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How School Science Lies

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ABSTRACT: School science lies. It lies about Mendelian genetics, the peppered moth, male and female, the motion of a pendulum, the Bohr atom, the fluid model of electricity and many other basic concepts, all due to simplification. Real science relies on domain-specific models and so always lies at some level. Teachers thus need to help students appreciate how science interprets complexity and how to manage with the lies they inevitably learn.

INTRODUCTION: FOUR CASES OF LYING

School science lies. It lies about history and nature of science (Brush 1974). It lies about the process of science (Nott and Smith 1995). It lies about content (Cartwright 1983, and below). Worse, it does not acknowledge its lies. But lying may nonetheless be warranted. It may well be inevitable. The challenge, then, is to help students appreciate how school science lies and how to cope with its inherent falsehoods.

Consider, by way of introduction, several familiar examples: Mendelian genetics, the peppered moth, male and female, and the motion of a pendulum.

Mendelian genetics. Everybody learns Mendelian genetics. Inheritance occurs through discrete units, genes. Heritable traits come in pairs, but only one trait is expressed; when combined, some are dominant, others are recessive. Unfortunately, these simple 'facts' are deceptive (Allchin 1999, 2000; Allchin & Paquin, forthcoming). First, we now know that for most traits many more than two genes exist. Second, at molecular and physiological levels, both genes are expressed. Genetically, we do not express traits, but compound pairs of traits. Only on some occasions—one-third or less— does the overall effect of one trait 'overshadow' the other, as dictated by the concept of dominance. Moreover, framing inheritance in terms of genes alone eclipses the importance of cytoplasmic inheritance, the intergenerational transfer of non-nuclear cell components, not composed of DNA. These include ribosomes, without which the very genes themselves could not be expressed, as well as the mitochondria, which process the energy that fuels the whole system.

While omitting these details may seem minor, even trivial—perhaps of concern only to professional biologists—they can have profound effect culturally. Such basic and widely taught concepts affect how non-biologists think about the world. They shape conceptions of and metaphors about nature and hence perceptions about what is 'natural', 'normal', or acceptable. For example, the Mendelian binary model suggests that choices are dualistic. The dominance concept further implies that such choices are either-or. Consider the implications for interpreting political relations, from marriages to legislative bodies and courts. Dominance gives a 'naturalness' to one voice wholly eclipsing all others. Shared voice, synergy, or the search for creative alternatives all become 'unnatural', or outside the norm. How teachers frame Mendelian genetics has cultural overtones.

In addition, the eclipse of cytoplasmic inheritance contributes to focusing almost exclusively on genes. In popular conceptions, genes are identity. The perceived significance of other biological dimensions, including the causal role of the organism's environment or context, or of long-term amplifications of minor chance variations, recede. The genes-as-identity misconception, in turn, cascades into misinformed views about cloning, genetic diseases, reduction of behavior to genes (genes for everything from homosexuality to altruism), the value of funding the Human Genome Project and more.

In the case of Mendelian genetics, a simplified version of reality is not merely modestly selective or streamlined. It is misleading. The simple concepts blinker our vision and reduce the scope of our awareness of the world. Mendelian genetics, as found in current textbooks, lies. How does a student learn its lies and their implications?

The peppered moth. Everybody learns, too, about the peppered moths and their evolution from light to dark forms during Britain's industrial revolution. The case is now a classic for teaching natural selection. The images of the light and dark moths against different backgrounds, light and dark, epitomize selective predation visually; teachers hardly have to work at explaining anything! (One text even uses the same images twice!) Students readily recall this case years after their last science class, indicating the potency of the images.

Unfortunately, the widespread textbook story and images are, again, incomplete and misleading (Allchin, forthcoming). First, peppered moths come in several forms, from light to dark. The now canonical image omits the intermediates, reducing nature to 'black and white'. While this does not subvert the ultimate conclusions about evolution, it does significantly alter images of natural selection and competition that, once again, govern both scientific and cultural understanding. For example, students already tend to conceive natural selection in stark, life-or-death terms: competition has winners and losers; organisms are either fit or unfit. Simplifying the peppered moth case into a black-or-white, either-or framework merely reinforces this harsh stereotype. In addition, conceptions of competition and 'survival of the fittest' pervade our society, from the World Cup and the Super Bowl to international economics and ethnic homelands. As a 'natural' benchmark, the peppered moth case implicitly guides thinking. A win-lose model of competition is subtly written into and indirectly legitimized by the iconography of the moths (just as with simplified Mendelian genetics). The images confirm (informally, visually, and indirectly, of course) that competition and selection function through clear, dualistic choices. Our cultural perspectives are partly distorted by the lies of school science.

Similar omissions occur in textbooks that parade the experimental elements of this now classic case. Using mark-release-recapture techniques, H.B.D. Kettlewell compared the relative survival rates of the three different forms of peppered moth in the polluted woods outside Birmingham and among the lichen-covered trees of rural Dorset. The two contrasting environments represent a huge controlled experiment. Historically, however, the results from one half of the study were published independently, as though the second half was unnecessary. The parallel field study was certainly not conceived in one flash of insight, as the myth of scientific genius suggests. The second study was most likely motivated by peer criticism, another factor of science often missing from textbook accounts. Finally, textbooks present the reasoning as conclusive, though skepticism is also often considered a hallmark of science. In this case, there are certainly 'loose ends', such as unequal predation rates at the two sites and other possible differences that might account for the results. Ultimately, a simple account of Kettlewell's work distorts the process of science, while perpetuating stereotypes about scientific insight and experimental evidence. The textbook case of the peppered moth lies, too. And the innocent, naive student never knows.

Male and female. You don't need a science class to know that sexual organisms are classified into male and female. But you probably do need a good biology class to learn that these categories are not exhaustive. First, many species are asexual (no male *or* female). Even among sexual organisms, some species or individuals can be neuter (no sex) or hermaphroditic (both male and female). Even humans. There are a variety of intersexuals, whose chromosomes, internal gonads and external genitalia do not 'match', or fit comfortably into the simple male-female dichotomy (Dreger 1998, Fausto-Sterling 1992). Among humans (at birth), approximately one in a thousand falls into one of these 'ambiguous' categories. How does a new parent respond to the primary question of identity in our culture: 'is it a boy or a girl?' Where do these individuals belong in the natural order?

According to the simple male-female dichotomy, these intersexuals are anomalies. They are freaks. Though they are products of nature, many regard them as 'unnatural', or outside the norm. Surgery is often recommended, so that the individual can conform to 'nature's' categories—that is, the categories humans have imposed on nature. Who cherishes these individuals as rare biological gems? If the biological characterization of male and female is not absolute, then the cultural notions of gender must be even more insecure and problematic. Again, simple scientific categories can err, leaving effects that cascade into cultural practices.

The motion of a pendulum. The formula for the period of a pendulum is a standard favorite in introductory physics classes (e.g., Matthews 1999). The mathematics are simple enough that teachers and textbooks can, and often do, lead students through the derivation. There is a critical assumption in that reasoning process, however. At one step, a value for sin   is required, where   is the angle of displacement of the pendulum. One assumes that   is very small and then substitutes the value of   for sin , which makes everything much(!) easier and 'neater'. So students are cautioned (sometimes) that the formula only works for very small angles. Strictly speaking, though, the simplified formula is false. (In the same way, one assumes that the mass of the pendulum occurs at a single point—a false premise that makes the calculation workable.) The precision implied by the mathematics (and with it, the image of scientific authority) can easily be misleading. The formula only delivers, at best, an approximation. Understanding fully the nature of this approximation is important, but this involves a level of subtlety not usually found in the classroom.

The true complexity of pendular motion is exposed when one considers the formula for motion at large angles:

$$\frac{d^2x}{dt^2} + \frac{g}{L} \sin(x) = 0$$

(where g=9.8 m/sec; L is the length; and x is the angle). This is a transcendental equation, with no analytical solution. One typically approaches a solution by expanding the Taylor series approximation for sin (x) to the desired precision:

$$\sin(x) = x \quad x^3/3! + x^5/5! \quad x^7/7! + \ldots$$

One then tests values iteratively by substitution. No wonder that one only encounters this in far more advanced classes. In this context, one can see more clearly the small-angle formula for what it is: a lie. A convenient and useful lie, perhaps, but a lie nonetheless.

When students measure the motion of a pendulum in the lab, they also encounter another phenomenon not evident in the formulas and rarely profiled in the texts: damping. A pendulum loses amplitude with time, eventually stopping. In the real world there is friction. A pendulum loses energy. Of course, applying the principle of the conservation of energy to a pendulum is an idealization. Still, an idealization is just that. It is not the real world. The idealization lies. Physics lab equipment suppliers have gone to great lengths to develop frictionless' apparatus for studying dynamics. Why? Shouldn't we wonder why we must create an idealized, wholly artificial environment in the lab to examine the real world (Galison 1994; Cartwright 1983, 156)? Shouldn't students understand how the laws of physics depart from reality as much as they may reveal something of its nature?

Most physics students will likely never need to entrust their lives to knowing the limits of the formula for the period of a pendulum at small angles, and few will ever try to build a timepiece requiring a fricitonless pendulum. The value of the classroom exercise cannot be about the pendulum itself. Rather, it is to understand the mathematical representation of nature (here, the physics of movement) and the nature of science, more generally. Under these circumstances especially, it is all the more important to recognize that the simple lessons on the pendulum lie. But how many students understand the lies and can articulate their meaning?

THE DANGERS OF LYING

In all these cases (and others discussed below), school science lies by simplifying the world. But the simplification is not transparent. Why should this matter? Don't we need to simplify science—and, indeed, all knowledge—for the sake of teaching in school? I contend that we should question this widespread premise.

The danger is that we convey a false image of the world. Simple school science conditions students to expect simplicity. When they encounter complexity, they may feel betrayed, or 'simply' lack the skills to interpret the circumstances fully. In popular conceptions, science speaks the truth. The whole truth. It does not err. Nor does it speak partial truths or incomplete truths. It leaves no ambiguities or uncertainties. (That is what makes it science, after all!) Moreover, the categories of 'right' and 'wrong' are themselves clear and well differentiated.

The implications of the simple perspective for society are profound. Nowadays, when scientists make mistakes, people sue (Steinbach 1998). In one case, researchers at Carnegie Mellon University deleted two sentences from a paper on absestos after reviewers noted that the data did not fully warrant the particular conclusions. Decades later, in 1994, they were sued for the omission, ostensibly because later results validated the claims. In another case in 1995, Syracuse University defended a researcher who had advocated a method of 'facilitated communication' for autistic patients, later shown to be flawed. The plaintiffs deemed the researcher responsible for actions by certain therapists, based on the scientific error. Legislation to avert such frivolous lawsuits has been proposed in the U.S. Congress. Yet consider the simple conception of science that allowed this litigation to emerge at all.

Sociologists of science document how the public tends to cast scientific debates into either-or extremes and to view scientific theory and evidence as simple. For example, the controversy on flouridation of water is sharply polarized, with 'pro' and 'con' sides each claiming science for themselves and denying credibility to any 'opposing' position (Martin 1991, Toumey 1996). Indeed, good data supports elements of each of their divergent contentions, but each group conceives its own supporting evidence as complete and 'right' on its own. Ultimately, decisions about flouridation involve values. Members of a community need to resolve conflicting risks and benefits. But, again, each group presents science as the final arbitrer and the evidence as univocal. Similar polarities and simplifications permeate debates on HIV testing and the teaching of evolution in the U.S. (Toumey 1996). Where do such simple—and socially problematic—views of science originate?

Much of the current problem originates, I contend (as illustrated in the four cases above), in the well intentioned effort of educators to simplify science for school settings. Simple versions are presumably easier to teach and easier to learn. But if we justify science education in part through its role in informing public decision-making, this strategy is misguided. Most issues of science in public decision-making are quite complex. Yet we only prepare students for simple problems. That is the message of cookbook labs and heroic tales of scientific genius. Students, as future citizens, need to understand, for example, that science can involve uncertainty, ambiguous results and mixed evidence. That is, evidence may be incomplete. Data may fit contrasting interpretations. Different studies may support contradictory conclusions. Theories that are supported by some evidence can still be in error. Simple concepts can be misleading. In short, science—and the world it describes—are complex.

THE INEVITABILITY OF LYING

Perhaps the optimal solution would be to teach everything in its full complexity. But this is patently impossible. Another maxim advises, 'Teach the basics first'. Basic concepts seem secure and, at the very least, foundational. One certainly hears that kind of rhetoric in the Science Wars. Unfortunately, as sketched above, the basic concepts epitomize the very problem itself. Can one ever escape lying?

According to physicist and philosopher of science Nancy Cartwright (1983), no. The very laws of physics lie. By this she means that even though the theories of physics have extraordinary explanatory power, one cannot construe them realistically. They carry with them certain boundary conditions, or specific domains of application (p.12). They also typically carry an unstated, but nonetheless critical, *ceteris paribus* clause (e.g., Snell's law of refraction, pp. 45-47). We can only explain real events by combining causes from different theoretical laws and making approximations (as in the pendulum case). These are important caveats. Until one fills in the context for a particular event, Cartwright claims, the typical abstract equation that one finds in physics is literally false. She agrees that idealizations are just that: idealizations, not reality (pp. 109-112, 153-156).

In unfolding her argument, Cartwright advocates a particular metaphysical posture of anti-realism. I have no such ambitions. However, I do want to underscore the pragmatic dilemma she dramatizes. The practice of abstraction, which Matthews (1998) parades in the pendulum case and hails as the hallmark of the Scientific Revolution, is both a blessing and a curse. As one generalizes, one also loses realism and its particulars (Levins 1966). The simpler, more elegant and more encompassing a concept, the more it lies.

Other philosophers echo Cartwright's basic themes, though in less inflammatory images and in ways more vividly relevant for public understanding of science. Ultimately, all theories, all models, all concepts, are selective. They isolate certain variables as relevant. At the same time, they ignore other dimensions of the same reality. In this view of science, theories are like maps (Turnbull 1989, Judson 1980, Monmonier 1991). They depict a certain empirical territory, but highlight only certain features of the landscape. For clarity, they actively suppress other elements that would tend to confuse the picture. Some maps are topographical, others are political. Some show soil types, some biotic zones, some population densities, some highways, some watersheds, etc. All may be important, for example, in resolving an environmental issue. But none individually is complete. This does not make maps or scientific theories useless. Nor does it mean they have no correspondence with reality. Only that the correspondence is limited. Moreover, imagining the model as a guide outside its proper scope or domain can lead to error. Mendelian genetics and other basic concepts do not tell the whole story. The conceptual map is misleading when used to intepret the complete landscape. Unfortunately, a map cannot report all its own limitations. Scientific theories, like maps, reveal truths *and* lie simultaneously.

This applies in school settings as much as anywhere. Consider, for example, the Bohr model of the atom, standard fare in most chemistry courses. Bohr envisioned electrons orbiting around a nucleus at various energy levels. Historically, the model was especially effective in explaining, or mapping, spectra lines (the Balmer series) and chemical bonding. But according to currently accepted quantum theory, the Bohr model is wrong. There are no discrete electrons moving in discrete orbits. They are a fiction. Should teachers thus abandon the Bohr atom as a lie? Or should we accept it as a model, for the truths it does reveal? If so, should we tolerate the inevitable lies without also elucidating the nature of models?

The fluid model of electricity serves similar functions. As a model or mechanical metaphor for understanding the 'flow' of electrical 'current' in circuits, it is effective. It makes sense of voltage, resistors, capicitors, switches and circuits arranged in parallel versus in series. Circuits do really behave in fluid-like ways. But electricity is not a fluid. It does not 'flow' in a 'current' like a river. Electricity in circuits is about displaced electrons. Many texts acknowledge the lie, but exploit the fluid analogy anyway. Why? Can we use a general understanding of the nature of models to resolve the tensions between fuild models of electricity and more complete (or 'honest') lessons about electricity (Stocklmayer and Treagust 1994)?

Lies and truths coexist. Thus, theories we conventionally say 'lie' may convey some truth. One overstates the case, for instance, to claim that the Copernican Revolution eliminated any warrant for thinking in geocentric terms. Even today, celestial navigators are Ptolemaic astronomers. They use an Earth-centered model appropriate to the limited domain of navigation. Within that model there are right ways and wrong ways to navigate. One need not claim that heliocentrism or geocentrism is absolutely true—*or* false. Each perspective captures enough reality appropriate to different occasions.

In the same way, relativistic physics has not wholly eclipsed Newtonian physics, though strictly speaking, the latter is false (Kuhn 1970, pp. 98-99, 101-102). No one includes a factor of $1 \ (v^2/c^2)$ when calculating the velocity of automobiles in crash-tests. The lie is inevitable, but allowance for imprecision gives limited warrant to classical mechanics in nonrelativistic domains, where objects travel at far below the speed of light. Teachers cannot escape the lie, but students may be able to interpret its meaning.

Finally, consider the common caricature of phlogiston as the quintessential embarassment of science. In its original role during the eighteenth century, phlogiston explained oxidation and reduction reactions at a macroscopic level. No one needed to refer to electrons. Indeed, like many chemists after the discovery of oxygen, we can still talk meaningfully in terms of phlogiston, regarding it, like energy, outside the domain of weight (Allchin 1992). Phlogiston helps unify combustion, calcination, tarnishing, rusting, explosions, reduction of ores, animal respiration and photosynthesis (and even electrochemistry and acids) in a common conceptual framework. Accordingly, it can provide valuable lessons in the introductory classroom (Allchin 1997a). Lies may still convey an essence of reality.

BEING HONEST ABOUT LYING

So *all* scientific theories inherently lie. What a dismal conclusion for the science teacher who wants to lead her students to the truths of the world! What potential despair! The solution is 'simple', though: be honest about lying. Telling lies and telling *that* you are telling lies are complementary tasks.

Merely announcing the lies, though, is not enough. The teacher cannot (as many already do now) dismiss the problem casually: 'of course, the world is more complex than this, but this is all you need to know for the test'. Rather, one must teach fully the process of lying as a way to interpret the meaning of the lies. On at least one occasion, the teacher must unleash the whole complexity of a problem, concept or historical episode. Teachers must 'go complex' (Jungck 1996). To be complete, the lesson should contrast simple and complex versions. Students must see—or better, analyze themselves—exactly *how* a simple conception can be misleading. They should learn how to diagnose such cases and how to pose the relevant questions that will help expose the complexity. Even one example can serve as a precedent and caveat, and help justify the inevitable lies on other occasions.

The cases profiled briefly above are samples. Consider, as a further example, the story of Nobel Prize winner Christiaan Eijkman (Allchin 1996, 1997b). Eijkman was searching for the cause of beriberi, a weakening disease prevalent in southeast Asia in the late 1800s. Following Koch's dramatic recent discoveries on tuberculosis, cholera and diphtheria, germ theory served as a model for investigation. Through a lucky accident, Eijkman was able isolate the cause of beriberi to a minimal diet of polished (white) rice. All the evidence fit neatly with the notion that a bacterium in the rice caused the disease and that an agent in the rice covering (cuticle) cured it. Further, a monumental controlled study, involving 100 prisons and almost 280,000 prisoners, confirmed Eijkman's hypothesis. Now, however, we view beriberi as a nutrient deficiency. Historically, Eijkman's work contributed ultimately to the discovery of vitamins. Ironically, though, Eijkman rejected the vitamin explanation when first proposed. How could Eijkman have been both 'right' and 'wrong' at the same time? Unraveling a paradox such as this is central to understanding how some scientific concepts can lie. (Other Nobel Prize winners besides EIjkmkan have also erred; Darden 1998.)

Many new national and state educational standards already mandate lessons in history and nature of science. This rubric is foundational. However, the category alone is too broadly stated. Simplified histories that idealize science are widespread. Like simple concepts, they lead away from, rather than towards, deeper understanding of science (Allchin 1995). Curriculum standards should imply or state explicitly the need for students to understand the limits and potential errors of scientific theories, especially when simplified.

Educational settings especially need to be sensitive to how scientific concepts map circumscribed domains, as they form the bedrock of conventional curriculum. For some, basic concepts constitute a pure, unbiased and unimpeachable foundation. But as the analysis above indicates, even simple concepts have (sometimes hidden) philosophical and cultural content and overtones. Many science educators fear missing content. I fret instead about *mything* content. Mything content perpetuates a simple image of science that is historically and philosophically misinformed and that distorts public discourse on science. Teachers should worry as much about myth-conceptions as *mis*conceptions. Teaching *how* school science lies will help remedy the potential consequences of the lies themselves.

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