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ARTICLE

Who Says Scientific Laws Are Not Explanatory?

On a Curious Clash Between Science Education and Philosophy of Science

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Abstract
In this article, we tackle the phenomenon of what seems to be a misunderstanding between science education theory and philosophy of science—one which does not seem to have received any attention in the literature. While there seems to be a consensus within the realm of science education on limiting or altogether denying the explanatory role of scientific laws (particularly in contrast with "theories"), *none* of the canonical models of scientific explanation (covering law, statistical relevance, unification, mechanistic-causal, pragmatic) lends any support to this view of laws. We will reconstruct three different versions of this demotion of laws (i.e., laws are merely descriptive; laws are explanatory only of singular events, not of laws; laws are explanatory but only in a "superficial" way), propose possible grounds for them, and illustrate why these perspectives pose a conceptual challenge as they contrast with epistemological approaches to the problem of explanation. We will also suggest the potential negative outcomes that would arise from science teachers adopting these approaches in the classroom when aiming to assist students in moving beyond mere description and towards explanation.

1 Introduction and Outline

1.1 An Apparent Misunderstanding Between Philosophy of Science and Science Education

According to philosophy of science, scientific laws, in particular paradigm cases such as Newton's, play a central (sometimes a *spectacular*) role in explaining phenomena in the world. Even more interestingly, they have a fundamental function in explaining lower-order laws—which is the relationship between Newton's and Galileo's laws and Newton's and Kepler's laws. This crucial explanatory role is accorded to laws (at least to *certain* laws) not only by the highly influential covering-law model (CLM) of scientific explanation, but

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also by alternative proposals such as Wesley Salmon's statistical relevance and causal-mechanistic models, by Friedman's and Kitcher's unification model, and by Van Fraassen's pragmatic approach. Therefore, as far as the epistemological approach is concerned, there is *no* relevant proposal which have denied this role to scientific laws. However, several authors in science education seem to believe that scientific laws (in contrast to "theories") are not explanatory but merely "descriptive," that they are explanatory only of particular instances, but not of other laws, or that they are explanatory, but only in a "superficial" level.

In this article, we will propose possible grounds for this conception of laws as merely descriptive, we will attempt to demonstrate why considering them in this way poses a conceptual problem, and we will explore the potential deleterious consequences of adopting this approach in the classroom in the didactic task of helping students to be able not only to *describe* but to *explain* reality, to move from the "what" to the "why" of the world around us.

But before we begin, it is important to distinguish between two levels in which the following discussion could unfold. The first level is that of a theoretical discussion within the community of science educators and epistemologists, while the second level is a practical discussion regarding how to effectively bring these theoretical discussions into the classroom and whether it is indeed necessary to do so. In this article, we will focus on the first issue—although we will also make some comments regarding the second one—because we believe that in order to later decide on the appropriate approach when establishing didactic transposition strategies, it is necessary to first reach an agreement on theoretical concepts that go beyond mere terminological problems and are rooted in deep conceptual matters.

1.2 Two Levels in the Characterization of Scientific Laws: a Minimal, "Neutral" Definition of "Scientific Law"

We are going, then, to discuss whether scientific laws have such a limited explanatory role as those approaches that demote them claim. Now, in order to do this, we will need to appeal to some important *counterexamples* (for instance Newton's laws), which function as such because, on the one hand, they fulfil the definition for "law" but, on the other hand, are indeed explanatory. However, the obvious risk in proceeding this way is to operate on the basis *of a different definition* of what a scientific law is. Obviously, if the approaches which demote the explanatory role of laws define "law" in such a way that our alleged counterexamples *simply do not count as laws*, our objections will not be tenable. We need, thus, to be able to identify some general traits, *apart from the explanatory character*, to establish common ground and permit us to identify certain statements *as laws*, in order to assess, at a second moment, whether or not they are explanatory. In other words, we will be dealing with scientific laws as a two-tiered affair. First, there must be some general *defining* characters of the notion (such as "laws are *universal* statements"); secondly, we have the issue of their explanatory character. Naturally, we are excluding the possibility that non-explanatoriness may be part of the very *definition* of a scientific law—in which case there would be no point in showing arguments, because the approaches we are discussing would be reduced to the tautology "Some statements which are not explanatory (=laws) are not explanatory." But we cannot, either, "tip the balance" in our favor—that is, appeal to definitions of "scientific laws" which are heavily associated with the idea that laws do in fact explain. What we will do, instead, is to appeal to traits present in the very definitions provided by some of the approaches we want to discuss, and which can therefore count as "neutral" between the standard epistemological tenet that laws are interestingly explanatory and the approaches in science education which demote them.

By doing this, of course, we are also appealing to the idea that laws can somehow be defined by means of *their traits*, and not only exemplified by appealing to statements which are *called* "laws" or "theories." We mention this specifically because some texts in science education seem to appeal simply to the *names* of certain constructs in science. In this vein, for example, the education scientist William McComas writes that "laws are the generalisations or principles (*i.e. Newton's law of gravity*), while theories are the explanations (*i.e. the germ theory of disease*) for laws" (McComas, 2017, p. 74), as if the mere fact that they receive different *names* was transparently informative of a real difference between them.

So, let us now turn to the general traits of laws. We will consider:

- the problem of *universality*
- that of their *relational* character
- that of their alleged *observational* character

First, scientific laws are commonly described as *universal* statements, which means (roughly speaking) that they refer to a regularity, to something applicable to all the members of a class, at least under certain circumstances. A scientific law does not refer to a spatiotemporally individuated event, but to something that "always" happens. McComas writes that "Laws are generalizations, principles or patterns in nature." His example are "the basic laws of physics described by Isaac Newton," which refer to "the relationship of mass and distance to gravitational attraction between objects" (McComas, 1998, p. 54, see also 1996, p. 11, 2017, p. 74). Similarly, in an article attempting to clarify the notions of laws, hypotheses, and theories, Rao writes that "When we pour water from a vessel, we expect it to flow down and not fly up. When we heat water, we expect it to boil and not freeze. Belief is implicit, in all such actions, that events in the world do not happen at random, but that they take place in an orderly manner" (Rao, 1998, p. 72). Along the same lines, Eastwell states that "A law (or rule or principle) is a statement that summarises an observed regularity or pattern in nature" (Eastwell, 2014, p. 17). Rubba and Horner claim that laws "describe *regularly observed* relationships" (1979, p. 31; emphasis ours). In Silverstein's words, "A law is a concise verbal or mathematical statement of a relationship between experimentally observed parameters *that is always the same under the same conditions*" (Silverstein, 1996, p. 905; emphasis ours). Braaten and Windschitl, analogously, point out that "Laws often provide mathematical means of representing *persistent* patterns observed in nature" (Braaten & Windschitl, 2011, p. 642; emphasis ours).

This characterization of laws as universal is also shared by a variety of science textbooks. Metcalfe et al. write that "The *generalizations* which describe behavior in nature are called laws or principles" (1974, p. 5; emphasis ours). According to Tocci and Viehland, "A scientific law is a statement or mathematical expression of some *consistency* about the behavior of the natural world" (1996, p. 20; emphasis ours). Chang and Overby write that "a law is a concise verbal or mathematical statement of a relationship between phenomena *that is always the same under the same conditions*. For example, Sir Isaac Newton's second law of motion […] means is that an increase in the mass or in the acceleration of an object will *always* increase its force proportionally, and a decrease in mass or acceleration will *always* decrease the force" (Chang & Overby, 2022, p. 4. Emphasis ours). In fact, laws can sometimes take a weaker, probabilistic form, and state that *in a certain proportion of cases*, under certain circumstances, some other event will take place (as when we claim *a certain probability* of contracting a disease after close contact with an infected person). The National Academy of Sciences defines and exemplifies "law" in terms that they refer to "how the physical world behaves under certain circumstances"; for example, "how objects" (objects in general) "move when subjected to certain forces" (National Academy of Sciences (U.S.), 1998, p. 5).

In these quotations, a second trait of scientific laws has already tangentially emerged: apart from being universal statements, they are statements about *relationships* between phenomena—or, in other words, statements that claim that *when* a first kind of phenomenon takes place, another kind of phenomenon takes place too (either subsequently or simultaneously). This relationship can be introduced in terms of the logical *form* that laws present. That is, laws usually take the form of conditional ("if… then…") statements.

Now, we need to consider whether or not to include a *third* trait, which seems to create a tension in the scenario we have just reconstructed: the trait that laws should refer to *observable*, "empirical" and not "theoretical" entities and processes. On the one hand, the idea that laws are not only *universal* statements which refer to *relationships* but, more specifically, to *observed* relationships is at least suggested by passages such as those by Rubba and Horner or Braaten and Windschitl which we have just seen. On the other hand, however, authors such as Chang and Overby and (quite insistently) McComas take as a paradigm case *Newton's* laws, which are obviously not empirical—insofar as they posit traits which cannot be directly observed, such as "gravity." It would be simply incoherent to claim both that Newton's laws are laws and that only those statements which refer to observable entities and processes can be called "laws." Even more, Newton's are also taken to be paradigm cases of laws in philosophy of science, so stipulating by definition that only *empirical* statements count as laws is certainly no "neutral" basis to approach the misunderstanding we introduced in Section 1.1.

Naturally, there is *much* more that has been written, in the realm of philosophy of science, in order to characterize what scientific laws are—in particular, in order to distinguish paradigm cases of laws, on the one hand, from *accidental generalizations* (such as "All the coins in my pocket are silver"), on the other. Along this line, philosophers of science have dwelled in considerations about, among other problems, the relationship between scientific laws and so-called counterfactual or subjunctive conditionals (Goodman, 1955, p. 25), the distinction between "strict" and "numerical" universality (Popper, 1935, 1949), or the demands that authentic scientific laws should not refer to individual entities, and should hold in all times and places (Smart, 1963). These precisions are indeed crucial for epistemology, but, rightly or not, do not seem to play a role in the approaches we are discussing here and which demote the explanatory role of laws. That is, the proposals we will discuss in Sections 4, 5, and 6 *do not* appeal, for their demotion of laws, to, for example, the difficulties in clearly distinguishing them from accidental generalizations. So, in order to speak a common language, our neutral, rather minimal, characterization of laws, then, will only appeal to the fact that they

A) must be universal statements which
B) claim there is a relationship between two or more variables

We will have to see whether this basis is enough for demoting their explanatory role.

1.3 Is It Really Important to Distinguish "Laws" and "Theories"?

Now, it might be argued that in fact, there is not a sharp distinction between laws and theories, but rather a continuum between them. It would be pointless, then, to try to determine whether it is laws or theories which have an explanatory role. In fact, *from an epistemological perspective*, "laws" and "theories" are certainly not opposed since epistemology usually refers to "*theoretical* laws"; namely, to statements which simultaneously show the traits (1) of being universal and (2) of referring to unobservable entities. In any case, *it is in the realm of science education* where we find an insistence on the allegedly "crucial" character of a distinction between "laws" and "theories." This point is repeated in Rubba and Horner (1979, p. 31), Rubba, Horner, and Smith (1981, p. 222), Ryan and Aikenhead (1992, p. 571), Silverstein (1996, p. 904), Lederman and El-Khalick (2002, p. 109), Schwarz, Lederman, and Crawford (2004, p. 613), Lederman (2006, p. 305, 2007, pp. 833–834), Özgelen (2010, p. 26), Tuberty (2011, p. 29), Eastwell (2014, p. 17), and Bazghandi et al. (2015, p. 13). Let alone the large number of times McComas refers to this distinction (McComas, 2003, p. 143, 2008, p. 261, 2014, p. 107, 2017, p. 74) even pointing out that theories and laws are related, but they are *different kinds of scientific knowledge* (McComas, 1998, p. 54, 2015, p. 60).

1.4 General Outline

In this article, we will proceed as follows:

- In *Section 2*, we will try to show the relevance of the debate by briefly reconstructing how the curricular guidelines of different countries attribute a central role to scientific explanation—which is why it is indispensable to know what exactly is demanded from teachers and students when this emphasis is made.
- In *Section 3*, we will show that the imprecisions regarding the notion of scientific explanation which we want to tackle in this article, and which have *not* been discussed in the literature, are to be distinguished from the debate regarding the well-trodden field of the relationship between scientific explanation and *argumentation*. Whereas the assimilation of explanation to argumentation has been accused of setting the bar too low (i.e., of neglecting what is *specifically* explanatory in explanations), the approaches which we want to discuss (namely, the "descriptivist", the "restrictivist," and the "sophistication-demanding" approaches to laws), quite on the contrary, risk setting the bar too *high*, thus dismissing as non-explanatory what are in fact perfectly acceptable examples of scientific explanation.
- In *Section 4*, we will deal with the "descriptivist" approach to laws, according to which scientific laws are not explanatory, but only descriptive. We will show that this approach has been adopted by a variety of influential schoolbooks and college materials and we will try to find its theoretical grounds through the works of Rubba and Horner, Lederman, and Bazghandi et al. Then, we will show how this approach clashes with two standard epistemological models of explanations of singular events: the *CLM*, championed by Popper, Hempel, and Carnap among many others, and the *statistical relevance model*, proposed by Salmon. We will also briefly mention Woodward's manipulationist model, which is considered less influential but offers interesting insights regarding the limitations of the CLM. We will close the section by sketching the deleterious pedagogical consequences which *would* ensue if teachers followed this "descriptivist" approach to laws.

- In *Section 5*, we will reconstruct the approach according to which laws do explain, but only *particular events, not other laws*—i.e., the approach which restricts the explanatory role of laws and which we therefore propose to call "restrictivist." Expressions of this approach are to be found in some passages by McComas and by Braaten and Windschitl. We will see how this "restrictivism" finds no support in epistemology, and clashes with the near consensus which we find along a variety of canonical models of scientific explanations: the CLM, Friedman's unification model, Salmon's causal-mechanical model, and Van Fraassen's pragmatic model *all* either allow the possibility of laws explaining other laws or even explicitly state that laws can explain other laws, and highlight some spectacularly successful cases of this kind of explanation (as we find in the relationship between Newton's and Kepler's laws, among others). In closing, we will note, again, what unfortunate consequences this approach *would* have if taken up by teachers.
- In *Section 6*, we discuss the last of the idiosyncratic approaches in science education which clash with philosophy of science: the "sophistication-demanding" approach that holds that laws only provide superficial explanations. Both in (again) McComas and in Braaten and Windschitl, we can find remarks which claim that explanations which appeal to laws are not "sophisticated" or "deep"—because, as we will see, these authors assimilate *laws*, in general, with *empirical* laws, and simply overlook the distinction between the latter and *theoretical* laws. We will show that this, again, clashes with well-supported approaches in epistemology. The distinction between these kinds of laws was already present in the CLM but was taken up in the statistical relevance model, and plays an utterly central role in the unification model (which relies heavily on it) and in the causal-mechanical model. Overlooking the distinctive character of *theoretical* laws, furthermore, involves a naively inductivist view of how "laws," in general, are supposed to be elaborated. Once again, we will finish by showing how this demand for "sophistication" and "depth" *would* have unsuitable consequences for the educational practice.

2 The Central Role of Scientific Explanation

As evidenced in the curricular guidelines of different countries, scientific explanation plays a central role in the educational approach to scientific content. For example, in *Benchmarks for Science Literacy*, the American Association for the Advancement of Science (AAAS) considers as a central element of "scientific literacy" the ability to "recognize and weigh alternative explanations of events" (American Association for the Advancement of Science, 1994, p. XI). This characterization is consistent with the fact that, while describing the nature of science, the authors of the document emphasize "the improving ability of scientists to offer reliable explanations and make accurate predictions" (AAAS 1994, p. 8). Scientific theories, the document continues, "are judged by how they fit with other theories, the range of observations they explain, how well they explain observations, and how effective they are in predicting new findings" (AAAS 1994, p. 13). In a similar vein, the National Research Council summarizes that, in learning science, "students describe objects and events, ask questions, acquire knowledge, *construct explanations of natural phenomena, test* *those explanations in many different ways*, and communicate their ideas to others" (National Research Council, 1996, p. 20; emphasis added). The activity of "inquiry" in which students are expected to engage implies that they will "describe objects and events, ask questions, *construct explanations, test those explanations* against current scientific knowledge, and communicate their ideas to others" (National Research Council, 1996, p. 2; emphasis added).

This centrality of scientific explanation can be traced not only in the didactic orientations developed in the USA but also in the curriculum frameworks from countries all around the world. Some representative examples from various continents and cultural backgrounds are shown next.

In the case of England, we find that students are expected to "relate scientific explanations to phenomena in the world around them and use modeling and abstract ideas to develop and evaluate explanations." In Lithuania, they are similarly asked to "apply scientific knowledge to explain phenomena." Norwegian guidelines establish the aim that students "formulate questions, arguments, and explanations in natural science." According to the Australian guidelines, "Science understanding is evident when a person selects and integrates appropriate science knowledge to explain and predict phenomena." Students in New Zealand are expected to "Appreciate science as a way of explaining the world […]; ask questions, find evidence […], and carry out appropriate investigations to develop simple explanations." Russia states the similar requirement to "Use scientific texts (…) to find and retrieve information, answer questions [and] find explanations," and to "Use ready-made models (e.g., globes, maps, and plans) to explain phenomena." In South Africa, guidelines highlight the importance of "hypothesizing," as "Putting forward a suggestion or possible explanation to account for certain facts (Mullis et al., 2016)." In Argentina, the Priority Learning Cores identify as an educational objective "The identification and explanation of certain phenomena" (*Núcleos de Aprendizaje Prioritarios*, 2005, p. 58). Primary school children in Spain are required to "Recognize and explain relationships among physical world factors." Similar requirements involving explanation can be traced, for more specific scientific contents, in the guidelines from Chile, Finland, France, Germany, and Italy (Mullis et al., 2016).

However, in marked tension with the centrality given to scientific explanation in the framework of science teaching, there is no consensus in the didactic community as to what, specifically, is to be understood by "scientific explanation." And this is clearly a problem because how could we ask students (and train teachers) to develop the ability to "scientifically explain" if we do not agree on what exactly this ability consists of? Let us briefly present the disagreements—which we will analyze in depth later—that exist *within* the didactic community and *between* this community and the philosophy of science in this regard.

3 A Debate and a Lack Thereof: Two Different Problems Concerning the Construal of "Scientific Explanation"

First, we find a widely debated disagreement between those who consider that an explanation should be assimilated to a general argument and those who consider that scientific explanation should be clearly distinguished from scientific argumentation. The latter argue that though explanations *are* arguments, they are a certain *particular type* of them and, therefore, explanations have to satisfy more specific requirements than those demanded of *any* argument. They claim that there are characteristic aspects of explanation that are overlooked when we focus only on its relationship with the more general practice of argumentation (Osborne & Patterson, 2011, 2012; Brigandt, 2016). On the contrary, those who argue in favor of equating explanation with argumentation hold that the distinction between both types of discourse is unnatural and may even be counterproductive (McNeill & Krajcik, 2007; Berland & McNeill, 2012). This approach to scientific explanation which does not distinguish it from *argumentation* (College Board, 2009) can be characterized as a *scarcely demanding* elucidation of the notion: under this interpretation, a scientific explanation fits Toulmin's general pattern involving the relationship between a claim and the evidence supporting it[1] (a pattern initially developed for the analysis of arguments, not explanations), and, according to some, it sets the bar too *low*. "Standards of explanatory adequacy are important as they correspond to what counts as a good explanation [...]. In contrast, science education approaches to explanation that emphasize evidence-based argumentation *obscure the standards of what makes an explanation explanatory*" (Brigandt, 2016, p. 252; emphasis added). In the view of these critics, the relationship between a claim and the supporting evidence is something we can assess with purposes other than determining that an *explanation* is appropriate; a claim can be well supported by evidence without there being an *explanatory* relationship involved. For example, it would be quite trivial to *justify* the statement "The paper burned." If the justification took the form of an argument, we could say that we saw it burn and, under normal conditions, what we see is what actually happens. But it is much more difficult to *explain* why the paper burned, what chemical processes gave rise to what we are actually *seeing*.

In any case, as we mentioned before, this relationship between explanation and argumentation constitutes an aspect in which the characterization of scientific explanation in science education has undoubtedly been subjected to debate. However, there is a different trend in science education which to the best of our knowledge has *not* been considered yet in debates and which, curiously, sets the bar for scientific explanation rather *high.* In this case, the tendency is to exclude from the realm of explanation the kind of analyses which science can obtain by means of the use of scientific *laws*, on the grounds that laws allegedly lack explanatory power. In the works of Rubba and Horner (Rubba & Horner, 1979), Lederman (2007, pp. 833–834), Bazghandi et al. (2015, pp. 12–13), and McComas (McComas, 1998, pp. 54–55, 2014, p. 58), we find a remarkable characterization of laws as *not explanatory, but only descriptive.* In other words, scientific explanations are allegedly something more than what laws can provide–something that is in clear contradiction with the definition that epistemology traditionally gave for an explanation.

In the following, we will discuss in depth what we consider to be three idiosyncratic assumptions made in science education and their consequences at both the theoretical and practical levels when analyzing the scientific explanation. The following table summarizes our findings and the didactic obstacles that we believe the commission of such assumptions represent.

[1] Toulmin's model (1958) establishes that everyday argumentations do not follow the classical rigorous model of deductive logic and develops one suitable for analysing any type of argumentation in the framework of social discourses. It considers that an argument is a complex structure that involves a movement from evidence (grounds) to an assertion (claim) through a warrant that enables the connection.

Idiosyncratic assumption	Authors that make this assumption	Epistemological models with which it clashes	Theoretical consequences	Practical consequences
Laws are not explanatory ("descriptivist approach")	• Rubba and Horner • Lederman • Bazghandi *et al.*	• CLM • Statistical relevance model	The distinction between an explanation and a description is blurred.	The identification of the progress that students can make when they move from merely *describing* a phenomenon to *explaining* it becomes difficult.
Laws are not explanatory of other laws ("restrictivist approach")	• McComas • Braaten and Windschitl	• CLM • Unification model • Mechanistic model • Pragmatic model	The spectacular unifying achievement of laws like Newton's is lost from sight.	Loss of sight of a) why certain milestones in the history of science are particularly important, and b) from the perspective of NoS, the purpose of scientific activity, which is to offer an increasingly unified and describable image of the world based on fewer theoretical elements.
Explanations provided by laws are superficial ("sophistication-demanding approach")	• McComas • Braaten and Windschitl	• CLM • Statistical relevance model • Unification model • Mechanistic model	The specificity of theoretical laws is lost.	The problem of students who fail to reach the theoretical level is misdiagnosed. It leads to the idea that students can "discover" laws by themselves merely by observing the world.

4 A First "Round": Are Laws Not Explanatory *at All*?

4.1 The "Descriptivist" Approach to Laws

We first encountered this "descriptivist" approach to laws when analyzing some clearly canonical schoolbooks and college materials. Therein, we found these astonishing characterizations of laws and theories:

- "A hypothesis predicts an event. A theory explains it. A law describes it" (Tocci & Viehland, 1996, p. 20). Laws, then, would apparently not have explanatory capacity, but only descriptive.

- “[S]cientific laws describe the behavior (the ‘what’) of nature, but do not provide explanations” (Hunt, 1996, p. 399; emphasis added).
- “Law: a *descriptive* generalization about how a certain aspect of the natural world behaves under stated circumstances” (National Academy of Sciences (U.S.), 1998; emphasis added).
- “[Laws are] statements about a relationship between phenomena”; “[a theory] explains a body of facts and/or the laws that are based on them” (Chang & Overby, 2022, p. 4). While it is not explicitly stated here that laws do not explain, they are presented in contrast to that which would fulfill that role.
- “[A] law *is descriptive, not explanatory*, and applies to a well-defined set of phenomena, so it cannot be taken as an absolute truth” (Mondragón Martínez et al., 2010, p. 11; emphasis added).

According to these materials (and in clear contradiction with decades of developments in philosophy of science, as we will show), it appears that scientific explanation must be something more than what laws can provide, since laws are allegedly only “descriptive.” We wondered, then, whether the source for such a curious understanding of laws and explanations might be found among more “theoretical” productions in science education. And indeed, we were able to track expressions of this “descriptivist” approach in the works of Rubba and Horner, Lederman, and Bazghandi et al.

To begin with, Rubba and Horner point out that “the ideal gas laws as formulated by Boyle and Charles […] *describe* regularly observed relationships among the observable properties pressure, temperature, and volume” (1979, p. 31; emphasis in the original) and, similarly, “the valence laws assert that ions bear integral charges, but do not explain why” (Rubba & Horner, 1979). Unfortunately, this one-page article gives no citations or references as to what the origin of this conception might be.

In 2007, Lederman writes on the distinction between scientific laws and theories:

(…) among other things, theories and laws are different kinds of knowledge […]. Laws are statements or *descriptions* of the relationships among observable phenomena. Boyle’s law, which relates the pressure of a gas to its volume at a constant temperature, is a case in point. Theories, by contrast, are inferred *explanations* for observable phenomena (e.g., kinetic molecular theory provides an explanation for what is observed and described by Boyle’s law). (Lederman, 2007, pp. 833–834; emphasis ours)

Bazghandi et al. (2015) approvingly quote Lederman and point out that:

laws are the *descriptive* predicates of the relations among the phenomena observed. For example, the Boyle–Mariotte law *describes* the relation between the pressure and volume of gas at constant temperature. On the other hand, the theories are deduced *explanations* for observed phenomena. As an example, the kinetic molecular theory offers an *explanation* for what Boyle–Mariotte law and Charles and Gay-Lussac Law *describe*. (Bazghandi et al., 2015, pp. 12–13; emphasis ours)

Note that this passage not only confuses a *predicate* (which is a sub-propositional element) with complete propositions, but also contrasts, once again, the allegedly descriptive character of *laws*, on the one hand, with the explanatory character only recognized to theories, on the other.

It is important to remark that what we are dealing with are universal negative propositions: for *every* law, it is not the case that such a law can be explanatory. This is similar to a proposition such as “There are no black swans”: it claims that, for *every* entity that is a swan, it is not the case that such an entity is black. Or, equivalently, these claims are negative existential propositions: the “descriptivist” approach affirms that there is *no* entity which is a law and which is explanatory. This, again, is similar to the claim that there exists *no* entity which is a swan and which is also black. This logical reconstruction may sound unnecessary, but it is important to bear in mind what a criticism of the "descriptivist" approach to scientific laws needs to do. Just as a refutation of the claim that there are no black swans does not need to show that *all* swans are black, but simply that *some* swans are, a criticism of the claim that *no* law is explanatory does not need to take the form of a thesis that *all* laws are explanatory, that, in every science, laws always play an explanatory role. It suffices to defend the much weaker claim that *some* laws are explanatory—for example, that causal laws are, even if non-causal laws are not. Therefore, assuming that a criticism of the "descriptivist" approach to laws involves making a universal claim about the exceptionless explanatory power of laws would amount to misinterpreting the burden of proof here.

The same point can be formulated in terms of a difference in the kinds of explanations which we find in different *disciplines*—for example, it might be argued that explanations in physics are typically not of the same kind as those in chemistry or biology. We will, in fact, see some arguments as to whether or not the leading models of scientific explanation are applicable to a variety of sciences; there are indeed those who claim that a certain model is better suited to physics than to biology, and those who reply. But again, even if we agree with this kind of claim (and we have no strong reasons not to), it does not constitute a defense of the "descriptivist" approach to laws, *because such approach is itself precisely a sweeping, universal attempt to characterize scientific explanation in general*. A line of argument that insists on the irreducible specificity of particular sciences will simply be of no avail for the "descriptivist" approach.

A related but different distinction is between claiming that laws are *necessary* for explanation (the "necessity thesis") and claiming that laws, in conjunction with other statements, are *sufficient* for explanation (the "sufficiency thesis"). If, when denying (as a universal claim) that laws are explanatory, this denial meant that laws are not *necessary* for explanation, then such a position would be supported by showing counterexamples in which we *do* have an explanation but there are no laws involved: those examples would show that we have succeeded at explaining a phenomenon without needing to appeal to laws after all. However, claiming, as, e.g., Rubba and Horner, that laws "describe" and "do not explain" involves a thesis about sufficiency, not a thesis about necessity. Asserting "laws do not explain" is tantamount to asserting, say, "water does not dissolve fat"; it means that a certain factor is incapable of achieving certain result, of bringing about some state of affairs; laws, in this view, are never sufficient to elaborate an explanation, whereas "theories" are. Of course, as we will see in Section 4.2, no model attributing an explanatory role to laws ever claimed that laws *by themselves*, without being conjoined with other statements, explain something; to take a trivial example, to sufficiently explain that a free-falling ball has an acceleration of 9.8 m/s^2, we not only need the general law which claims that all free-falling objects on Earth have that acceleration, but also the singular statement that this particular ball is in free fall. But, in any case, the point is still that this information is *sufficient* to provide an explanation—that we do not need a "theory," understood as something different from a law. Therefore, what we need to discuss is the universal claim that laws (in conjunction with singular statements, but in absence of "theories") are *never sufficient* to provide explanations.

So, our next step will be to show that philosophy of science undoubtedly attributes an explanatory role to at least some laws, in at least some sciences, and that this leads to a curious clash between this discipline and the "descriptivist" approach present in science education. To do so, we will consider two of the five most influential models of scientific explanation, along with some brief references to another model (Woodward's) which, though less influential, includes some interesting remarks concerning the limitations of the CLM.

4.2 The Clash with Epistemological Approaches

4.2.1 The Explanation of Singular Events in the CLM

As is well known, the CLM developed by Hempel and Oppenheim considers that to explain a phenomenon is to subsume it under a law; a particular event will be explained to the extent that we can present it as *an instance of* a regularity (Hempel, 1942, 1965; Hempel & Oppenheim, 1948). Before their article, similar ideas (though less influential before the translation of the book to English) had been presented in Popper's *Logik der Forschung* (Popper, 1935).

Hempel and Oppenheim's proposal, from the outset, attempted to fit examples of explanations from a variety of sciences. As early as 1942, Hempel defended the view that to scientifically explain a phenomenon amounts to showing how a sentence *E*, describing the phenomenon in question, can be inferred on the basis of, on the one hand *(1)*, some "statements asserting the occurrence of certain [individual] events," and, on the other *(2)*, "a set of universal hypotheses," that is, of "general laws" (Hempel, 1942, p. 36). According to Hempel, the fact that *E* can be inferred on the basis of those other statements shows that the event itself to which *E* refers was predictable, "had to occur", given the individual events and general laws presented in *(1)* and *(2)*—and this is what turns the phenomenon into something explained, something unsurprising. Now, it might be argued that such a proposal (and consequently our use of it to undermine the "descriptivist" approach to scientific explanation) is applicable only to the realm of "classical physics." However, and perhaps surprisingly (von Wright, 1971, p. 11), this early presentation of the explanatory model, which in turn produced its labelling as "covering law" by one of its critics, William Dray (Dray, 1970) was focused, not on physics or chemistry, but on *history*.[2]

Laws which play an explanatory role are not always strictly universal, i.e., laws which state that under certain conditions a certain sort of event *always* takes place. Laws can also be of probabilistic character, and this is something Hempel exemplifies with a case from biomedical science: "When little Henry catches the mumps, this might be explained by pointing out that he contracted the disease from a friend with whom he played for several

[2] In Hempel's proposal, historical explanation of a certain event "aims at showing that the event in question was not 'a matter of chance,' but was to be expected in view of certain antecedent or simultaneous conditions. The expectation referred to is not prophecy or divination, but rational scientific anticipation *which rests on the assumption of general laws*" (Hempel, 1942, p. 39. Emphasis ours). This is exemplified, among other instances, by McConnell's explanation of why government offices and bureaus tend to "fortify themselves" and "enlarge the scope of their operations": the explanation appeals to general laws such as those according to which "People who have jobs do not like to lose them; those who are habituated to certain skills do not welcome change" (Hempel, 1942, p. 40), and so on. But, of course, the same model is applicable to the explanation of physical events, such as the cracking of a car radiator during a cold night, which appeals to general laws such as the one which establishes the temperatures at which water freezes and increases the pressure it exerts (Hempel, 1942, p. 36). Explanations by means of subsumption under general laws can also be found, according to Hempel and Oppenheim, in other realms: it is by means of laws that we explain why the prices of cotton suddenly dropped in 1946, or why northern and southern France have such different linguistic resources to say "bee" (Hempel & Oppenheim, 1948, pp. 140–141).

hours just a day before the latter was confined with a severe case of mumps." Now, the law in question here, which helps us track Henry's disease back to his friend's, is not "a general law to the effect that under the conditions just mentioned, the exposed person invariably contracts the mumps." What we have, instead, is a statistic law according to which "the disease will be transmitted with high statistical probability" (Hempel, 1965, p. 302).

It is important to note, then, that the two types of laws allow, in the CLM, for two accordingly different types of explanation: the first type is what Hempel labelled *nomological-deductive* explanations—which are those that appeal to strictly universal laws, from which the statement describing the phenomenon to be explained follows with deductive necessity. The second type, which appeals to statistical laws, is what Hempel labels "explanation by inductive subsumption under statistical laws, or briefly, an inductive explanation" (Hempel, 1965, p. 302).

Now, a critic might insist that in spite of efforts made by defendants of the CLM as to its applicability to explanation in all sciences (not only natural but also social), it was never *proven* to fit, for example, history (which was, as is known, the thesis of Dray, 1970). Be that as it may, however, this argumentative gambit would not serve the purposes of a defense of the "descriptivist" approach, which is committed to the much stronger claim that, *as a general rule*, laws are not explanatory. *Even if* the CLM cannot be applied to some sciences, it might still be of value for others.

Now, although the "descriptivist" proposals which we have reconstructed do not appeal to any *criticism* against the CLM (instead, they simply seem to ignore it entirely), it might be argued that such a model suffers from some fatal flaws and that alternative models of the explanation of singular events might perhaps not make use of laws. However, as we will try to show, this is certainly not the case. Let us delve into the "statistical relevance" model of explanation developed by Wesley Salmon.

4.2.2 The Explanation of Singular Events in the "Statistical Relevance" Model of Explanation

Against Hempel's CLM, Wesley Salmon offered the following counterexample, which serves as the starting point for his own positive proposal: John Jones avoided becoming pregnant during the past year, for he has taken his wife's birth control pills regularly, and every man who regularly takes birth control pills avoids pregnancy. (Salmon et al., 1971, p. 34).

Predictably, as Salmon comments, the problem with this example is that "Men do not become pregnant, pills or no pills, so the consumption of oral contraceptives is not required to explain the phenomenon in John Jones's case (though it may have considerable explanatory force with regard to his wife's pregnancy)" (Salmon et al., 1971, p. 34). That is to say, even if the premises "John Jones has taken his wife's birth control pills regularly" and "every man who regularly takes birth control pills avoids pregnancy" *do* deductively imply "John Jones avoided becoming pregnant during the past year," this flawless logical relation does not amount to an identification of a factor which actually *explains* his lack of pregnancy: Jones's consumption of pills is simply *unnecessary* to explain it, and so "the 'explanatory' argument" is simply "not needed to make us see that the explanandum event was to be expected. There are other, more satisfactory, grounds for this expectation. The 'explanatory facts' adduced are irrelevant to the explanandum event despite the fact that the explanandum follows […] from the explanans" (Salmon et al., 1971, p. 36). A more realistic counterexample which illustrates this irrelevance, taken from medical science, is "John Jones was almost certain to recover from his cold within a week, because he took vitamin

C, and almost all colds clear up within a week after administration of vitamin C." Against the popular insistence on the efficacy of this vitamin to fight common cold, Salmon argues that its intake is explanatory irrelevant: "colds tend to clear up within a week regardless of the medication administered, and […] that the percentage of recoveries is unaffected by the use of vitamin C" (Salmon et al., 1971, p. 33). So, in contrast to this pseudo-explanation, what *does* count as a satisfactory explanation? We must focus, Salmon answers, on the notion of *statistical relevance*. "A property C is said to be statistically relevant to B within A if and only if P(A.C,B) ≠P(A,B)" (Salmon et al., 1971, p. 42). In our example, the probability of a case of pregnancy conditional to being the case of a (cisgender) man and his taking pills is not different from the probability of a case of pregnancy conditional to being the case of a (cisgender) man, period. His taking pills are statistically irrelevant. This is certainly an alternative to Hempel's CLM. Now, does this mean that laws are finally out of the picture in explanations?

Salmon makes it very explicit that this is not the case. "It is evident," he writes, "that explanations as herein characterized are nomological"—that is, supported by laws[3]. And this is because "frequency interpretation probability statements are statistical generalizations, and every explanation must contain at least one such generalization" (Salmon et al., 1971, p. 78). The "kind of explanation" he discusses, he adds, "is explanation by means of empirical laws" (Salmon et al., 1971, p. 81)[4]. So, to sum up, not only Hempel's canonical CLM is centered on the explanatory role of laws; Salmon's radically different proposal naturally needs to appeal to laws as well. Once again, this analysis contradicts those of the NAS (and, in the area of science education, those of Rubba and Horner, Lederman, and Bazghandi et al.) according to which laws are merely descriptive, not explanatory.

4.2.3 The Explanation of Singular Events in the CLM, According to the Manipulationist/Interventionist Model of Causal Explanation

Now, it might be said that, although Salmon's statistical model of explanation was presented as an alternative to the CLM, it was not much of an alternative after all, precisely because it still hinged on the idea that laws are the crucial element in an explanation, and only added the demand that such laws must make a difference in the probability which we attribute to a given *explanandum*. However, we might more fruitfully turn to a proposal which constitutes an alternative to the CLM in a deeper sense. Considering that, as we pointed out in Section 4.1, we are assessing the claim that laws are not *sufficient* for providing scientific explanations, we should consider the explicitly non-"nomothetical" account of explanation offered by Woodward. According to this author, examples such as that of the birth control pills we have just considered "show fairly conclusively" that the deductive-nomological model (one of the "submodels" of the CLM which we saw in Section 4.2.1) "does not state *sufficient* conditions for successful explanation. Explaining an outcome isn't *just* a matter of showing that it is nomically expectable" (Woodward, 2005, p. 155; emphasis in the original). We might expect, on the basis of such a passage, that Woodward would be an ally of the "descriptivist" thesis according to which laws are never sufficient to explain, and

[3] "Nomological" is technical jargon for "lawful," from the Greek "nomos," "law."

[4] Note here, by the way, how Salmon is well aware that *not all* laws are empirical. There are also theoretical laws—a point which will be central below, in Section 6.

only *something else* ("theories") can do the trick. Such a reading, however, would not be consistent with the concessions which Woodward makes only a few pages below; namely:

It is an undeniable fact that many explanations in both physics and chemistry, and in other sciences like economics and evolutionary biology as well, in which there is extensive reliance on mathematical theory, involve writing down systems of equations and solving them or *constructing derivations from them to relevant features of the phenomenon one wants to explain. Moreover, many of these equations are laws or at least fundamental explanatory principles of considerable generality*. Thus, […] explaining the behavior of a firm will involve the use of information about the marginal cost and revenue curves facing the firm and the general explanatory principle that the firm will act so as to maximize profits to construct a derivation of the behavior of the firm. More generally, although it is not true that *all* explanations involve the construction of explicit derivations from assumptions that include laws or general principles, the use of such derivations is a pervasive feature of explanatory practice in *many* areas of science, and a feature that any adequate theory of explanation must acknowledge. (Woodward, 2005, p. 185; emphasis modified)

So, again, although Woodward is not making the claim that appeal to laws (on the basis of which, as the CLM claims, we can "construct derivations" whose conclusion is a description of the *explanandum* phenomenon) is *always* sufficient to provide an explanation of a phenomenon, he is explicitly acknowledging that, "in many areas of science," providing an explanation consists *precisely* in appealing to laws. What separates Woodward from partisans of the CLM is *not* their "general point about the role of derivations from laws in explanation," but their "particular analysis of *how* such derivations work so as to provide understanding": where such a model "goes wrong," he goes on, "is not in its contention that derivation from laws plays an important role in many explanations, but in claiming that *all* explanation must have this structure and that explanation is simply a matter of providing nomic grounds for expecting" (Woodward, 2005, p. 185; emphasis in the original). So, in fact, none of these two caveats, vis-à-vis, the CLM makes Woodward an ally of the "descriptivist" position. Denying that *all* explanations appeal to explanatory *laws* is not the same as denying that in some cases ("in *many* cases," he writes) explanations take this form—and it is the latter denial, not the former, which is necessary to concur with the sweeping claims we saw in Section 4.1. And claiming that explanation does not reduce to "nomic expectability" means that covering law theorists did not accurately identify *what* exactly is the virtue which makes derivations from laws genuinely explanatory. But this criticism is very different from one which insisted that such derivations never explain.

So, summing up:

- In the enormously influential CLM, laws, far from being merely "descriptive" (as the NAS definition would have it), constitute the core of scientific explanations.
- In an important alternative developed as a plausible overcoming of the defects of the CLM, the statistical-relevance model, explanations are explicitly supported by laws.
- Even in the context of an explicitly non-"nomothetic" approach to explanation, such as Woodward's manipulativist model of causal explanation, the criticism levelled against the CLM is *not* that it elaborates derivations from laws, but its inaccurate analysis of *what exactly* makes those derivations explanatory.

4.3 Possible Consequences of the "Descriptivist" Approach

Now, the problem with the "descriptivist" approach is not simply that it clashes with canonical epistemological approaches but that it would have deleterious consequences when providing orientations to science teachers[5]. If the line between an explanation and a description becomes unclear, it becomes challenging to identify the advancements that students can achieve when transitioning from merely describing a phenomenon to providing an explanation for it as we can see by means of the following examples.

Take the Italian curricular guidelines, according to which students should "Explain the mechanisms of solar and lunar eclipses, using simulations" (which, it must be noted, is a demand for the explanation of a regularity, not of a singular event). If a law-like response such as "*If* the Moon gets between Earth and the sun, *then* it casts a shadow over Earth" only counts as descriptive, not explanatory, *what exactly would we want students to say*? What would constitute a satisfactory *explanation* of the phenomena?

Take another example, now from the German guidelines: "Explain causes of earthquakes and volcanoes". Now again, if a claim such as "*When* there is a certain accumulation of energy due to the friction between two tectonic plates, *then* there is a release of that energy in waves" only counts as "describing", not "explaining" the earthquake, it is again unclear what the student should do.

Now, it might be replied that the real dispute, in fact, is not whether laws are explanatory *tout court*, but whether laws are explanatory *of other laws* or if, on the contrary, the explanation of laws themselves involves an appeal to something else, "theories." This is, in fact, what we find in some remarks by William McComas. As we will try to argue, however, this view clashes not only with some proposals developed as alternatives to the CLM, but also with this model itself. And, once again, this is troublesome not because of a need to stick to epistemological orthodoxy, but because it obscures differences which are relevant for pedagogical purposes. Let us now turn to this problem.

5 A Second "Round": Can Laws Not Explain Other Laws?

5.1 The "Restrictivist" Approach to Laws

5.1.1 The Case of McComas: Newton as a "Cookbook Scientist"?

The case of McComas is the most intriguing one: some passages of his texts seem to go along the line of suggesting that laws are not explanatory *at all* (i.e., the "descriptivist" approach) but in some *other* passages, he acknowledges that laws are indeed explanatory at least in one level: that of individual events. Laws, according to McComas, "explain why particular instances occur (ex. Objects fall at a particular speed because of the law of gravity)" (McComas, 2014, p. 58); they "explain and predict individual occurrences or instances" (McComas, 2003, p. 146); they "are explained by theories but

[5] Of course, we are *not* claiming that *teachers themselves* commit the kinds of misunderstanding we are reviewing here. However, insofar as theoretical proposals in science education at least *aim* at guiding the actual practice of science teaching, it is perfectly reasonable to assess what *would* be the consequences of the approaches we are considering, *if* they were taken up by teachers (whether they currently do or not is an empirical question which goes beyond the scope of this article).

can themselves be used to explain instances". Moreover, in his article "The Nature of Science & the Next Generation of Biology Education" (2015) he states that:

Laws are explained by theories but can themselves be used to explain instances. So, if one goes to the Grand Canyon and notes the progression of fossils in the rocks (from less complicated lifeforms deep in the rock layer to more complicated and "modern" higher up in the younger rocks), it is reasonable to ask two questions: "Why are the fossils the way they are in the rock layers?" and "How did this happen?" Even if one had no idea of a mechanism, the realization that a process called "evolution" was responsible for the pattern in the rocks would be a reasonable explanation for this instance. (McComas, 2015, p. 489)

This is what we have called the "restrictivist" approach to laws. However, this is simply not enough to acknowledge their explanatory power.

To begin with, McComas is not consistent with this remark. To stick to this (partial) recognition of the explanatory role of laws, he would need to claim that it *contradicts* the misleading characterization by the National Academy of Sciences, according to which a law is simply "a *descriptive* generalization about how some aspect of the natural world behaves under stated circumstances" (National Academy of Sciences (U.S.), 1998; emphasis added). Instead, he simply quotes this definition without apparently noting the inconsistency with his own proposal (McComas, 2014, p. 58).

Even more remarkably, in his reading, it is difficult to understand how Newton's laws can be explanatory *even of particular instances*, because he reduces such laws to the status of mere "cookbook science," something which "works," but does not provide us with understanding of why certain phenomena occur—at the same level as the practical lore of some traditional peoples. McComas begins by pointing out that Dunbar calls laws "'cookbook science,' and the explanations 'theoretical science.'" Dunbar, according to McComas, "labels the multiple examples of the kind of science practiced by traditional peoples as 'cookbook' because those who apply the rules after observing the patterns in nature, do not understand why nature operates in the fashion that it does. The rules work and that is enough." And then he goes on to add that "Even in more sophisticated settings, cookbook science is occasionally practiced. For example, Newton described the relationship of mass and distance to gravitational attraction between objects with such precision that we can use the law of gravity to plan spaceflights" (McComas, 1998, pp. 54–55, emphasis added, See also 2008). This is not, by the way, a mere exceptional remark: more than 20 years later, McComas reflects on Newton's laws in the same terms (McComas, 2020, pp. 43–44). In this way, then, McComas does not acknowledge, even for the explanation of particular events, the superiority of causal laws such as Newton's over the practical knowledge held by traditional peoples which can establish correlations such as, in the example Dunbar takes from Gale, "If Sirius becomes visible just as the sun rises, then the river will flood" (Gale, 1979, pp. 64–65. Emphasis added)—a correlation which does not consider the real causal processes involved.

But there is a more curious consequence: to restrict the explanatory role of laws to "particular instances," he would need to deny the fact that Newton's laws have done explanatory work *in relation to lower-level laws, such as Kepler's or Galileo's*—which is something beyond discussion among physicists. In his repeated demotion of laws, McComas has once and again taken the case of Newton's, not mentioning that they are explanatory of other laws, but insisting that Newton's laws *themselves* are in need of explanation, which would be provided by a "*theory* of gravity" (McComas, 1996, pp. 10–11, 1998, pp. 54–55, 2017, p. 74, 2020, pp. 43–44).

So, summing up, McComas at least partially adheres to the “descriptivist” approach, according to which explanation must be something more than what laws can offer, because he:

- approvingly quotes the definition by the NAS according to which laws are “descriptive”, and assimilates Newton’s laws to “cookbook science”, the kind of merely practical knowledge held by “traditional peoples”
- never acknowledges the explanatory role of Newton’s laws *with respect to other laws*

but he also considers that laws can explain singular events, because he:

- states that even though laws are explained by theories, laws themselves can be used to explain instances

5.1.2 The Case of Braaten and Windschitl: “Covering Law Explanations” as Referred to “Events”

McComas does not seem to be alone in the belief that laws are explanatory only of particular events. In the proposal made by Braaten and Windschitl (2011) with the purpose of achieving “a stronger conceptualization of scientific explanation for science education,” although the authors do not explicitly *deny* that laws are explanatory of other laws, they repeatedly associate what they call “covering law *explanations*” (Braaten & Windschitl, 2011, pp. 641, 642, 645) with “seeking an explanation *for an event*,” “natural laws which can account for *particular events*,” “showing how *specific observable events* are logical outcomes of well-known patterns” (Braaten & Windschitl, 2011, p. 642; emphasis ours), “showing *an event* to be the expected result of a natural law” and “explaining *a specific event* by citing a law” (Braaten & Windschitl, 2011, p. 643; emphasis ours).

There is, to begin with, a serious mistake in believing that there is a specific *kind* of explanations which are “covering law” and which need to be contrasted with other *kinds*—such as “statistical/probabilistic *explanations*” (Braaten & Windschitl, 2011, pp. 645, 646) and “causal *explanations*” (Braaten & Windschitl, 2011, pp. 646, 647). Different *models* of scientific explanation do not refer to different kinds of explanations any more than the different *models* of the atom refer to different kinds of atoms. As we have already begun to see in Section 4.2.2, what distinguishes, e.g., Salmon’s statistical relevance *model* from the CLM is not that the former refers to a specific kind of explanations *for which the demand of statistical relevance would be appropriate.* Salmon’s point was, instead, that the CLM of scientific explanations (of scientific explanations *in general*) was not suitably tailored to accommodate the difference between a *good* explanation which appeals to a law and a *bad* explanation which also appeals to a law (such as the explanation of the non-pregnancy of a cisgender man in terms of his intake of contraceptive pills). Similar considerations apply to the idea that a causal *model* refers to a specific sub-type of explanations—as opposed to its laying certain claims about what explanations *in general* should provide.

In any case, what we need to consider now is whether there is any support for the belief that an appeal to laws is only appropriate for explaining particular events, and not also for explaining laws. What we will try to show is that:

- explaining regularities expressed by laws, and not only particular events, was undoubtedly a central concern of the CLM, and

- none of the mainstream alternatives (such as Kitcher and Friedman's unification model, Salmon's causal-mechanical model and Van Fraassen's pragmatic model) rejects the possible use of laws as devices for explaining other laws

5.2 The Clash with Epistemological Approaches

5.2.1 The Explanation of Laws by Other Laws in the CLM

We have already seen that (against the purely "descriptivist" approach to laws which we find, e.g., in the NAS document) the CLM made laws the very core of the explanation of singular events. However, what is crucial for our purposes now is (*contra* McComas and Braaten & Windschitl) to add that covering-law theorists clearly did not restrict the explanatory role of laws to their relation to singular events. Laws themselves can also be explained by reference to higher-level laws. Although Hempel begins with "the deductive explanation of particular occurrences by means of empirical laws," he immediately adds that empirical science raises the question "Why?" also in regard to the uniformities expressed by such laws and often answers it, again, by means of a deductive-nomological explanation, in which the uniformity in question is subsumed under more inclusive laws or under theoretical principles. For example, the questions of why freely falling bodies move in accordance with Galileo's law and why the motion of the planets exhibit the uniformities expressed by Kepler's laws are answered by showing that these laws are but special consequences of the Newtonian laws of gravitation and of motion. (Hempel, 1965, p. 343; see also Hempel & Oppenheim, 1948, p. 136)

So "Newtonian laws of gravitation and of motion" are at play not only for the explanation of particular events, but also for the explanation of Galileo's and Kepler's laws. The same view is held, by the way, by Carnap, who points out that the explanatory relation that certain laws have with respect to some facts is "somewhat analogous" to the relation that still other laws have with those first laws. Explaining laws also involves a resort to laws (Carnap, 1966, p. 229).

Now, just as we saw in Section 4.2.1 concerning the explanation of singular events, maybe an appeal to the CLM is unconvincing given the several criticisms to which the model has been subjected—though, again, it is still true that McComas does not refer to such criticisms. In any case, is it possible that, when we look at other models of scientific explanations, the idea of explaining laws by recourse to other laws disappears? Let us see now why this is not the case, by focusing on Friedman and Kitcher's unification model of scientific explanation.

5.2.2 Friedman's Criticism of the CLM, and His Explicit Appeal to the Explanatory Role of Laws in the Unification Model

To begin with, Friedman calls into question the claim, made by Hempel, that being able to predict an event suffices to actually explain it—insofar as explanation should, in turn, involve an increase in our *understanding* of a phenomenon (Friedman, 1974, p. 6), of why it occurs. Canonical examples of laws which have "predictive but not explanatory power" are "'A fall of the barometer (of such and such an amount) is followed by a storm', and 'Small whitish spots on the mucous linings of the cheeks ('Koplik spots') precede a characteristic rash, high temperature (etc.)'"—that is, "'diagnostic' or 'indicator' laws" (Suchting, 1967, p. 48). To make matters worse, Friedman goes on to claim that there is, after all, something to "the old argument that science is incapable of explaining anything because the basic phenomena to which others are reduced are themselves neither explained nor understood"—that is, because "science merely transfers our puzzlement from one phenomenon to another; it replaces one surprising phenomenon by another equally surprising phenomenon" (Friedman, 1974, p. 18). It will not do, Friedman goes on, to reply "that a phenomenon's being itself unexplained does not prevent it from explaining other phenomena in turn," because "the critic of science may legitimately ask how our total understanding of the world is increased by replacing one puzzling phenomenon with another" (Friedman, 1974, p. 19). It is easy to perceive how this affects a proposal which attempts to explain a given phenomenon by means of "covering" it under a corresponding law: if we begin by wondering why the phenomenon in question occurs, then we will be left wondering why the *law* holds.

This sounds rather similar to McComas' remarks concerning explanations by means of the law of gravity, which leave gravity itself unexplained. Nonetheless, Friedman is far from attempting to demote the potentially explanatory role of laws—his point is simply that such a role has been misunderstood by the CLM. For Friedman, the reason laws are explanatory is not their predictive power but the fact that they allow us to *unify* phenomena. In fact, he *explicitly* claims that "Newton's laws are a good candidate for explaining Boyle's law" (Friedman, 1974, p. 17). Now, why is this the case? Unlike the scenario we found in the CLM, the explanatory relationship would not have to be analyzed in terms of the fact that Newton's laws would allow us to *entail* something like Boyle's law, but in terms of that, by accepting Newton's laws, we also explain Graham's law, Galilee's law, and Kepler's laws—that is, because by accepting Newton's laws, "our over-all understanding of the world is increased; our total picture of nature is simplified via a reduction in the number of independent phenomena that we have to accept as ultimate" (Friedman, 1974, p. 18). There is, indeed, something that remains (at least temporarily) mysterious, which are Newton's laws themselves, but the amount of unexplained, "ultimate" phenomena has in this way diminished. And this is why such laws remain after all (*pace* McComas) explanatory.

Whereas Friedman took the example of Newton's laws to argue for the central role of unification in scientific explanation, Kitcher's version of the unification proposal appeals to Darwin's program as well as Newton's. And, as in the case of Friedman, even though Kitcher is articulating a criticism of the CLM, his point is, again, to show that the problem with the CLM is not its recourse to laws but the fact that it overlooks the *real* reason why they are sometimes useful for increasing our understanding. With respect to Newton, Kitcher argues that the natural continuation of his program by his successors was the attempt to "isolate a few basic force laws, akin to the law of universal gravitation, so that, applying the basic laws to specifications of the dispositions of the ultimate parts of bodies, all of the phenomena of nature could be derived" (Kitcher, 1981, p. 513). Concerning Darwin, Kitcher remarks that the unificatory (and hence *explanatory*) power of *The origin of species* rests on the fact that he offers "derivations of descriptions" of certain biological phenomena "which would instantiate a common pattern". In such derivation, in turn, Darwin appeals, in spite of still not knowing them, to "laws of variation and inheritance" (Kitcher, 1981, p. 515). Again, the point here is not to highlight the well-known fact that Darwin constantly speaks of laws, but to clearly identify the condition, *unification*, under which such laws can contribute to our understanding and therefore to explanation.

So, summing up:

- the "unification" approach, though it is an explicit criticism of the CLM, in no way supports a global demotion of laws to a merely descriptive, non-explanatory, role; it simply restates in terms of unification the conditions under which laws can in fact explain
- this unificatory role of laws takes place specifically at the level of explaining regularities (e.g., Newton's laws explaining Galileo's laws), so (*pace* McComas) in this model laws are certainly not restricted to explaining only individual instances

Now, things get even worse for a proposal like McComas' when we turn to the causal model favored by Salmon, who explicitly takes the very same example as McComas–Newton's laws and the explanation of the tides. Let us turn to this proposal.

5.2.3 Salmon's Criticism of the CLM, and His Appeal to the Explanatory Role of Laws in the "Mechanistic" Model

As is known, after proposing the statistical relevance model, Salmon grew increasingly dissatisfied with the idea that explanatorily relevant relations could be analyzed in purely statistical terms. He began to consider that such a statistical analysis constituted only a first stage of scientific explanation, a phase in need of complementation with a precise specification of the causal mechanisms at work in the phenomenon to be explained. More importantly, when presenting this new proposal (in Salmon, 1984, p. 19), he pointed out that whereas Hempel had attempted to prove that scientific explanations "provide a systematic understanding of empirical phenomena by showing that they fit into a nomic nexus," a more suitable approach would require substituting "the words 'how they fit into a causal nexus' for 'that they fit into a nomic nexus'"—that is, his own causal approach seemed to involve a displacement of the centrality of the notion of a scientific *law* (from which the term "nomic" derives). This abandonment (at least in principle) of the "nomic" element is accompanied by the usual remarks about how certain alleged "explanations" based on laws are, from a causal point of view, undoubtedly non-explanatory: as we saw, trying to explain the clearing up of a cold within two weeks on the basis of a law about the efficacy of vitamin C (Salmon, 1984, pp. 30–31) would not be getting things right. Real explanations seem to require something totally different from what the CLM, in both its nomological-deductive and its statistical-inductive versions, provides. Even more interestingly, in this same book, Salmon takes pains to highlight "that mere subsumption under laws—mere fitting of events into regular patterns—has little, if any, explanatory force." A pattern, he clarifies, "is constituted by regularities in nature—regularities to which we often refer as laws of nature," which "may be either universal or statistical" (Salmon, 1984, p. 121). Seemingly, nothing more is required to conclude that, in his new proposal, Salmon distanced himself as much as possible from the CLM.

Nonetheless, if a reader expects to find in this proposal by Salmon some support for the view which demotes the explanatory role of laws, she will be surprised to find that the author explicitly points out that his new "causal/mechanical version" of scientific explanation "is as much a covering-law conception as is any version" of the kind of proposal favored by Hempel (Salmon, 1984, p. 262). Hempelian emphasis on the centrality of laws for all explanations was, after all, alive and kicking. Now, how is this possible? How do the two passages we have just cited square with each other?

To begin with, the context of the reference to the lack of explanatory force of the "*mere* subsumption under laws" makes it sufficiently clear that, whereas some cases of subsumption are indeed non-explanatory, some others are, on the contrary, paradigm cases of explanation. Indeed, Salmon's paragraph continues by making clear that

the pre-Newtonian knowledge of the relationship of the tides to the position and phase of the moon [is] a prime historical example of subsumption of natural phenomena under regularities that was totally lacking in explanatory value. It was only when *the Newtonian explanation of that regularity in terms of the law of gravitation* became available that anyone could maintain plausibly that the tides had been explained. (Salmon, 1984, p. 121. Emphasis added)

It is rather ironic that Newton's *laws*, which surprisingly appeared in McComas analysis as scarcely explanatory, in the absence of a "theory" (and as something which at most could explain particular instances, not regularities such as those discoverable in the tides) are precisely *the* example Salmon appeals to in order to illustrate what constitutes a successful explanation. Or, in terms of a previous work:

Mariners, long before Newton, were fully aware of the correlation between the behavior of the tides and the position and phase of the moon. But inasmuch as they were totally ignorant of the causal relations involved, they rightly believed that they did not understand why the tides ebb and flow. When Newton provided the gravitational links, understanding was achieved. (Salmon, 1978, p. 687)

The case of causal laws such as Newton's is, in Salmon's proposal, radically different from that of non-causal laws: "Non-causal regularities," according to Salmon, "instead of having explanatory force which enables them to provide understanding of events in the world, cry out to be explained" (Salmon, 1978, p. 687). Against a global demotion of *all* laws, the "obvious moral to be drawn from this example, and many others as well", concludes Salmon, "is that *some* regularities have explanatory power, while *others* constitute precisely the kinds of natural phenomena that demand explanation" (Salmon, 1984, p. 121). In other words, a correlation such as that discovered between tides and phases of the moon is not explanatory but *in need of* explanation because it is not a causal regularity. The kind of regularity expressed by Newton's laws *is*, on the contrary, paradigmatically explanatory.

The demand, *contra* Hempel and Oppenheim, that scientific explanations include explicitly *causal* aspects (instead of *any* kind of law) converges, by the way, with the remarks made by George Gale, and later taken up by McComas via Dunbar, concerning the difference between "theoretical science" and "cookbook science." But we need to understand correctly (*pace* McComas) what this distinction refers to:

[T]he Egyptians […] managed to make many correlations between the various positions of the stars and what was happening on the face of the earth. […] In particular, they were attracted to the star Sirius. As it turns out, every year just before the onset of the flood, Sirius rises into view at just the instant the sun rises. Thus, the Egyptians were able to formulate the following generalization of the correlation: "If Sirius becomes visible just as the sun rises, then the river will flood […]". Since Sirius occupies the dawn position only once each year, this generalization is a very effective predictor. / But it is crucial to note exactly what this conditional statement, this prediction, is not. The statement is not an explanation; *it does not claim any causal relation* between the positions of sun and Sirius on the one hand, and the flooding on the other. (Gale, 1979, pp. 64–65. Emphasis added)

So, Gale's proposal was directed against attributing explanatory role to correlations insofar as they did not involve *causal* attributions. Explanations in general require, according to his proposal, the identification of causes: "by necessity, human consciousness demands that […] our minds be satisfied that we understand the objects and interactions which explain the observed natural phenomena," and—Gale goes on—"causes satisfy" such a demand (Gale, 1979, p. 70). Following in Gale's footsteps, Dunbar pointed out that certain peoples lacking scientific knowledge may be guided by a law of the type "If you sow crops when the birds come, then you will get good harvests." These people, strictly speaking, may have an effective rule, but they do not understand why plants grow in the desired way (Dunbar, 1996, p. 17). Dunbar's point, in any case, is that not all knowledge expressed in the form of laws ("if… then…") will constitute *why*-knowledge; that is, as the example of bird migrations and harvests shows us, knowledge of the *causes* of a phenomenon will not always be at stake. Evidently, what underlies the success of the practical rule in question is simply that the translation of the Earth, in conjunction with the tilt of its axis, is the cause of both the migrations of birds and the greater propensity of plants to grow at certain times. The rule mentioned by Dunbar does not adequately capture the relation between a cause and an effect but only the correlation between two effects of the same cause.

With these considerations in mind, a more satisfying way to understand what a scientific explanation is involves acknowledging explanatory power *only to those laws which are causal*. But this is certainly very different from claiming that *no* laws have an explanatory power.

Salmon makes it even harder to read his "causal-mechanical" model as a support for the "restrictivist" tenet that laws are not explanatory whereas "theories" are: in fact, he analyzes the explanatory power of theories *precisely* in terms of the laws they include. This relationship between theories and laws appears in the context of his remark that a (non-causal) regularity such as the "strict positive correlation between the amount of time required for clothes hung out on a line to dry and the distance required to get an airplane off of the ground at a nearby airport" (Salmon, 1984, p. 268). The explanation for this correlation involves the fact that "When oxygen or nitrogen molecules are replaced with water molecules in a given volume of air," as it happens on a humid day, the mass of the molecules in a given volume of air "is decreased; consequently, the density is lessened and the efficiency of the airfoils is reduced. This explains why a greater takeoff distance is needed." But this, in turn, is only understandable if we know that, "*According to Avogadro's law*, for fixed values of pressure and temperature, a given volume of gas contains the same number of molecules, regardless of the type of gas it is. A cubic meter of […] dry air contains the same number as a cubic meter of moist air." This is why, in Salmon's terms, "*Avogadro's law, which is embedded in the kinetic-molecular theory of gases*, will enable us to do the job" of explaining the initially mysterious regularity (Salmon, 1984, p. 269. Emphasis ours). Such a law, far from being explanatory only "of particular instances" and itself in need of an explanation offered by a "theory," is itself a crucial element of the kinetic-molecular theory.

But there is even more. To complete his point, Salmon needs to show more precisely why the explanation at stake here is indeed causal. And he does it by appealing, *again*, to *laws*: Newton's—which, as we previously saw concerning Avogadro's, appear not as something *to be* explained by a theory, but as what *does* the explaining. "The causal character of this explanation," Salmon comments, "lies within the molecular-kinetic theory of gases. According to this theory, *any gas is composed of particles in rapid motion that behave according to Newton's laws*" (Salmon, 1984, p. 269. Emphasis ours).

And this lawful behavior of the molecules in a gas extends to other basic constituents of reality: "Causal processes and causal interactions *are governed by basic laws of nature*. Photons, for instance, travel in null geodesic paths unless they are scattered or absorbed upon encountering material particles. Freely falling material particles follow paths that are nonnull geodesics. Linear and angular momentum are conserved when particles interact with one another. Energy is conserved in isolated physical systems" (Salmon, 1984, p. 262. Emphasis ours). This is why Salmon concludes, as we saw, that his own "causal/mechanical version" of scientific explanation "is as much a covering-law conception" as Hempel's.

This kind of causal explanation is to be understood on the background of Salmon's more general analysis of what causality amounts to; in particular, his proposal attempts to distinguish causal processes from "pseudo-processes." When a car moves at 100 km/h, and its shadow displaces at the same speed, then the "moving car, like any material object, constitutes a causal process; the shadow is a pseudo-process." This difference is to be understood in terms of the possibility for causal processes to *transmit a mark*, a change, to another process: "If the car collides with a stone wall, it will carry the marks of that collision […] along with it long after the collision has taken place." On the contrary, if the shadow "collides" with the stone wall, "it will be deformed momentarily, but it will resume its normal shape just as soon as it has passed beyond the wall" (Salmon, 1984, p. 143). All the causal "mechanisms" which Salmon appeals to in order to characterize the causal-mechanical model of explanation involve, then, transmissions of "marks." Now, it might be thought that this proposal is only applicable to physics. What about its extension to other sciences, such as biology?

Our reply to this concern is twofold. To begin with, we must insist that the bare fact that a certain model of scientific explanation, incompatible with the "restrictivist" approach, might not be applicable to a given science is not by itself an argument to defend the approach in question. Even if a causal-mechanical model of explanation does not apply to biology, this does not mean by itself that the concrete alternative according to which laws are not explanatory and "theories" are fares any better. And, even more, even in this case, all that would have been proven is that the account which regards laws as non-explanatory fits *biology* well—but this would be a much weaker claim than what the "descriptivist" approach affirms, namely, that laws are non-explanatory of other laws *in all disciplines*.

But in any case, it is not even obvious that the causal-mechanical model, with its focus on mark-transmission and which is explicitly presented as a continuity of the CLM, is not applicable beyond physics. According to Vineis, for example, biological research at the molecular level "almost literally refers to Salmon's idea of a mark that can be followed along time" (Vineis, 2000, p. 653). The idea that a cause is "a kind of signature that persists over time" can be found, this author claims, in the proposals according to which the cause of cancer "is identified with a genetic alteration such as a mutation in the *p53* gene, or […] in the *ras* oncogene." A "carcinogenic chemical would be able to leave a characteristic signature in a specific cancer gene, and this fingerprint would be transmitted through generations of cells" (Vineis, 2000, p. 652).

So, to sum up, based on its critique to Hempel's CLM, Salmon's causal/mechanical model of scientific explanation initially appeared as the most promising alternative, up to this point, in our search for epistemological foundations for the approaches in science education which question the explanatory role of laws. But such hopes quickly turned out to be groundless. Salmon, in fact,

- explicitly *distinguishes* "patterns" which are causal from those which are not, and *acknowledges* explanatory power to causal patterns
- mentions laws (such as Avogadro's and Newton's) as crucial explanatory devices for *theories* (such as the kinetical-molecular one), and
- insists that such laws rule the behavior of the very basic causal processes (molecules, photons, etc.) which constitute reality

5.2.4 Van Fraassen's Pragmatic Model of Scientific Explanation: Another Blow to the Demotion of the Explanatory Role of Scientific Laws

Salmon's causal-mechanistic proposal, then, certainly does not favor to the idea that laws in general are not explanatory—it only demands that the laws in question be *causal* ones. But even this, according to Van Fraassen, is too restrictive. He claims, in fact, that "many scientific explanations certainly do not look as if they are causal explanations in Salmon's sense. A causal law is presumably one that governs the temporal development of some process or interaction"—but these are not all the laws which carry explanatory power: "There are also 'laws of coexistence', which give limits to possible states or simultaneous configurations" (Van Fraassen, 1987, p. 122). So, after all, "the type of explanation characterized by Salmon, though apparently of central importance, is still at most a subspecies of explanations in general"(Van Fraassen, 1987, p. 123).

More in general, Van Fraassen attempts to demolish the proposals in which "explanation was conceived of as a relation like description: a relation between a theory and a fact." Against these proposals, the author remarks that "no single relation between theory and fact ever managed to fit more than a few examples!" (Van Fraassen, 1987, p. 156)—and this includes, of course, the case of the CLM and its insistence on the explanatory role of laws. But Van Fraassen's point, unlike that of the approaches which we have been considering, is not directed to the tenet that scientific laws are sometimes *sufficient* to obtain scientific explanations, but against the tenet that there is any theoretical element which is always *necessary* to construct such explanations. This makes Van Fraassen's proposal, in fact, nothing less than the polar opposite of analyses such as McComas'. According to this author, scientific explanations can simply be of many different sorts. "Being an explanation is essentially relative, for an explanation is an answer," and so "it is evaluated vis-à-vis a question, which is a request for information. But exactly what is requested, by means of the interrogative 'Why is it the case that P?', differs from context to context" (Van Fraassen, 1987, p. 156). It will then certainly *not* be the case that Van Fraassen demotes the explanatory role of laws.

Up to this point, then, we have not found any epistemological support for the approach according to which laws are not explanatory of other laws, and explanations require something more, offered only by "theories," whose way of providing explanations is allegedly not that which is characteristic of laws.

5.3 Possible Consequences of the "Restrictivist" Approach

As in the case of the "descriptivist" approach, a "restrictivist" approach to the role of laws in scientific explanations would also lead to undesirable didactic consequences. Given that under this framework something like the unifying achievement of laws like Newton's is lost from sight, then it would be difficult for teachers to justify the significance of specific milestones in the history of science, and, even more worrying, the very purpose of scientific activity. Similarly, the importance of Maxwell's laws stems from the fact that they play a crucial unifying role with respect to those previously elaborated by Coulomb, Gauss, Ampere, Faraday, and others—all of which can be deduced from them. And the ideal gases law plays the same kind of role with respect to Boyle-Mariotte's, Charles and Gay-Lussac's, and Avogadro's laws. If teachers ignored the fact that some of these laws play such a unifying role, they would either fail to perceive the importance of including them in their courses, or else present them to students in such a way that the history of science will appear as a mere *addition* of always new laws, without making it clear that the scientific enterprise strives towards achieving more unity.

6 A Third "Round": Do Laws Provide "Superficial" Explanations?

6.1 The "Sophistication-Demanding" Approach to Laws

It might be argued, however, that (once again) the real debate lies somewhere else. Perhaps the problem is not actually whether laws are entirely non-explanatory, or whether they are explanatory only of particular events and not of other laws—perhaps the problem is not *what* laws explain, but, instead, *what kind* of explanation they provide. Explanations by means of laws perhaps exist, but, in a pedagogic setting, they are, to use Braaten and Windschitl's slightly condescending words, "students' *first attempts* at explanations" and something which "Fosters algorithmic reasoning but may not develop students' conceptual reasoning or theory-building abilities" (Braaten & Windschitl, 2011, p. 643; emphasis ours); they certainly do not foster "sophisticated reasoning" (Braaten & Windschitl, 2011, p. 644). In other words, explanations which appeal to laws would be somewhat *superficial*. Allegedly following Driver et al., the authors claim that many everyday ways of explaining events take the form of "Covering Laws." For example, the authors envision a child asking a parent why the frying pan has a plastic handle, rather than a metal one. The parent responds that plastic does not conduct heat, but metal does; therefore, plastic handles do not get hot when the pan is on the stove. The parent's explanation involves a statement asserted as a fact in a "law-like" form […]. There are certainly more details that could be included in the explanation, but the parent's response essentially takes the form of a Covering Law explanation with "plastic does not conduct heat" being used as a sort of law. Driver and her colleagues encourage teachers and students to explore additional models of explanation *to foster deeper understanding* in science. However, the CLM of scientific explanation does satisfy some of our intuitions […]. In science classrooms, students often *begin their attempts* at providing scientific explanations by creating statements that resemble "Covering Law" explanations. (Braaten & Windschitl, 2011, pp. 644–645; emphasis ours).

By recognizing the law-like quality of students' initial attempts at explanation, we are given a starting place for pressing students to move beyond chalking up a phenomenon to a law or a generalization when it is often possible for them *to dig deeper and think in terms of underlying causes or in terms of powerful theories*. Rather *than simply criticizing students for failing to fully explain a phenomenon*, we can recognize their *initial attempts at explanation* as being similar to Covering Law explanations and then give explicit types of feedback. We can communicate with students about how their initial attempt at explanation *lacks certain attributes such as a causal relationship or an overarching scientific theory* in an effort to press them to construct deeper scientific explanations. Alternatively, we may choose to accept students' Covering Law explanations in certain circumstances, such as during a physics unit focused on mechanics, where law-like statements are the disciplinary norm for sufficient scientific explanations. (Braaten & Windschitl, 2011, p. 645; emphasis ours)

Now, why are explanations based on laws allegedly so unsophisticated? A first element which has come to the fore is that, according to Braaten and Windschitl's reconstruction, "covering law explanations" are to be distinguished from "causal explanations"—so it is no wonder that, in the passage we have just cited, the former are said to lack "certain attributes such as a causal relationship." We have already seen that this is a misunderstanding: laws can, of course, be *causal*, and provide the basis for *causal* explanations. But we need to turn to a second aspect of the alleged superficiality of the explanations based on laws: laws are supposed to differ from "theories" insofar as the former allegedly refer only to *observable* events and entities, and only the latter to unobservable "theoretical" ones. But this is, *again*, a mistake. Just as the opposition "causal/noncausal" is not one between laws and something else, but *internal* to the realm of laws, which can be of both kinds, the opposition "empirical/theoretical" does not oppose laws as a whole to something which lacks a law-like character, but simply divides laws into two kinds. Let us now turn to this point.

6.2 The Clash with Epistemological Approaches

There is probably no better way to introduce the point than appealing to an example of laws which are time and again demoted in McComas' work: Newton's. According to McComas, "laws are the generalisations or principles (i.e. Newton's law of gravity), while theories are the explanations (i.e. the germ theory of disease) for laws" (McComas, 2017, p. 74). We need to turn to the historical fact that, predictably, classical epistemology did not fail to acknowledge Newton's laws as a paradigm example of *theoretical* laws.

This point is, to begin, a historical one, but speaks (again) to the unfortunate mutual neglect between philosophy of science and science education. Carnap claimed as a platitude, not in need of a lengthy defense, that "Newton's universal law of gravitation was the *theoretical law* that explained for the first time both the fall of an apple and Kepler's laws for the movements of planets" (Carnap, 1966, p. 246; emphasis ours).

Now, it is not hard to see why, instead of an opposition between "laws" and "theories" (which demotes the spectacular theoretical work done by Newton's laws), Carnap, among many others, spoke of theoretical *laws*. Whereas Kepler's laws were in fact empirical insofar as they still referred to an observable property (*motion*) of certain observable entities (*planets*), Newton's postulated an explanatory principle, "gravity," which is quite obviously not perceivable. In fact, it is difficult to imagine what could be *more* "theoretical" than this (in particular, the example McComas gives, the germ theory of disease, is certainly much *less* theoretical than Newton's laws).

Whereas Carnap is a supporter of the CLM, the recognition of the existence of theoretical laws is certainly not an exclusive characteristic of this model. As we have also seen, Salmon's statistical relevance model appealed, it is true, to *empirical* laws (Salmon et al., 1971, p. 81), but made this clarification *precisely* to state that *not all laws* are empirical. In other words, whereas his exposition of that model may have focused on attributing an explanatory role to laws which do not refer to theoretical entities, he made it clear that this was not a limitation which defines laws *in general*. His later causal-mechanical model, in turn, refers to "laws of nature" as governing the behavior of highly theoretical entities such as gas molecules or photons. Similarly, Friedman writes that from "the fact that all bodies obey the laws of mechanics it follows that the planets behave as they do, falling bodies behave as they do, and gases behave as they do" (Friedman, 1974, p. 15), and we can do this because we assume that "*molecules* obey the laws of mechanics" (Friedman, 1974, p.

14; emphasis ours). Again, the scope of laws goes well beyond the realm of observable phenomena—it involves claims about theoretical entities such as molecules.

It is difficult to track how exactly this demotion of laws, in general, to the level of *empirical* laws may have emerged. In any case, rather than being supported by analyses which are *currently* canonical in philosophy of science, it seems to constitute a relapse into themes of *classical* positivism—well before the logical positivism of Hempel and Carnap. Indeed, it was Comte himself who, in his *Discours sur l'esprit positif*, opposed "the *simple* (!) search for laws," on the one hand, and the "inaccessible determination of causes properly so-called," *on the other hand*. This is because, according to Comte, scientific laws only state "constant relations between *observed* phenomena" (Comte, 1908, pp. 19–20; emphasis ours). In other words, classical positivism assumes that scientific laws, so to say, do not dig particularly deeply in the structure of reality. Although Comte was *celebrating*, as evidence of the "maturity" of thought, that laws did not attempt to grasp causes, whereas the approach we discuss in this section tends to *reject* such a limitation as a show of superficiality, both this rejection and that celebration concur in precisely the kind of image of laws which we are questioning. In any case, this view of laws has long ago ceased to be influential in philosophy of science.

Now, the way in which the highly theoretical character of many scientific laws is overlooked is accompanied by a remarkable distortion of the way in which "laws" and "theories" are said to emerge. In other words, the only way to insist that laws are unsophisticated and restricted to the realm of observable entities is to support a naïve inductivist mythology of scientific discovery.

In McComas' approach, "laws" "are generally considered discovered rather than invented" (McComas, 2003, p. 144); "theories," on the contrary, "are generally considered to have been invented rather than discovered" (McComas, 2003, p. 145). More explicitly, McComas writes that laws "are considered to be discovered *using induction* rather than invented" (McComas, 2014, p. 58; emphasis ours). The only sense which we can give to this, and which is consistent with the repeated omission of the highly theoretical character of Newton's laws, is that "laws," in general, are "discovered" *in a naively inductivist sense*. That is to say, a "law" would have to be a statement *which only appeals to the same kind of concepts which are used in empirical statements describing observable phenomena*. A typical example of this is the fiction according to which a typical scientific law would take the form of "This first animal is a raven and is black; this second animal is a raven and is black; this third animal is a raven and is black; *therefore, all ravens are black*." Now, even if there are examples of important scientific laws which have been "discovered" in this way, it is highly implausible to imagine that *Newton's* laws may have this kind of origin. In fact, in order for them to be "discovered using induction," Newton would have needed to be able to describe observable, singular events in the world in terms of gravitational attraction and *then* elaborate an "inductive law" which simply amounted to a "generalization" of such observations. But this would mean that, far from introducing novel vocabulary, Newton limited himself to simply "generalizing" on the basis of singular statements about what anyone could simply *see* in the world.

6.3 Possible Consequences of the "Sophistication-Demanding" Approach

Now, the problem with this approach, which views explanations based on *laws* (on *any* laws) as not "sophisticated" is that it *misdiagnoses* what the matter is with students who, according to reconstructions such as Braaten and Windschitl's, cannot go beyond the level of observable events and entities. By lumping together empirical and theoretical laws and assuming that all of them are based on observations just because they are called "laws," this approach ends up suggesting that an explanation which arrives at the level of using highly theoretical concepts such as "gravity" or "electron" is not "sophisticated" simply because they appear in *laws*. The problem of getting students to appeal to "deep" structures, beyond what is observable, is a very real and pressing one—but it is *orthogonal* to the question whether or not their explanations appeal to laws. In suggesting that laws (in general) are not "sophisticated" or "deep," this approach simply invites teachers to look in the wrong direction. Complementarily, when students *are* able to raise to the use of theoretical laws, it would be very discouraging for them to hear that the use of highly abstract statements such as Newton's or Maxwell's laws is not "deep" enough because they are "mere" laws.

Simultaneously, insofar as it includes the remarks that laws (again, laws *in general*) are "discovered by induction," this approach fosters the naïve suggestion that science is made by simply observing the world. This naive inductivism is, alas, one of the most deeply rooted popular prejudices about how science works, and it has the potential to become an obstacle when it comes to making students understand, for example, the very nature of a *hypothesis*. Scientific hypotheses are not justified by previous "inductive observation" of particular instances but are creatively invented and *then* tested against data. Even worse, such inductivism is associated with the idea that scientific *objectivity* depends on approaching reality "with no preconceptions," with the aim of merely *seeing* what "is out there" in the world. Feeding these prejudices would do a teacher no favor when it comes to helping students understand the actual scientific practice, as can be studied by means of an appeal to the *history* of science. It is inconsistent to insist, as many science education writers do, on the importance of including a historical perspective on science as part of a NOS approach, on the one hand, and to expect that students be able to square such historical data in the framework of a naïve inductivism, on the other.

7 Summing Up

In this article, we explored a surprising and concerning conflict that has practical implications between the established models of scientific explanations in mainstream epistemology and three different assumptions that we consider idiosyncratic within the realm of science education. These assumptions demote scientific laws to a marginal function within scientific explanation (when they do not exclude it completely). We argued that the problem is not merely *terminological*—i.e., it does *not* boil down to the fact that, *to refer to the same set of statements*, philosophers of science use the term "theoretical *laws*" whereas science education theorists employ the term "theories," which would allegedly refer to something different from laws. The issue is, instead, that the *global* demotion of "laws" fails precisely to distinguish between, for example, Kepler's laws, which refer to observable entities such as planets, and Newton's, which postulate an unobservable entity, "gravity," to explain a variety of empirical laws. For each assumption, we discussed its implications on both theoretical and practical levels.

The global demotion of scientific laws to a merely "descriptive," non-explanatory role which we find in a variety of authors in science education is deleterious to the aim of achieving a deeper scientific understanding of reality among students. It is also deleterious, we believe, to acknowledge such an explanatory role only to the relation between *laws* and *particular instances*. The most worrying idiosyncratic assumption, however, is the third one—precisely because it *seems* more plausible than the others. As we tried to argue, it stems from confusing *scientific laws*, in general, with *empirical*, *non-theoretical*, laws, in particular. And it leads to *misdiagnosing* a very real problem: when students only achieve a “superficial” understanding of natural phenomena insofar as they cannot transcend the level of observable processes and entities, we reckon that the problem which should be tackled is not the recourse to “laws” and “covering laws explanations” but the recourse to *empirical* laws instead of theoretical ones. Scientific laws are not always empirical—there is a variety of *theoretical* laws which postulate unobservable entities and appeal to them in order to provide a very deep understanding of observable phenomena.

What seems to lay behind this neglect of the distinction between empirical and theoretical laws, in turn, seems to be a notion of “law” which quickly assimilates it to “generalization” *in a naively inductivist sense*. That is, under this understanding, a “law” would have to be a statement which only appeals to the same kind of concepts which are used in empirical statements describing observable phenomena (as in the typical example of “All *ravens* are *black*”). Needless to say, several paradigm cases of scientific laws can hardly be described in this fashion.

Science education writers have regrettably confused the distinction between different *models* of scientific explanation (e.g., CLM, causal-mechanistic model, etcetera) with a distinction between different *kinds* of scientific explanation (thus speaking of covering-law *explanations* and causal *explanations*). This is a mistake similar to believing that different *models of the atom* describe different *kinds of atoms*. And it is, in fact, a serious mistake, because it neglects the fact that different models usually overlap in the kinds of explanations which they take as acceptable. In this vein, it is too often forgotten that causal explanations typically *are* explanations which appeal to laws (and which could be analyzed by the CLM).

By pointing out what we take to be a troublesome clash between science education and epistemology, our aim is not to *deepen* the gap between these two disciplines. Quite on the contrary, we are all in the same boat, and we all strive to make science literacy as broad and accurate as possible. The authors of this article come each from a different discipline (we are a science education researcher and an epistemologist) and humbly hope that this piece will contribute to continuing a fruitful interdisciplinary conversation.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

References

American Association for the Advancement of Science. (1994). *Benchmarks for science literacy*. Oxford University Press.

Bazghandi, P., Zarghami-Hamrah, S., Ghaedi, Y., Mahmudnia, A., & Noaparast, K. B. (2015). Theoretical explanation of the implications of complex systems theory for teaching science. *Problems of Education in the 21st Century, 65*(1), 6–17. https://doi.org/10.33225/pec/15.65.06

Berland, L. K., & McNeill, K. L. (2012). For whom is argument and explanation a necessary distinction? A response to Osborne and Patterson: Is Argument and Explanation a Necessary Distinction? *Science Education, 96*(5), 808–813. https://doi.org/10.1002/sce.21000

Braaten, M., & Windschitl, M. (2011). Working toward a stronger conceptualization of scientific explanation for science education: Scientific explanations. *Science Education, 95*(4), 639–669. https://doi.org/10.1002/sce.20449

Brigandt, I. (2016). Why the difference between explanation and argument matters to science education. *Science & Education, 25*(3–4), 251–275. https://doi.org/10.1007/s11191-016-9826-6
Carnap, R. (1966). In M. Gardner (Ed.), *Philosophical foundations of physics. An introduction to the philosophy of science. Edited by Martin Gardner*. Basic Books. http://gen.lib.rus.ec/book/index.php?md5=3cdf63ea0939cac55a19b93eb2f80650
Chang, R., & Overby, J. (2022). *Chemistry* (14th ed.). McGraw-Hill Book Company, Inc.
College Board. (2009). *College based science standards*. College Board.
Comte, A. (1908). *Discours sur l'esprit positif*. Société positiviste internationale. http://archive.org/details/discoursurlesp00comt
Dray, W. (1970). *Laws and explanation in history*. *Oxford University Press*.
Dunbar, R. I. M., & Robin, I. M. (1996). *The trouble with science*. Harvard University Press.
Eastwell, P. (2014). Understanding hypotheses, predictions, laws, and theories. *Science Education Review, 13*(1), 16–21.
Friedman, M. (1974). Explanation and scientific understanding. *The Journal of Philosophy, 71*(1), 5–19. https://doi.org/10.2307/2024924
Gale, G. (1979). *Theory of science: An introduction to the history, logic, and philosophy of science*. McGraw-Hill College.
Goodman, N. (1955). *Fact, fiction, and forecast* (1st ed.). Harvard University Press.
Hempel, C. G. (1942). *The Function of General Laws in History* (Vol. 15). Routledge.
Hempel, C. G. (1965). *Aspects of scientific explanation, and other essays in the philosophy of science*. Free Press.
Hempel, C. G., & Oppenheim, P. (1948). Studies in the logic of explanation. *Philosophy of Science, 15*(2), 135–175. https://doi.org/10.1086/286983
Hunt, K. (1996). *Chemcom: Chemistry in the community* (3rd ed.). Kendall Hunt Pub Co..
Kitcher, P. (1981). Explanatory unification. *Philosophy of Science, 48*(4), 507–531.
Lederman, N. (2006). Syntax of nature of science within inquiry and science instruction. In L. B. Flick (Ed.), *Scientific inquiry and nature of science: Implications for teaching, learning, and teacher education*. Springer.
Lederman, N. (2007). Nature of science: Past, present and future. In S. K. Abell & N. Lederman (Eds.), *Handbook of Research on Science Education* (1st ed.). Routledge. https://doi.org/10.4324/9780203824696
Lederman, N., & Abd-El-Khalick, F. (2002). Avoiding de-natured science: Activities that promote understandings of the nature of science. In W. F. McComas (Ed.), *The Nature of Science in Science Education: Rationales and Strategies* (pp. 83–126). Springer. https://doi.org/10.1007/0-306-47215-5_5
McComas, W. F. (1996). Ten myths of science: Reexamining what we think we know about the nature of science. *School Science and Mathematics, 96*(1), 10–16. https://doi.org/10.1111/j.1949-8594.1996.tb10205.x
McComas, W. F. (1998). The principal elements of the nature of science: Dispelling the myths. In *The nature of science in science education* (pp. 53–70). Springer.
McComas, W. F. (2003). A textbook case of the nature of science: Laws and theories in the science of biology. *International Journal of Science and Mathematics Education, 1*(2), 141–155. https://doi.org/10.1023/B:IJMA.0000016848.93930.9c
McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17*(2), 249–263. https://doi.org/10.1007/s11191-007-9081-y
McComas, W. F. (Ed.). (2014). *The language of science education: An expanded glossary of key terms and concepts in science teaching and learning*. Sense Publishers.
McComas, W. F. (2015). The nature of science & the next generation of biology education. *The American Biology Teacher, 77*, 485–491. https://doi.org/10.1525/abt.2015.77.7.2
McComas, W. F. (2017). Understanding how science works: The nature of science as they foundation for science teaching and learning. *The School Science Review, 98*, 71–76.
McComas, W. F. (Ed.). (2020). *Nature of science in science instruction: Rationales and strategies*. Springer International Publishing. https://doi.org/10.1007/978-3-030-57239-6
McNeill, K. L., & Krajcik, J. (2007). Middle school students' use of appropriate and inappropriate evidence in writing scientific explanations. In *Thinking with data* (pp. 233–265). Lawrence Erlbaum Associates Publishers.
Metcalfe, H. C., Harold, C., Williams, J. E., & Castka, J. F. (1974). *Modern chemistry*. Holt, Rinehart and Winston.
Mondragón Martínez, C. H., Peña Gómez, L. Y., Sánchez de Escobar, M., Arbeláez Escalante, F., & González Gutiérrez, D. (2010). *Hipertexto. Química 1*. Santillana.
Mullis, I. V. S., Martin, M. O., Goh, S., & Cotter, K. (2016). *TIMSS 2015 encyclopedia: Education policy and curriculum in mathematics and science*. TIMSS & PIRLS International Study Center.
National Academy of Sciences (U.S.). (1998). *Teaching about evolution and the nature of science*. National Academy Press.
National Research Council. (1996). *National Science Education Standards*. National Academies Press.
Núcleos de Aprendizaje Prioritarios. (2005). http://www.bnm.me.gov.ar/giga1/documentos/EL000972.pdf

Osborne, J. F., & Patterson, A. (2011). Scientific argument and explanation: A necessary distinction?: Scientific Argument And Explanation. *Science Education, 95*(4), 627–638. https://doi.org/10.1002/sce.20438

Osborne, J. F., & Patterson, A. (2012). Authors' response to "For whom is argument and explanation a necessary distinction? A response to Osborne and Patterson" by Berland and McNeill. *Science Education, 96*(5), 814–817. https://doi.org/10.1002/sce.21034

Özgelen, S. (2010). *Exploring the development of pre-service science teachers' views on nature of science in inquiry-based laboratory instruction*. Springer.

Popper, K. R. (1935). *Logik der forschung; zur erkenntnistheorie der modernen naturwissenschaft*. J. Springer.

Popper, K. R. (1949). A note on natural laws and so-called contrary-to-fact conditionals. *Mind, 58*(229), 62–66.

Rao, J. R. L. (1998). Scientific "laws", "hypotheses" and "theories": Meanings and distinctions. *Resonance, 3*(11), 69–74. https://doi.org/10.1007/BF02838710

Rubba, P. A., Homer, J. K., & Smith, J. M. (1981). A study of two misconceptions about the nature of science among junior high school students. *School Science and Mathematics, 81*(3), 221–226. https://doi.org/10.1111/j.1949-8594.1981.tb17140.x

Rubba, P. A., & Horner, J. (1979). *The Laws are mature theories Fable* Science Teacher 46 31

Ryan, A. G., & Aikenhead, G. S. (1992). Students' preconceptions about the epistemology of science. *Science Education, 76*(6), 559–580. https://doi.org/10.1002/sce.3730760602

Salmon, W. C. (1978). Why ask, "Why?"? An inquiry concerning scientific explanation. *Proceedings and Addresses of the American Philosophical Association*, *51*(6), 683. https://doi.org/10.2307/3129654

Salmon, W. C. (1984). *Scientific explanation and the causal structure of the world*. Princeton University Press. http://archive.org/details/scientificexplan0000salm

Salmon, W. C., Jeffrey, R. C., & Greeno, J. G. (1971). *Statistical explanation and statistical relevance* (1st ed.). University of Pittsburgh Press. http://gen.lib.rus.ec/book/index.php?md5=25939a8672b46e8e516a3d4b74a7f982

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*(4), 610–645. https://doi.org/10.1002/sce.10128

Silverstein, T. P. (1996). Evolution teaching. *Science, 274*(5289), 904–905. https://doi.org/10.1126/science.274.5289.904.d

Smart, J. J. C. (1963). *Philosophy and scientific realism*. Humanities Press. https://books.google.com.ar/books?id=L_EYAAAAMAAJ

Suchting, W. A. (1967). Deductive explanation and prediction revisited. *Philosophy of Science, 34*(1), 41–52.

Tocci, S., & Viehland, C. (1996). *Holt chemistry: Visualizing matter*. Holt, Rinehart and Winston.

Toulmin, S. (1958). *The uses of argument*. Cambridge University Press.

Tuberty, B. (2011). Student understanding of scientific hypotheses, theories & laws: Exploring the influence of a non-majors college introductory Biology course. *International Journal of Biology Education, 1*(1), 23–44.

Van Fraassen, B. (1987). *The scientific image*. Clarendon Press. http://gen.lib.rus.ec/book/index.php?md5=34aa5e7f83bf5049b52aba2203fde62c

Vineis, P. (2000). Exposures, mutations and the history of causality. *Journal of Epidemiology & Community Health, 54*(9), 652–653. https://doi.org/10.1136/jech.54.9.652

von Wright, G. H. (1971). *Explanation and Understanding*. Routledge & Kegan Paul.

Woodward, J. (2005). *Making things happen: A theory of causal explanation (Oxford Studies in the Philosophy of Science)*. Oxford university press. http://gen.lib.rus.ec/book/index.php?md5=eb1912c07716e5be9973745ff64899a2