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ARTICLE

The Value of False Theories in Science Education

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Abstract

Teaching false theories goes against the general pedagogical and philosophical belief that we must only teach and learn what is true. In general, the goal of pedagogy is taken to be epistemic: to gain knowledge and avoid ignorance. In this article, I argue that for realists and antirealists alike, epistemological and pedagogical goals have to come apart. I argue that the falsity of a theory does not automatically make it unfit for being taught. There are several good reasons for teaching false theories in school science. These are (a) false theories can bring about genuine (non-factive) understanding of the world; (b) teaching some false theories from the history of science that line up with children's ideas can provide students "intellectual empathy" and also aid in better grasp of concepts; (c) teaching false theories from the history of science can sharpen students' understanding of the nature of science; (d) scientists routinely use false theories and models in their practice and it is good sense for science education to mirror scientific practice; and (e) learning about patently non-scientific and anti-scientific ideas will prepare students to face and respond to them. In making arguments for the foregoing five points, I draw upon the work of a variety of philosophers and historians of science, cognitive scientists, science education scholars, and scientists. My goal here is not only to justify theories considered false already being taught, but also to actively endorse the teaching of some theories considered false that are by and large not currently taught.

Keywords Scientific realism · Science teaching · History of science · Philosophy of science · Science learning

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1 Introduction

Theories regarded as false form a big part of school science. Today, we consider Newtonian mechanics to be false in light of Einstein's theories of gravitation and quantum mechanics; we consider Rutherford's and Bohr's planetary models of the atom to be false in light of quantum mechanical models; and we consider Lamarckism to be false in light of Darwinian and Mendelian genetics. But these continue to be taught in K-12 science. In fact, it is not until late in high school or in many cases only in college that the accepted-as-true—and often more sophisticated—theories are taught. As Matthew Slater (2008) has noted, such a practice goes against the prima facie pedagogical and philosophical belief that we must only teach and learn what is true. In general, the goal of pedagogy is taken to be epistemic: to gain knowledge and avoid ignorance. Why then are some theories regarded as false still taught? Are we wrong in teaching them? In this article, I argue that there are indeed several good reasons for teaching false theories in school science. Briefly, these are:

(a) False theories can bring about genuine (non-factive) understanding of the world;
(b) Teaching some false theories from the history of science that line up with children's ideas can provide students "intellectual empathy" and also aid in better grasp of concepts;
(c) Teaching false theories from the history of science can sharpen students' understanding of the nature of science;
(d) Scientists routinely use false theories and models in their practice and it is good sense for science education to mirror scientific practice; and
(e) Learning about patently non-scientific and antiscientific ideas will prepare students to face and respond to them.

In making my case for the teaching of false theories, I draw upon the work of a variety of philosophers and historians of science, cognitive scientists, science education scholars, and scientists. I see this project as—to put it in Kate Manne's (2017) words—"joining dots well-drawn by other theorists" (p. xv) and practitioners in various related fields. My goal here is not only to justify teaching theories considered to be false, but also to actively endorse the teaching of some such theories (some of which are by and large *not* currently taught). I should say at the outset that this is not an empirically grounded project: the justification and endorsement are based on theoretical (philosophical, historical, cognitive scientific) perspectives. The central contribution of this article is a robust catalog of principled reasons supporting the teaching of certain false theories.

Slater (2008) has given an excellent analysis of teaching false theories in school science. He notes that, although truth is traditionally highly valued, it is not the case that we teach any and all truths—we want to weed out the trivial, the obvious, the tautological, and so on. So—he goes on to note—what those who value the teaching of truth really want is the teaching of *significant*[1] truths. He then argues however that significance and truth may come apart, and that only the former is necessary for pedagogical justification. I think this hits the nail on its head. False theories can be significant in various ways, and this significance is what warrants their teaching. Here, I discuss various ways in which false theories can be significant.

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[1] See Philip Kitcher (2001) for a related discussion.

With respect to the prescription of teaching false theories and models though, although arguing in favor of teaching them, the bulk of Slater's paper is about why and how *not* to teach them. For instance, he argues that the teaching of false theories cannot be defended on the grounds of their social utility; that the high level of complexity of more advanced and modern theories by itself is no reason to teach simpler, falser theories from history; and that an instrumentalist perspective does not ameliorate the situation since taking that perspective would make nonsense of our current education—we teach things just "for the sake of curiosity" all the time. While I mostly agree with these negative arguments, the paper leaves much to be desired in terms of positive arguments. When it comes to reasons *for* teaching false theories and models, the only point he makes is that when these are taught from within their historical contexts, they serve as exemplars of how science was and is done: that is, as I understand it, they (crucially) serve to teach about the nature of science. I agree with him on this of course, but contend that there are several other arguments for teaching false theories. In the present article, I discuss these.

While the call for teaching false theories in science education is not new—there have been repeated calls from science education scholars for teaching at least one variety of false theories, superseded theories—I think it is still worth underlining the following. Philosophical views on the epistemic goals of science, and pedagogical goals—in particular, the epistemic status of what is taught in the science classroom—cannot always go together. Many educators believe that science is in the business of uncovering truths about reality, and this belief spills over into the science classroom. They believe that it is better to stick to theories well accepted as being true, and deem refuted theories to be irrelevant and fear that teaching them would confuse students (Galili and Hazan 2001). As Igal Galili (2014) has noted, several textbooks in optics for instance omit any discussion of the theories of Heron, Archimedes, Fermat, or Descartes. The present article joins the calls for the inclusion of certain theories taken to be false, in the science curriculum.

Further, it is often held that while false theories of various stripes can be taught, they should be taught as *false* (for instance Slater 2008), thereby still upholding the epistemological goal of truth—if you teach a false theory as false, the ultimate claim that it is false is true. While I do not disagree with this prescription, I think that with some false theories, depending on the goal of their use in the classroom, it might be better not to foreground the falsity. We should teach it as false if learning it as false contributes to the overall learning goals at hand, but we should put the falsity in the backseat—or at most the front passenger seat—if entertaining the theory seriously (despite its falsity) will contribute to the overall learning goals at hand. Learning goals should be the driver here. In cases where knowledge of the falsity could interfere with learning goals, the falsity can be conveyed to students *after* teaching the theories. Or if teachers want to present it alongside the content of the theories, they can at least do so without necessarily underlining or foregrounding it. Students should appreciate and wrestle with the theories as much as possible in order for the relevant learning goals to be met. If the falsity is foregrounded, it might bias and interfere with students' learning. Knowledge of the falsity of the theories does not trump learning goals.

Before proceeding, I should clarify that my use of the word "theory" in this article will be fairly loose and informal. I use the term to include not just theories[2] proper—both empirical/phenomenological such as the Kinetic Theory of Gases and, fundamental, such as Newton's theory of Gravitation/the General Theory of Relativity—but also as a shorthand for models, explanations, arguments, and bodies of theoretical and empirical facts drawn from a range of sciences supporting empirical phenomena such as climate change; and collections of ideas, broadly speaking. A precise definition of theory will not be as important to this project as the fact that the theories I discuss here are widely considered to be false and/or discredited.

2 What Is a False Theory?

First of all, what makes a theory false? In general, we can say that a theory is false if the central claims it makes about the phenomenon it purports to describe or explain are untrue. Philosophers of science—especially since Bas van Fraassen's *The Scientific Image* (1980)—generally make a distinction between truth and empirical adequacy. A theory generally consists of what we call theoretical as well as observational claims. On the one hand, theoretical claims are claims about things deemed unobservable,[3] such as fields and subatomic particles, usually posited to explain observable phenomena. Theoretical claims are claims about an ontology underlying the observable world—like claims about quarks, fields, and genes. A theory is then said to be true if its theoretical claims are true (assuming of course, that there is such a thing as a true theoretical claim and that we can come to know of its truth—more on this below). On the other hand, a theory is said to be empirically adequate if (most of the central) claims it makes about observable phenomena within its domain—i.e., its observational claims within its domain—are true. If a theory's theoretical claims are true, it also has to be empirically adequate since empirical claims are generally implied by the theoretical claims, but an empirically adequate theory need not be true.[4]

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[2] In philosophy of science, there have been two prominent views of scientific theory: the syntactic view which takes a theory to be an axiomatized collection of sentences, and the semantic view which takes a theory to be a collection of non-linguistic models. My use of "theory" in this article is I think most aligned with the use of the term in the pragmatic view of scientific theory—that a theory, in Savage's (1990) words "is an amorphous entity consisting perhaps of sentences and models, but just as importantly of exemplars, problems, standards, skills, practices and tendencies." (pp. vii–viii) I should clarify though that here I am not defending the pragmatic view—I am in fact not defending any particular philosophical view of scientific theory. And in discussing, for instance, intelligent design or climate change denial as a false "theory" to be taught, I am not claiming that either should qualify as a theory according to any philosophical view—all I am doing here is using the word "theory" as shorthand for "body of views".

[3] There is a long-standing debate in philosophy of science on the legitimacy of the observable/unobservable divide. See Hempel (1950), Hanson (1958), Feyerabend (1959), Kuhn (1962), Popper (1965), and van Fraassen (1980) for key debates. Issues include entities not considered observable earlier (like microbes) now being considered observable; deciding a standard (human sense organs? hypothetical advanced human sense organs? lab instruments?) with respect to which entities are considered observable; and so on. Here, my larger goal is to show that some theories not favored by antirealists (and some by realists) can be valuable in the classroom, and taking a side in the observable–unobservable debate will not be pressing.

[4] The question of what features—if any—a theory needs besides empirical adequacy to make it true is a long-standing one in philosophy of science. See Duhem (1954), Kuhn (1962), Laudan (2004), and Douglas (2013) for key debates. Antirealists generally maintain that nothing can ever establish that a theory is true, while realists generally take it that based on a theory's empirical adequacy, although one cannot logically deduce that it is true, there are ampliative arguments for inferring that it is true. And whether such ampliative arguments work is at the core of the realism–antirealism debates.

If "false" is taken to be the opposite of "true" as construed above, then by false theories, we mean those that get the theoretical claims wrong. For example, Newton's theory of gravitation, although largely empirically adequate in domains of experience we ordinarily deal with, is wrong about the existence of an (unobservable) action-at-a-distance force in light of Einstein's general theory of relativity according to which massive objects cause a distortion in space time itself. Hence, Newton's theory of gravitation is false. Of course, a theory that does not even get (at least many or most of) the empirical facts right would be obviously false. (I should add here that "truth" in the sense discussed above does not apply to all theories I discuss here, for not all theories *make* theoretical claims. There are theories that only make empirical claims. With theories that are not in the business of making theoretical claims—i.e., for theories that only make empirical claims—by "false" I will mean "false about empirical claims" - or 'False According to Empiricists' as below.)

First, I want to distinguish my view about teaching false theories from a few others. Someone who prizes teaching theories that get the facts right might hold that if a false theory is taught, it should at least be one that is reasonably empirically adequate: most of its empirical claims should be (at least approximately) true. So one could defend teaching Newton's theory on the grounds that although it is false, it is largely empirically adequate in domains of ordinary experience: the teaching of Newtonian gravitation can be defended on empiricist grounds. This line parallels the empiricist view in the realism debates in philosophy of science. While there are several different realist and antirealist views, the commonly accepted positions are as follows: realism has it that the science does/aims to come up with true theories, while antirealism—specifically empiricism—has it that science only does/aims to come up with empirically adequate theories.[5] Theories that are True-According-to-Realists (TAR) are those that are highly empirically adequate, and based on the empirical adequacy realists infer that they are true—i.e., that their theoretical claims are true—usually by means of some sort of ampliative reasoning like inference to the best explanation. (The best explanation of empirical success of theories is that they are true.) Clearly, teaching theories that are False-According-to-Realists (FAR)—i.e., those such as Newton's theory, that make false theoretical claims—goes against the epistemological goals of science according to realists. But is it the case that teaching FAR theories is *only* a problem for realists?[6]

Slater answers this question in the negative for the reason that the realism–antirealism debates are still alive in philosophy of science—it has not been conclusively settled that one or the other is the right way to think about science. I take it that his point here is that if it is not settled as to whether realism or antirealism is the correct view about science in the first place, then antirealists cannot defend the teaching of false theories on antirealist lines. I choose to tackle this a bit differently. Teaching FAR theories is not necessarily a problem for realists alone—it can be equally problematic for antirealists. This is because not only do I think that FAR but empirically adequate theories (that is, theories that are True-According-to-Empiricists (TAE)) have a place in school science; I also think that empirically inadequate theories have a place as well. The falseness I endorse here includes not only theories that are false but

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[5] A common reason for this is that the observable has a privileged epistemic status since it is—at least in principle if not practically—accessible to us with our unaided senses (van Fraassen 1980). Hence, this variety of antirealist argument goes we should only pursue knowledge of the observable.

[6] In this regard, Slater brings to our attention a version of realism—one that van Fraassen (1980) underlined—that only claims that science has an *aim* of attaining truth, not that our best theories *are* (approximately) true. And such a realist would also be at loggerheads with my view since I also endorse the teaching of some theories that did not/do not purport to be true; they might be purely instrumental or heuristic. But teaching false theories is not a problem just for realists as we are about to see.

empirically adequate. I also endorse the teaching of some FAR theories that may be empirically inadequate, that is, I also endorse the teaching of FAR theories (and theories that only make observational and not theoretical claims) that are False-According-to-Empiricists (FAE).[7] Realists and antirealists would both be equally troubled by this view if their pedagogy aligns with their epistemology. I argue that once one sets the epistemic goal of truth aside, there is much to gain by teaching theories taken to be false.

Instrumentalism, a variety of antirealism, is the view that science does/aims to construct theories that are practically useful. Here, the goal is not epistemic, but practical or instrumental—like usability for building bridges or curing diseases. My view here is not a blanket pedagogical equivalent of instrumentalism either. While the grounds for teaching *some* false theories might be their instrumental value, as we will see, I think there are good pedagogical reasons to teach some other theories that are not true, empirically adequate, or instrumentally valuable. I think this way of tackling instrumentalist responses—that is, to argue that there are cases where instrumental value is immaterial to pedagogical value—is better than Slater's (2008) response, which was that an instrumentalist could not defend the teaching of false theories on the basis of instrumental value since that would "make nonsense of our current teaching practices" (p. 529). He noted that we do continue to "teach the sciences of cosmology and physics often for the sake of 'curiosity'" (p. 529). But an instrumentalist might appeal to the is/ought distinction and argue that the fact that practically useless theories *are* taught does not mean that they ought to be taught.

Before we proceed, a final note about fundamental theories is in order. On the one hand, some empiricists might contend that while we are not on strong ground to take the theoretical claims of an empirically adequate theory to be true, we can be more sure that the theoretical claims of an empirically inadequate theory are false—for empirical adequacy is necessary (but strictly speaking not sufficient) for the theory being true. According to such an empiricist, fundamental theories may be in the business of uncovering truths about reality, but it is just that we will never know if and when they really do. But—they contend—we can know when a theory does *not* yield truths about reality: when it is empirically inadequate. On the other hand, certain stronger empiricists might object that there is no such thing as a false theory to begin with: a theory does not even *purport* to describe reality, so attaching the terms truth and falsity to it is meaningless. Theoretical claims serve as useful fictions, and empirically adequate and empirically inadequate theories are all there are, and we should be aiming for empirically adequate theories. Similarly, some instrumentalists (like Duhem 1954, in his more instrumentalist moments) might object that there are only more and less useful theories, not true and false theories; and instrumentally valuable theories are what we should be aiming for. TAR and FAR would then not make any sense since according to this view theoretical claims cannot be true or false. My response to this is the following: whether such a view is right or defensible is not something that I am interested in here. Rather, I would just say that false can simply be read in more specific terms: it could mean FAR, or FAE, or Instrumentally Useless (IU), as the case may be. For antirealists like the ones just described, my goal can be described as one advocating for FAE and IU theories in science education. My project can then be seen

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[7] For this reason, according to my arguments, one cannot defend the teaching of false theories in general by downplaying the falsity of certain theories being taught today, like Newtonian mechanics, on the grounds of its being highly empirically adequate/approximately true/partially true. I argue that even theories that according to most would *not* fit any of these adjectives can be taught for other good reasons. Slater (2008) on the other hand takes the route of arguing that it is not easy or straightforward to argue that Newtonian mechanics is approximately true and defend its teaching on those grounds. He also presses that its empirical adequacy does not make its underlying falsity go away—if we have to defend its teaching, we *have* to confront its falsity.

as one that makes a case for teaching some theories that are—as the case may be—FAR, or FAE, or IU. The important point here is that I make a case for teaching certain theories that, in general, both realists and antirealists would either be wary of teaching and/or the *grounds* for teaching which both might be in need of clarification.

3 Why Teach False Theories?

False theories can have several pedagogical benefits. To put it in Slater's (2008) terms again, there are several false theories—and several kinds of them—that are *significant*, although false. I discuss three broad types of false theories that I think have a legitimate place in science education. These are the following:

1. Theories from the history of science that are purported to be true, but which have since been superseded;
2. Theories/models not even purporting to be true, used by scientists purely for heuristic purposes;
3. Ideas that patently go against, and deny, scientifically accepted ideas.

I now discuss each of the above, divided into subsections based on the *roles* they can play in science education.

3.1 Theories from the History of Science That Are Purported to Be True, But Which Have Since Been Superseded

Before I get into the advantages of teaching theories of the past, I want to underline that this section is not a blanket appeal for the inclusion of theories from the history of science in the science curriculum, which several scholars have made. First, as mentioned in Section 1, it is commonly held that even when we teach historical theories, we should only teach those that are correct, or the correct aspects of them. Here, I emphasize the false theories and join the calls of scholars who have argued that there is much to be gained from teaching some theories that are not deemed correct according to today's science. Second, several different reasons have been advanced for including false theories from the past in the science classroom (see Matthews 1994, for a list of common reasons for teaching history of science at large (including scientists' biographies, and social contexts), many of which apply specifically to teaching *theories* from the history of science). But here, from among the commonly cited reasons, I only focus on the following: they promote better comprehension of current scientific concepts and methods; they help contextualize current science; they help understand the nature of science; they can connect the development of individual thinking with the historical development of scientific ideas leading to better pedagogy. In presenting these reasons, I rehearse well-known arguments made in these contexts. I would like to note here that these reasons involve treating past theories as a means to certain ends such as better comprehension of current science and better grasp of the nature of science. But certain past theories can be valuable in themselves. So, in addition to the above common reasons, I argue that superseded theories can help us gain genuine understanding (of specific types) of the natural world; and (following Chang 2012) that some superseded theories did not deserve to be superseded after all, and a revival of them would lead to a healthy pluralism in science. These last two involve treating the theories at hand as ends in themselves. Let us now move on to the benefits of superseded theories.

3.1.1 Theories from the History of Science Can Provide Genuine Understanding of the World

I discuss two distinct types of understanding, counterfactual understanding and partial realist understanding.

Let us begin with counterfactual understanding. As Bhakthavatsalam and Cartwright (2017) have argued, there is genuine understanding that comes from being able to see counterfactual possibilities (see Lipton 2009, for a fairly detailed account of this kind of understanding). Consider the Rutherford model of the atom. Today, the model is considered to be highly theoretically inaccurate. According to modern quantum mechanical models, the electron does not revolve around the nucleus in planetary orbits as the Rutherford model pictures. The model is also empirically inadequate: supplemented with the later idea of an accelerated charge losing energy, it predicts that the electron will continuously lose energy and spiral into the nucleus causing the atom to collapse—and of course, atoms do not collapse, for if they did, matter would not exist the way it does. But it is owing to its empirically incorrect prediction that it shows how an atom *could not* be: it illustrates a physical impossibility. While the model was proposed by Rutherford in the hopes of giving a true picture of the atom, today we can use it for gaining counterfactual understanding: if electrons revolved around the nucleus the way the model says they do, then matter could not exist as we know it. Similar arguments can be made about gaining understanding from other failed ideas such as luminiferous ether and the geocentric model of the solar system. Here, rather than teaching the theory as false upfront, students can be led to understand why it conceptually *has* to be false.

Turning to partial realist understanding, let us take the Rutherford model of the atom again. As Bhakthavatsalam and Cartwright (2017) have argued, despite the flaws, the model affords us not only counterfactual understanding, but also some degree of *realist* understanding: understanding based on correctness of theoretical features where we take our current models to be more correct than older ones. Then the Rutherford model was on the path to these current models—it was significantly more correct than its predecessor, the plum pudding model, which takes the atom to be a “pudding” of positive charge with electrons embedded in it. As Catherine Elgin (2009) argues, understanding, unlike knowledge and truth, comes in degrees. This means that according to traditional epistemological theories, either a belief is knowledge or it is not. Popular criteria for a belief to count as knowledge are that it must be justified and true. (This is the JTB account of knowledge.) Similarly, truth is binary: either a belief is true or it is not. However, as Elgin notes, understanding can be subject to gradation: one can have more or less understanding of something. The Rutherford model then gives us partial realist understanding because (among other things) it tells us that the positive charges in an atom are concentrated in a central nucleus containing protons and neutrons, and electrons surround it—a feature it shares with even the most modern model of the atom.

To reiterate, we can say we have “complete” or “total” realist understanding when a theory/model gets just right the theoretical features of its target phenomenon. In the same sense, one that is false and empirically inadequate can give us some, less-than-complete realist understanding of the target owing to being in the vicinity of the true theoretical story. If one is wary about the realism claim here and wants to steer away from the term true, we might use the word “correct” or “most updated” instead. If we consider the modern quantum mechanical model to give us the most correct/updated understanding of the atom, then the Rutherford model gives us a partially correct/updated understanding of the atom. The bottom line is that the atom is something like what the model says, and the model is better than some others that are further away from the theoretically true/most correct/most up-to-date story.

But one might ask, why settle for partial understanding? The simple answer is that when complete understanding is hard to achieve, partial understanding is better than no understanding at all. When explaining things to children, the correct/true story can often be too complex. Given this, it should be uncontroversial that it is better for a child to have partial understanding of something than no understanding at all. For example, as Elgin (2009) points out, a child's understanding of evolution according to which humans descended from apes although false is better than one according to which humans descended from butterflies. This could be a reason why the Rutherford model still finds a place in school science textbooks: when presented at a stage when students have not yet learned more advanced concepts (like that of an accelerated charge losing energy), the Rutherford model can provide a partial understanding of atomic structure that is appropriate for that grade level. Even if students did not learn more advanced conceptions of the atom and stopped with the Rutherford model, they can still be considered to have some (partial) understanding of atomic structure—an understanding that is part of the trajectory toward our current understanding. Since the goal here is (partial) positive understanding of the given phenomenon, underlining the falsity of the theory wouldn't be advisable. We might rather say, "It is something like what the theory says."

With both these kinds of understanding, the past theories are being valued for their core content and are not seen as a means to understand, or a stepping-stone to, better/current science.

3.1.2 Theories from the History of Science May Have Been Given Up Prematurely; There Is Pedagogical Value in Scientific Pluralism

Hasok Chang (2012) has made a persuasive case that certain ideas from the history of science were given up prematurely. Most realists and antirealists would consider the phlogiston theory to be false (FAR and FAE respectively), but Chang has argued that it still had many things going for it.[8] For instance, it had good explanatory power when it came to the production of a flame in combustion. On the other hand, he noted, "Lavoisier's theory of combustion never got very far in explaining the release of heat and light in combustion, without the concept of energy available" (p. 46). Further, the phlogiston concept also explained well the common properties of metals; and it shares a significant resemblance to the modern idea that metals have a "sea" of free electrons. More to the point here, Chang argues for an "active pluralism" in science: it is fruitful to actively entertain multiple conflicting theories at once, for each can help achieve different aims. Just as Newtonian, Lagrangian, and Hamiltonian formulations of mechanics and the Heisenberg, Schrödinger, Feynman, and Bohm versions of quantum mechanics give us different perspectives on the same problem/topic and serve different purposes, we should have both the oxygenist and phlogistonist systems on the table at once, so we can use each where it excels. I think this is sound advice for scientific practice.

Passmore et al. (2014) have drawn attention to the sensible call for science education to mirror actual scientific practice: "Over the last few decades, there has been a 'practice turn' in the philosophy of science and, more recently, in science education. That is, there has emerged in both fields an effort to understand and apply ideas about how science is actually practiced to issues in philosophy and education" (p. 1171). This is on the grounds that this way what students would get is more authentic science. Now combine the above two points: active pluralism in scientific practice and a science education mirroring scientific practice. What we

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[8] It is worth noting that there has been a similar call for reviving a discarded idea in biology by Michael Skinner (2015), who has argued that a unified theory of evolution incorporating both neo-Lamarckian and neo-Darwinian ideas is useful in understanding environmental epigenetics.

get is a science education that encourages teaching current and past theories in parallel, highlighting the benefits (and shortcomings) of each. I should add here that this suggestion to teach outdated theories is not empty philosophizing: Douglas Allchin (1997) has in fact used the concept of phlogiston to successfully teach modern-day students the chemistry of reduction–oxidation (redox) reactions.

Surely, attacking a problem via two contrasting conceptual frameworks should be beneficial to students of science. As Chang notes, just like being multilingual is widely considered beneficial, it seems very plausible that speaking various "scientific languages" would also be beneficial to scientific thinking. (Chang is careful to disclaim that the language metaphor is imperfect, but very suggestive nonetheless.) In Kuhnian jargon, there is value in getting students to "puzzle-solve" from various paradigms. Doing this would challenge them to engage in what I call "constrained thinking"—thinking constrained by different, and perhaps incompatible, conceptual toolkits. This would enhance reasoning skills by pushing students to reason from within different conceptual/theoretical constraints. Again, the past theory in question here is not used simply as a means to contextualize current science or as a stepping-stone to current science, but is valued for its core content. Also, in such cases, telling students that the theory is false/outdated should happen with care and caution lest it come in the way of them fully appreciating it. Teachers could either hold off on talking about it until after students have satisfactorily demonstrated a grasp of the theory, or at least emphasize the advantages and relevance of the theory alongside talking about its status in current science.

3.1.3 Theories from the History of Science Can Serve To Be Instructive on the Nature of Science

It has been argued by several scholars like William McComas (2014) that to be truly scientifically literate, it is not sufficient for a student to just learn science content, but that they must also learn the nature of science—overarching, general features of scientific knowledge and practice. Presenting an accurate picture of the nature of science—what science is and how it is done—is also common to most science education standards documents including the National Science Education Standards (National Reasearch Council 1996) and Science for All Americans (American Association for the Advancement of Science 1989). As many have argued (Solomon et al. 1992; Abd-El-Khalick and Lederman 2000; Lin and Chen 2002), turning to the history of science can be helpful in this regard. Teaching the history of the sciences would help reveal to students the revisionary and iterative processes behind the scientific acceptance of a theory. History would tell students how science was and is actually done. Specifically, false theories from the past can provide many lessons about the nature of science. As Slater (2008) notes, "We can appreciate the epistemic significance of even false (or merely approximately true) theories from within their historical context: as exemplars of how science was or is done, as waypoints on the way to our current best understanding, or as illustrations of the fact that confidence in a theory (even given its elegance or impressive track record) need not betoken its truth" (p. 540). Slater notes that, often, false theories serve as crucial stepping-stones to their successors. For instance, thanks to Bohr's idea of quantized angular momentum of electrons, Heisenberg, de Broglie, and others wondered *why* that was, which led to the wave model of the electron. And noting these stepping-stones immensely helps us understand the nature of science.

As above, Slater goes on to stress that these theories should be taught as false, and in their historical contexts, so that there is no confusion about their status. Under discussion here is the goal of driving home aspects of the nature of science—such as how theories undergo revision in light of new evidence; how evidence-based explanations are constructed across various historical periods. So here, teaching past theories as false would be beneficial. (I think I have made my point about when to teach theories as false and when not to foreground the falsity and shall not discuss this point further in what is to come.)

Further, I suggest that teachers can get students to actively engage in constrained thinking as discussed in the previous section. This would make students get a feel for what it was like to do science at a certain time, with a scientific arsenal that was different from what we currently have. Let us consider Bohr's model of the atom. According to this model, electrons revolve around the nucleus and can do so stably without radiating energy, as long as they are in "stationary" orbits at certain discrete distances from the nucleus. Electrons can only lose or gain energy by jumping between orbits. From within the Bohr paradigm, the model seemed plausible. Given Bohr's conceptual toolkit at the time, the model was reasonable: it overcame a major pitfall of the Rutherford model and it made sense of quantized emission spectra. After about a decade, Schrödinger came up with the quantum mechanical model once de Broglie had conceived of matter waves. So, teachers could put students in Bohr's metaphorical shoes, and ask them, given the evidence at the time, and without the idea of matter waves, to come up with a model that accommodates the empirical findings. This could lead to a rich discussion of why Bohr came up with the model that he did. Not only would getting students to think from within different perspectives help with their reasoning skills as discussed in the previous section, but it would also be an effective way to teach the nature of science, for it is reflective of how science actually gets done. Of course, going into the genesis and conceptual constraints of a theory is general pedagogical advice and does not have specifically to do with false theories, but the more students are equipped with rich accounts of how various theories—true and false—were constructed, the better their appreciation of scientific practice. In particular, going into these details about false theories can illustrate a crucial aspect of scientific practice: that theories seeming to be reasonable at a given time may have to be revised in light of new evidence.

3.1.4 Theories from the History of Science Can Serve To Be a Source of Intellectual Empathy for Children's Ideas and Provide Better Pedagogy for Conceptual Comprehension

Many science education scholars and cognitive scientists have pointed out that, in many areas of science, naive conceptions held by children match those held by early-modern scientists. For example, as Colin Gauld (2014) has noted:

> … Piaget and Garcia (1989, 30–87) argued that the development of the conception of force in young people follows very much the same path as that in the history of mechanics between the times of Aristotle and Newton. This has suggested to many science educators that reference to the way in which the history of mechanics progressed may assist teachers in encouraging students to make the transition to more developed concepts such as those advocated by Newton. (p. 77)

Several other investigators have similarly noted startling parallels between children's intuitive ideas and ideas from the history of science in many domains such as mechanics, electricity (Clement 1983; Driver and Easly 1978), and human vision (Driver et al. 1985). Of course, these scholars have also warned us against reading too much into these parallels. As Gauld (2014) notes, while physicists are naturally interested in questions of motion and force for instance, and have a wide range of skills and interests relevant to them, students generally do not think of those questions on their own and lack the relevant range of skills and interests to think them through. Driver et al. (1985) also similarly note that often only a few features are similar between a child's idea and its historical counterpart, and that children's ideas are far from being a part of a coherent system as is often the case with historical science ideas such as the pre-Galilean impetus theory. Similarly, in biology, specifically in evolution education, Kampourakis and Nehm (2014) have argued against classifying student ideas as "Lamarckian" since "(1) different ideas are implied by the term *Lamarckian*, misrepresenting the actual content of students' preconceptions about evolution and (2) Lamarck's actual contributions to the history of evolutionary thought are also misrepresented" (p. 382).

Despite these limitations, I think there is an important pedagogical lesson to draw here. It is that when children do echo ideas from the past, it gives teachers an opportunity to say to them that scientists from the past have thought that way too. It is common pedagogical advice that when students are wrong, we must not immediately tell them that, but rather guide them to reason things out and arrive at the correct/accepted response. If as part of that first step, not only do we not tell them that they are wrong, but also tell them that eminent scientists from the past also thought similarly—possibly with caveats about the extent of the similarity so students are not misled—it could afford them intellectual empathy and cognitive resonance, and validate their thinking.

If the goal is making accurate cognitive scientific, historical, or philosophical claims about parallels in the thought processes of children and past scientists, the evidence-based literature in all these fields suggests that we should be careful to not stretch the parallels too far. But my claim is that if the goal is good pedagogy, we can work with the few parallels we generally see (like with the idea that any motion requires a force): when teaching *those specific* topics, teachers can cushion children's ideas with the parallel historical ideas. This has the potential benefit of reassuring children that their thinking was reasonable after all, and instill a certain confidence—empirical studies could test this hypothesis. It seems especially plausible that such an approach would be beneficial in light of the fact that many children are intimidated by science early on. Grounding and contextualizing children's pre-scientific ideas in history for them would also be a step in inculcating in them a historical–philosophical reflection of their own ideas, which would in its own way address the repeated calls for including the history and philosophy of science in science curricula.

We cannot always stop at providing intellectual empathy and teaching superseded ideas though. Often, our goal is to teach newer and currently more accepted ideas. In such a situation, how do we help students overcome their old ideas? The old ideas themselves could come in handy here: we could use them in teaching to students' prior conceptions. Nancy Nersessian (1989) has advanced a more nuanced account of the similarity in children's science and the history of science. Here, the similarity does not lie in the content of the ideas and concepts themselves, but rather in conceptual change—that is, when students have to revise and/or reorganize their conceptions in order to learn. She proposes a single cognitive model for conceptual change in science and in learning science. She argues that " … both the nature of the changes that need to be made in conceptual restructuring and the kinds of reasoning involved in the process of constructing a scientific representation are the same for scientists and students of science. That is, the cognitive dimension of the two processes is fundamentally the same"[9] (p. 165). Nersessian disclaims that

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[9] We should note here that, although there are few parallels between conceptual development in students and in the history of science at large, Nersessian has shown that there can be important similarities between the conceptual developments of certain individual scientists on the one hand and students of science on the other. A similar point about the obstacles that Charles Darwin faced and how they may be similar to those that students currently face in their learning of evolution is made in K. Kampourakis (2014).

this proposal is speculative and needs empirical grounding, but based this on the fairly uncontroversial points that (a) on the one hand conceptual change in science is as much a learning process for scientists as it is for students; and (b) on the other hand, students learning a new scientific representation must actively construct, much like scientists: “they must form new concepts and new relations among existing concepts and integrate the new representation to such an extent that they can make use of it” (p. 165).

The pedagogical import of this for Nersessian is that going through the historical trajectory of ideas aids in learning. She notes that most textbook presentations of science concepts are justificatory in nature: they give “reconstructed arguments that establish the correctness of the representation” (p. 179). She then makes the point that while such presentations are useful where the conceptual structure of the idea in question has been learned and we want to show why something—say a law—holds, they are less useful when the goal is to learn the concepts themselves. Here, she argues, what will help, rather than memorizing definitions of concepts, is “leading students through some of the same kinds of argumentation employed in the initial construction of a conceptual structure” (p. 179). This means wrestling with the old ideas and working through why exactly they did not work, and thereby using that as a stepping-stone to the newer ideas. She draws on Galileo’s writings in his *Dialogue Concerning Two Chief World Systems* and *Two New Sciences* to support this point: “In instruction he employs some of the same methods he used in construction. He begins by putting forth the position of his opponents, then exposes the difficulties in the position, and finally leads the reader through the construction of a new representation of the situation under discussion” (p. 176).

When students bear a flawed conception—especially if it happens to align with an idea from the history of science—it makes good sense to entertain it and see where it leads them, and ultimately show by reasoning why it in fact did not hold up. The idea here is to provide students with more sophisticated versions of their proto-ideas from the history of science—constructed by professional scientists—and show by scientific–historical reasoning why they did not work.

Going through the historical trajectory of a concept in the classroom—when it forms an important part of the construction of that concept—not only sensitizes students to the nature of science through a historical lens, but also—as argued above—might in fact be better pedagogy from a purely science comprehension point of view as well. And this might be the case even where historical ideas do not necessarily align with children’s proto-ideas. Introducing in the classroom the Rutherford model of the atom, the behavior of accelerated charges, the Bohr model, the Bohr-Sommerfeld model, the standing wave model, and then the modern cloud model—in that order—could have the benefit that Nersessian proposes: by mirroring instruction on construction and taking students through the steps of construction of the most modern and currently accepted ideas, there are good reasons to think that the conceptual grasp of these ideas in students will be stronger. First, going through a step-by-step progression of ideas provides cognitive *contextualization* for the newer theories thereby increasing the overall, big-picture understanding of them. As Ernst Mayr (1982) has said regarding understanding of scientific concepts, “Only by going over the hard way by which these concepts were worked out – by learning all the earlier wrong assumptions that had to be refuted one by one, in other words by learning all past mistakes – can one hope to acquire a really thorough and sound understanding. In science one learns not only by one’s own mistakes but the history of the mistakes of others” (p. 20).

Second, it seems very plausible that, in general, comparing and contrasting a given idea with competing ideas—past and present—will lead to a stronger appreciation, grasp, and understanding of the idea in question. Since many false theories can serve as pedagogically effective competitors of each other and of newer theories—like the various models of atomic structure discussed above—it makes good sense to teach those false theories.[10]

While empirical studies should confirm the claim that teaching false theories can better science comprehension; McKagan et al. (2008) have argued—based on empirical research—that while many physics educators believe that teaching the Bohr model of the atom is an obstacle to learning the more accurate Shrödinger model, it is in fact not. Based on a study conducted on students at the University of Colorado, they found that when the Bohr model is taught first, followed by the Schrödinger model, along with explicit emphasis on model building and comparing and contrasting the reasoning behind each of these models, students are able to move beyond the Bohr model and accept the Schrödinger model, and demonstrate a good grasp over the latter.

3.2 Theories/Models Not Even Purporting To Be True, Used by Scientists Purely for Heuristic Purposes

As mentioned earlier, there have increasingly been calls for science education to mirror scientific practice. Now combine this view with the fact that practicing scientists routinely construct and use false theories for various purposes. What we get is the idea that it is desirable to teach students certain false theories since scientists themselves engage with them. Scientists construct false models for various purposes all the time. William Wimsatt (2006) has listed several ways in which scientific models can be false: they can contain idealizations[11] and/or simplifications; they can be incomplete representations; they can have a very narrow, local applicability, and so on. Catherine Elgin (2012) calls these felicitous falsehoods: falsehoods that help us get to features of the target phenomenon we otherwise would not be able to discern. Familiar examples include frictionless planes and free falls with no air resistance. Clearly, these are observationally inaccurate (this could be shown by examining the surface of an inclined plane under a microscope) but assuming a plane to be frictionless helps us study the motion of objects sliding on it to a desired degree of approximation. We would not be able to study this in the way we do if we took friction into account. Models afford us "surrogative reasoning" (Swoyer 1991; Contessa 2007): understanding a target phenomenon by reasoning about a model of it—a surrogate—and often, the falsity of a model proves crucial for this as discussed above.

We can think of different kinds of false theories and models: those with varying degrees of empirical adequacy and with practical and/or cognitive utility. Newtonian mechanics although false in its theoretical claims can be seen as largely empirically adequate when restricted to the domain of medium-sized objects not traveling close to the speed of light, and its teaching can hence be defended on these grounds. But other theories like string theory or the MIT bag model for hadrons[12] are neither known to be true nor highly empirically adequate, but are used by scientists for various other reasons[13] like explanatory power, unifying power, and

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[10] See Marton et al. (2004) for an argument for the view that a concept is learned more effectively when presented with contrasting concepts.

[11] See Cartwright (1989) and more recently Potochnick (2017) for important discussions on idealization and abstraction in models.

[12] See Stephen Hartmann (1999) for a discussion of this.

[13] See Richard Dawid (2013) for arguments for valuing and legitimizing string theory as science, on grounds other than empirical adequacy.

mathematical elegance. The teaching of such theories can be defended on grounds of the practice turn in science education. I must note that I am not advocating the teaching of string theory or the MIT bag model in K-12 science in particular—they might be far too advanced. My point here is to advocate in general for the teaching of (grade-appropriate) theories that are not known to be true or empirically adequate, but that have other virtues; and this is on the grounds that practicing scientists often work with such theories.

3.3 Ideas that Patently Go Against, and Oppose, Scientifically Accepted Ideas

The point here is rather simple. If we want our students not just to be scientifically informed but also responsible citizens with an active interest in policy and advocacy, we need to educate them about opposition to scientific ideas in as much detail as possible. "False theories" here refer to those that rebut scientifically accepted theories, like ID. By and large, such theories currently do not find a place in science classrooms, but I think there can be value in discussing them. It would be good for students—possibly at the middle and high school levels—to be prepared to face opposition of various stripes to scientific ideas, be it vaccination, evolution, or anthropogenic climate change. The more in detail they learn about these views, the better equipped they are to challenge them. It could be greatly beneficial to educate students on how these opposing ideas come about, arguments and evidence given for them, and why they are problematic.

For instance, "irreducible complexity" is the centerpiece of Michael J. Behe's (1996) arguments in *Darwin's Black Box: The Biochemical Challenge to Evolution*. Take the bacterial flagellum, a whip-like cellular organelle used for motility, and the arrangements of the constituent proteins into motor components, a universal joint, and other structures like those that a human engineer might specify. Behe has argued that it is virtually impossible that such an arrangement would have resulted from evolutionary modification: it must be the result of an intelligent design. Yet, evolutionary biologists have answers to these challenges. Firstly, there exist flagella with forms simpler than the one that Behe cites: it is not necessary for a flagellum to be as complex as Behe describes it for it to be able to work. Secondly, the complex components of this flagellum have precedents elsewhere in nature, as noted by Miller (2010) and others. In fact, the flagellum in its entirety is very similar to an organelle that *Yersinia pestis*, the bubonic plague bacterium, uses to inject toxins into cells.

The key is that contrary to Behe's suggestion that the flagellum's component structures have no value other than their role in propulsion, these component structures can serve several different functions that could have helped favor their evolution. The final evolution of the flagellum might then have just involved the novel recombination of complex parts that originally evolved for other purposes. In fact, Shanks and Joplin (1999) have argued that biochemical systems in general exhibit a lot of redundant complexity, a feature characteristic of evolutionary processes. I therefore recommend that students be explicitly made aware of the nature and content of arguments such as Behe's—being as true to him as possible. While presenting the content of ID, teachers should strive to present it earnestly, from the perspective of its proponents (and without a dismissive attitude), so students get the accurate picture. But crucially, this should be followed by responses and challenges so that students are well equipped to deal with these conversations both in an academic setting and in the public sphere.

Further, discussing antiscience theories can be instructive in conveying ideas about the nature of science. While ID is rooted in current observations and has a certain degree of explanatory power in that it gives an explanation for evolutionary complexity in terms of an intelligent designer, it does not make predictions[14] or retrodictions; it is not mechanistic and does not specify any process behind the design; it has not made theoretical or empirical progress over time; although it makes one positive claim that irreducibly complex systems had to have had a creator, it rests more heavily on negating claims of evolution; it is not consistent with findings of other sciences like biochemistry and geology. Underlining all these can lead to important discussions on what makes something a science and what does not.

Although it should have been obvious by now, I wish to emphasize that what I am arguing for is not presenting ID and evolution side-by-side, as two equally legitimate theories. Rather, I am saying that ID should be *contrasted* with evolution. However, I concede that despite this, ID might be a contentious topic for the classroom given the politics surrounding it, as well as the (scientific/intellectual) stakes. I think concerns about discussing the topic in the classroom leading to confusions, or worse, inadvertently creating ID adherents, is legitimate. Hence, whether or not to raise the topic in the classroom might depend on the background, preparation, and maturity of the students as well as teachers. Teachers might have to decide if they want to broach the topic on a case-by-case basis.

4 Conclusion

I have argued that broadly, science pedagogy cannot be strictly aligned with either realist or antirealist epistemologies of science. There could be immense value in teaching various kinds of false theories—FAR and FAE included—in the science classroom. This comes from a broadly pragmatist view that different theories are suited for different goals and that choice of theories depends on our choice of goals (in this context, such as gaining specific understandings, better conceptual comprehension, and better grasp of the nature of science). The philosophy of science that this pedagogical view aligns with the most is pragmatism. While this project is theoretical in nature and not rooted in any empirical research on current teaching practices, I believe the view advanced here sits well with several aspects and recommendations of the empirically founded Next Generation Science Standards (NGSS). For instance, among the three "dimensions" of science in the NGSS (2013) are crosscutting concepts and science and engineering practices. According to Appendix G of the NGSS, crosscutting concepts—such as cause and effect, patterns, and systems and system models—have value because "they provide students with connections and intellectual tools that are related across the differing areas of disciplinary content and can enrich their application of practices and their understanding of core ideas" (p. 1). Studying some of the false theories from various historical periods can reinforce that these crosscutting concepts are at the core of scientific practice irrespective of whether the outcome is a true/currently accepted theory. For instance, the Rutherford model of the atom exemplifies the concept of cause and effect—a compact nucleus at the center is the cause for the deflection of few of the alpha rays passing through the gold foil in Rutherford's experiment. Further, this can serve to show students that the crosscutting concepts discussed in the NGSS does not only cut across various disciplines, but also various epochs. Very similar

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[14] See Mary Williams (1982) for a compelling argument that evolutionary biology does make predictions, contrary to common allegations that it does not. She notes that it is just that these predictions may differ from the ones made in physics in some ways. For instance, evolutionary biology often makes predictions not only about individual organisms, but also about patterns found in genuses; and these predictions are not only about the future, but also about the past.

things can be said about science and engineering practices. And speaking of practices, as underlined multiple times earlier, the use of false theories and models is very much at the core of actual scientific practice. Lastly, as argued earlier, incorporating false theories in the curriculum would also serve to teach about the nature of science, another component of the NGSS. While several of the basic "understandings" of the nature of science listed in Appendix H can be conveyed using various kinds of false theories, two stand out. The first is "Scientific investigations use a variety of methods" (p. 4)—of course this can be conveyed using true theories alone, but including false theories to make this point would emphasize that legitimate methods might still not lead to true theories, an important aspect of the nature of science. The second—and more obvious—among the points listed under nature of science that I think false theories from the past can illustrate is "Scientific knowledge is open to revision in light of new evidence" (p. 4).

I end with a few clarifications and concluding thoughts about how to teach false theories. I think the general worry attached to the idea of teaching false theories is the passing off of these as true. As valuable as I think the teaching of some false theories is, it is equally important for teachers to know how to present them. How much to emphasize the falsity should be dependent on pedagogical expediency. It is pedagogically important that the goal and context of teaching a false theory be clear. This is especially important when teaching antiscientific ideas like intelligent design or climate change denial. In cases like Newtonian mechanics, which is largely empirically adequate in familiar domains of middle-sized objects, when and how much to emphasize its falsity would depend on the context in which it is taught. Slater states: "Making the falsity of the Newtonian worldview clear rather than trumping up its approximate truth can lead to a deeper understanding of what are plausibly more important scientific notions: confirmation, explanation, causation, and so forth. It is with these that science begins, at the earliest level" (p. 541). Since Slater is only concerned with conveying lessons about the nature of science among the benefits that teaching false theories have, his view is reasonable. But I contend that given the several other benefits I have discussed above, rather than adhering to such a blanket prescription about how to teach false theories, teachers should be sensitive to pedagogical context. If the goal is mastering the use of the theory itself, then students might struggle with cognitive dissonance and not learn the theory effectively if they are told its falsity prematurely. But if the goal is to convey through it other things like the nature of science, or its role as a precursor to more advanced theories, then it would make sense to teach it as false.

Finally, critics might question which false theories to teach given practical constraints of time and other resources. I do not claim to have an answer to this question. Certainly, I am not claiming that all teachers *should* teach all of the (categories of) false theories discussed here. What I have done here is to give good reasons for teaching each of them. Teachers should decide which theories are worth incorporating in the curriculum and what roles they should play in it. This would involve a judicious evaluation of various factors including, but not limited to, students' background, preparation, and needs; teachers' understanding and grasp of the roles of false theories; and time availability. I would like to underline though that the fact that there are too many false theories is not a fair criticism of the view I am advancing since the same point can be raised about true/correct/accepted theories. Quantum field theory is a widely accepted theory but is not appropriate for K-12 education. My point is that being widely considered as false/outdated/empirically inadequate/observationally inaccurate does not automatically disqualify a theory from being teachable, much like being true/correct/accepted does not automatically qualify a theory to be teachable. I have noted that significance trumps truth, and it is up to educators to decide which significant theories—true or false—they want to incorporate in the curriculum.

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References

Abd-El-Khalick, F., & Lederman, N. (2000). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057–1095.

Allchin, D. (1997). Rekindling phlogiston: from classroom case study to interdisciplinary relationships. *Science & Education, 6*, 473–509.

American Association for the Advancement of Science. (1989). *Science for all Americans: a Project 2061 report on literacy goals in science, mathematics, and technology.* Washington, D.C.

Behe, M. (1996). *Darwin's black box: The biochemical challenge to evolution*. Free Press.

Bhakthavatsalam, S., & Cartwright, N. (2017). What's so special about empirical adequacy? *European Journal for Philosophy of Science., 7*(3), 445–465.

Cartwright, N. (1989). *Nature's capacities and their measurement*. Oxford: Oxford University Press.

Chang, H. (2012). *Is water H_2O? Boston Studies in the Philosophy of Science 293*. Dordrecth: Springer.

Clement, J. (1983). A conceptual model discussed by Galileo and used intuitively by physics students. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 325–340). Hillsdale: Lawrence Erlbaum.

Contessa, G. (2007). Scientific representation, interpretation and surrogative reasoning. *Philosophy of Science, 74*(1), 48–68.

Dawid, R. (2013). *String theory and the scientific method*. Cambridge: Cambridge University Press.

Douglas, H. (2013). The value of cognitive values. *Philosophy of Science, 80*(5), 796–806.

Driver, R., & Easly, J. (1978). Pupils and paradigms: a review of literature related to concept development in adolescent science students. *Studies in Science Education, 5*, 61–84.

Driver, R., Guesne, E., & Tiberghien, A. (1985). Some features of children's ideas and their implications for teaching. In *Children's ideas in science* (pp. 193–201). London: Open University Press.

Duhem, P. (1954). *The aim and structure of physical theory.* Princeton: Princeton University Press.

Elgin, C. (2009). Is understanding factive? In D. Pritchard, A. Millar, & A. Haddock (Eds.), *Epistemic value* (pp. 332–330). Oxford: Oxford University Press.

Elgin, C. (2012). Understanding's tethers. In C. Jäger & W. Löffler (Eds.), *Epistemology: contexts, values, and disagreement* (pp. 131–146). Heusenstamm: Ontos Verlag.

Feyerabend, P. K. (1959). An attempt at a realistic interpretation of experience. In P. K. Feyerabend (Ed.), *Realism, rationalism, and scientific method (philosophical papers I)* (Vol. 1985, pp. 17–36). Cambridge: Cambridge University Press.

Galili, I. (2014). Teaching optics: a historico-philosophical perspective. In M. Matthews (Ed.), *International handbook of research in history, philosophy, and science teaching* (pp. 97–128). Berlin: Springer.

Galili, I., & Hazan, A. (2001). Experts' views on using history and philosophy of science in the practice of physics instruction. *Science & Education, 10*(4), 345–367.

Gauld, C. (2014). Using history to teach mechanics. In M. Matthews (Ed.), *International handbook of research in history, philosophy, and science teaching* (pp. 57–96). Berlin: Springer.

Hanson, N. (1958). *Patterns of discovery.* Cambridge: Cambridge University Press.

Hartmann, S. (1999). Models and stories in hadron physics. In M. Morrison & M. S. Morgan (Eds.), *Models as mediators* (pp. 326–346). Cambridge: Cambridge University Press.

Hempel, C. (1950). Problems and changes in the empiricist criterion of meaning. *Revue Internationale de Philosophie, 41*(11), 41–63.

Kampourakis, K. (2014). *Understanding evolution*. Cambridge: Cambridge University Press.

Kampourakis, K., & Nehm, R. (2014). History and philosophy of science and the teaching of evolution: students' conceptions and explanations. In M. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 377–399). Berlin: Springer.

Kitcher, P. (2001). *Science, truth, and democracy.* New York: Oxford University Press.

Kuhn, T. S. (1962). *The structure of scientific revolutions* (p. 1996). Chicago: University of Chicago Press, reprinted.

Laudan, L. (2004). The epistemic, the cognitive and the social. In P. Machamer & G. Wolters (Eds.), *Science, values, and objectivity* (pp. 14–23). Konstanz: University of Pittsburgh Press Pittsburgh, and Universitatsverlag.

Lin, H., & Chen, C. (2002). Promoting preservice chemistry teachers' understanding about the nature of science through history. *Journal of Research in Science Teaching, 39*(9), 773–792.

Lipton, P. (2009). Understanding without explanation. In H. de Regt, S. Leonelli, & K. Eigner (Eds.), *Scientific understanding: philosophical perspectives* (pp. 43–63). Pittsburgh: University of Pittsburgh Press.

Manne, K. (2017). *Down girl: the logic of misogyny.* Oxford: Oxford University Press.

Marton, F., Runesson, U., & Tsui, A. B. (2004). The space of learning. In F. Marton & A. B. Tsui (Eds.), *Classroom learning and the space of learning* (pp. 3–40). Mahwah, NJ: Lawrence Erlbaum and Associates.

Matthews, M. (1994). *Science teaching: the role of history and philosophy of science*. Abingdon: Routledge.

Mayr, E. (1982). *The growth of biological thought.* Cambridge: Harvard University Press.

McComas, W. (2014). Nature of science in the science curriculum and in teacher education programs in the United States' assessments. In M. Matthews (Ed.), *International handbook of research in history, philosophy, and science teaching* (pp. 1993–2024). Berlin: Springer.

McKagan, S. B., Perkins, K. K., & Wieman, C. E. (2008). Why we should teach the Bohr model and how to teach it effectively. *Physical Review Special Topics – Physical Education Research, 4*, 010103–1–10.

Miller, K. R. (2010). The flagellum unspun: the collapse of "irreversible complexity". In A. Rosenberg & R. Arp (Eds.), *Philosophy of biology: an anthology* (pp. 439–448). Hoboken: Wiley-Blackwell.

National Reasearch Council. (1996). *National science education standards*. Washington D.C.: No. National Academy Press.

Nersessian, N. (1989) Conceptual change in science and in science education *Synthese*, Vol. 80, No. 1, History, Philosophy, and Science Teaching. Springer. 163–183.

NGSS Lead States (2013). Next Generation Science Standards: for states, by states. http://www.nextgenscience.org/search-standards. Accessed 01 Feb 2019.

Passmore, C., Gouvea, J. S., & Giere, R. (2014). Models in science and in learning science: focusing scientific practice on sense making. In M. Matthews (Ed.), *International handbook of research in history, philosophy, and science teaching* (pp. 1171–1202). Springer.

Popper, K. (1965). *The logic of scientific discovery.* New York, NY: Harper & Row.

Potochnick, A. (2017). *Idealization and the aims of science.* Chicago: The University of Chicago Press.

Savage, C. W. (1990). Preface in C.W. Savage (Ed.) *Scientific theories. Minnesota Studies in the philosophy of science.* Volume 14. University of Minnesota Press, vii–ix.

Shanks, N., & Joplin, K. (1999). Redundant complexity: a critical analysis of intelligent design in biochemistry. *Philosophy of Science, 66*(2), 268–282.

Skinner, M. (2015). Environmental epigenetics and a unified theory of the molecular aspects of evolution: a neo-Lamarckian concept that facilitates neo-Darwinian evolution. *Genome Biology and Evolution, 7*(5), 1296–1302.

Slater, M. (2008). How to justify teaching false science. *Science Education, 92*(3), 526–542.

Solomon, J., Duveen, J., Scot, L., & McCarthy, S. (1992). Teaching about the nature of science through history: action research in the classroom. *Journal of Research in Science Teaching, 29*(4), 409–421.

Swoyer, C. (1991). Structural representation and surrogative reasoning. *Synthese, 87*, 449–508.

van Fraassen, B. (1980). *The scientific image. The Clanderon Library of logic and philosophy.* Oxford: Oxford University Press.

Williams, M. (1982). The importance of prediction testing in evolutionary biology. *Erkenntnis, 17*(3), 291–306.

Wimsatt, W. (2006). False models as means to truer theories. In *Re-engineering philosophy for limited beings: piecewise approximations to reality* (pp. 94–132). Cambridge, MA: Harvard University Press.