scientists, and "school science," the reconstructed version that appears in teaching, especially for non-majors and K-12 teachers. The current goal of most school science (I contend), exemplified in the peppered moths, is to reduce real science to black and white. Why? Should we reassess the goal of simplicity?

The danger is that we convey a false image of the world (of nature and of science). In a sense, we condition students to expect simplicity. When they encounter complexity, they may feel betrayed, disillusioned or "simply" lack the skills to interpret the circumstances. Recently, several outraged individuals have sued scientists for making mistakes (Steinbach 1998). What fostered this black-and-white frame of mind that expects science never to err? Did cookbook school labs and textbook celebrations of famous experiments help shape their thinking?

Virtually all the recent calls to reform science education and promote "scientific literacy" appeal to the role of science in social decision-making. Most such issues are quite complex. Still, school science prepares students only for simple problems. As a result, public issues are typically cast in black and white. Brian Martin (1991), for example, has documented how the question of whether to flouridate water has been sharply polarized, with each "side" claiming science for itself and denying scientific credibility to any "opposing" position. Toumey (1996) comments on similar extreme responses regarding HIV testing and the teaching of evolution. How should science educators teach a citizenry conditioned to regard all scientific evidence as black-and-white? To be well informed means in part to understand that science can involve uncertainty (incomplete studies), ambiguous results (data subject to contrasting interpretations) and mixed evidence (different studies supporting contradictory conclusions).

We must understand the context that promotes simple science in school settings. Many teachers may assume that we must begin with the simple, and introduce the complex only gradually, layer by layer. "Basics first," so the maxim goes. Unfortunately, I fear, introductory students rarely, if ever, get to "Complexities later." Perhaps, on some occasions, we serve our students better by exposing them to a messy, unordered, complex world and then showing them how to negotiate their way through it. Sometimes, the primary challenge in science is not even to solve the problem, but to tease out a clear question from a tangled network of processes. Students may need lessons in how to address unruly complexity.

Others no doubt teach simple concepts intending to equip students with the fundamental tools for interpreting a world that is far too complex to master in its entireity. Unfortunately, curricula rarely include how to apply the simple concepts in complex scenarios. Students are thus underprepared.

As a "simple" solution I suggest teaching complexity (Jungck 1996). At least sometimes. Students deserve to see that nature does not always fit the simple models in the textbook.

Non-scientists, in particular, need to encounter ambiguity, qualified judgement and the limits of reasoning in science. They need to understand science as "work." They need some example, such as the "real" peppered moth case, not the diluted black-and-white one of school science. Not all introductory science can be taught this way, surely. Even one case, however—articulated well—can dispel myths that develop or persist when artificially crafted simplicity is the exclusive norm. Ideally, teachers will also explicitly contrast the simple and complex pictures, helping students to analyze how simple models can mislead us. Through experience with actual complexity, non-science majors and future science teachers can learn when to be wary of simple claims and how to pose the right questions that probe deeper.

Another strategy is to teach questions instead of answers. That is, replace prepackaged science-made with science-in-the-making (Latour 1987). When students confront genuine questions without obvious answers, they begin to understand the scientist's challenge of making sense of the world. They will soon find the need to target, organize and filter their observations. Guided through an investigation, they begin to exercise experimental reasoning with all its subtleties. Here, historical case studies can be effective vehicles for situating students in rich problem scenarios (Allchin 1997; see Hagen, 1996, for the Kettlewell case; also *JCST*'s Case Study column). The aim may not be to teach *about* Kettlewell, for example, but to pose Kettlewell's problem of industrial melanism. What alternative explanations are possible? What observations would help us determine which explanation is most reliable? How do we interpret various findings and draw conclusions, with what degree of confidence? Again, even one experience through a textured problem sets a context for interpreting all other scientific claims.

For the experienced teacher, the details of the peppered moths and Kettlewell's research can be entertaining and provide fascinating anecdotes or added depth for teaching this particular case. But I hope they are more than that. I hope they are an occasion to reflect on the difference between real science and school science—and on the nature of science teaching wherever anything that cannot be reduced to black and white is typically missing.

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References

Allchin, Douglas. 1997. Rediscovering science through historical case studies. Pp. 183-204 in *History and Philosophy of Science: A Means to Better Scientific Literacy?*, A. Dally, T. Nielsen and F. Reiß (eds.), Loccum, Germany: Evangelische Akadamie Loccum.

Allchin, Douglas. 2002. Dissolving dominance. In L. Parker and R. Arkeny (eds.), *Medical Genetics: Conceptual Foundations and Classic Questions*, Pittsburgh: University of Pittsburgh Press.

Endler, John. 1986. *Evolution in the Wild*. Princeton: Princeton University Press.

Hagen, Joel B. 1993. Kettlewell and the peppered moths reconsidered. *BioScene* 19(3): 3-9.

Hagen, Joel B. 1996. H.B.D.Kettlewell and the case of the peppered moths. In *Doing Biology*, J.B. Hagen, D. Allchin and F. Singer, Glenview, IL: Harper Collins, pp. 1-10.

Hagen, Joel B. 1999. Retelling experiments: H.B.D. Kettlewell's studies of industrial melanism in peppered moths. *Biology & Philosophy* 14:39-54.

Hagen, J. B. , Allchin, D. and Singer F. 1996. *Doing Biology*, J.B. Hagen, D. Allchin and F. Singer, Glenview, IL: Harper Collins

Jungck, John. 1996. Ignorance, error and chaos: local learning/global research [in Japanese]. *Japanese Journal of Contemporary Philosophy or Modern Thought* 24(11): 363-376. English translation at http://www.beloit.edu/~biology/ignorance.html.

Kettlewell, H.B.D. 1955. Selection experiments on industrial melanism in the Lepidoptera. *Heredity* 9:323-342.

Kettlewell, H.B.D. 1956. Further selection experiments on industrial melanism in the Lepidoptera. *Heredity* 10:287-301.

Kettlewell, H.B.D. 1959. Darwin's missing evidence. *Scientific American* 200(March): 48-53.

Kettlewell, Bernard. 1973. *The evolution of melanism: the study of recurring necessity; with special reference to industrial melanism in the Lepidoptera*. Oxford: Clarendon Press.

Latour, Bruno. 1987. *Science in Action*. Cambridge, MA: Harvard University Press.

Martin, Brian. 1991. *Scientific Knowledge in Controversy: The Social Dynamics of the Flouridation Debate.* Albany, NY: State University of New York Press.

Robins, H. 1992. *The Scientific Image: From Cave to Computer*. New York: H. N. Abrams.

Rudge, David W. 1999. Taking the peppered moth with a grain of salt. *Biology & Philosophy* 14:9-37.

Starr, Cecie. 1994. *Biology: Concepts and Applications*, 2d ed. Belmont, CA: Wadsworth.

Steinbach, S.E. 1998. How frivolous litigation threatens good science. *Chronicle of Higher Education* (Dec. 4): A56.

Toumey, Christopher. 1996. *Conjuring Science*. New Brunswick, NJ: Rutgers Univesity Press.

Tufte, Edward R. 1997. *Visual Explanations: Images and Quantities, Evidence and Narrative*. Cheshire, CT: Graphics Press.