SOME MORALS FROM THE PHYSICO-MATHEMATICAL CHARACTER OF SCIENTIFIC LAWS

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Abstract: This article derives some morals from the examination of the physico-mathematical view of scientific laws and its place in the current philosophical debate on laws of nature. After revisiting the expression scientific law, which appears in scientific practice under various names (such as laws, principles, equations, symmetries, and postulates), I briefly assess two extreme, opposite positions in the literature on laws, namely, full-blown metaphysics of laws of nature, which distinguishes such laws from the more mundane laws that we find in science; and nomological eliminativism, which ultimately contends that we should dispense with laws in science altogether. I argue that both positions fail to make sense of the laws that we find in scientific practice. For this, I outline the following twofold claim: first, most laws in physics are abstract mathematical statements; and second, they express some of the best physical generalisations achieved in this branch of science. Thus understood, a minimal construal of laws suggests that they are in principle intended to refer to those features of phenomena whose salience and stability are relevant for specific scientific tasks.

Keywords: Scientific laws. Laws of nature. Mathematics. Metaphysics. Physical systems.

INTRODUCTION[2]

In this article, I outline a physico-mathematical account of scientific laws. Such laws constitute one of the central issues in current debates in philosophy of science. This is partly because they occupy an important place in scientific practice; partly because they are our best grasp of the way reality is in some domains; and partly because the analysis of the character of scientific

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[2] This article was developed within the context of the FONDECYT 11160324 research grant, CONICYT, Chile. I am grateful for their financial support. Pablo Acuña, Bruno Borge, Otávio Bueno, Anjan Chakravartty, Aldo Filomeno, Roman Frigg, and Howard Sankey kindly engaged in discussions of some of the ideas contained in this article at different stages of the writing process. I am, of course, fully responsible for possible mistakes that may have gone unnoticed.

http://dx.doi.org/10.1590/0101-3173.2020.v43n4.04.p65

laws raises a cluster of philosophical questions. Focusing on physics, I shall address the following concerns: do metaphysical approaches to the laws of nature account for the laws that we find in science? Can we dispense with laws in our understanding of scientific practice? Do laws in physics amount to more or less complex, abstract mathematical statements that intend at least in principle to inform us about reality?

The structure of my argument is as follows. In section 2, I look into the expression *scientific law*, a notion that cannot but be overloaded with a variety of meanings. For one thing, speaking of laws may resemble the metaphysical discourse on the laws of nature. For another, a plethora of expressions that refer to nomic statements quickly come to mind, such as principles, equations, postulates and symmetries. I highlight that there is no general consensus as to when we should call scientific laws certain physically interpreted mathematical statements. However, I contend that we can still identify laws in terms of the tasks they accomplish, such as expressing physical generalisations of various scopes.

To situate the physico-mathematical view, I briefly outline two opposite views on laws in section 3. I firstly address, in 3.1, the metaphysical approach that reifies the laws of nature, taking scientific essentialism as an instance of such approach. In this respect, I argue that this approach should be rejected so long as it introduces a heavy metaphysical baggage, relying on a questionable distinction between *laws of nature* and *scientific laws.* By contrast, in 3.2, I address the second cluster of views, which corresponds to anti-metaphysical approaches that I label nomological eliminativism. In various guises, not only does nomological eliminativism promote the rejection of the metaphysicians' laws of nature, but it also advises us to dispense with laws in our construal of science altogether. Contrary to this, I shall argue that nomological eliminativism fails to account for the laws that we find in scientific practice.

In section 4, I advance my analysis of the physico-mathematical view providing evidence for the following claims: (4.1) most laws in physics are standardly articulated in terms of more or less complex, abstract mathematical statements; (4.2) Dorato's appraisal of the software theory of the universe delivers an exercise in the mathematics' contribution to the articulation of laws; and (4.3.) such laws inform us about some of the best physical generalisations achieved in science. Overall, I aim to show that laws in science are at least in principle intended to inform us about those features of phenomena whose salience and stability are relevant for various scientific tasks, which are associated, among other things, with the application of measurement and modelling procedures of various kinds. I argue that the physico-mathematical approach enables us to avoid both a metaphysics-minded account of laws and nomological eliminativism.

1 Scientific laws revisited

As practice in physics routinely demonstrates, law statements play a variety of roles. For one, they help scientists express some of the best physical generalisations achieved by means of empirical and mathematical research. An initial insight into what physical generalisation means can be obtained by looking at the distinction between *phenomenological* and *fundamental* laws.[3] The former describes physical systems. They succeed to do so in such cases as mathematical descriptions of specific physical systems, as is exemplified in the Fourier law of heat conduction or the Kepler laws of planetary motion. By contrast, fundamental laws aim at explaining ideal systems that fail to find an exact correlate in reality. Examples of this latter sort are those of the symmetries of the standard model of particle physics and the laws of general relativity, both of which require a good deal of mathematical idealisations that are satisfied by further, less-abstract mathematical models of the world. I shall return to this point in section 4, where I flesh out in further detail this distinction. For the time being, it is worth emphasising that the demarcation between *phenomenological* and *fundamental* seems to be at least partly grounded in an ontological consideration. Phenomenological laws describe phenomena of a well-delimited, restricted scale, whereas fundamental laws inform us about the construction of ideal systems that are intended to reveal pervading (ideal) features of reality as a whole.

Addressing the role of laws in expressing physical generalisations, it should be asked in a Shakespearian spirit: what is in the name *scientific law*?[4] The question is relevant, since the expression *scientific law* can work as a general label encompassing a variety of law-like mathematical statements that are usually called by different names in scientific jargon. Indeed, not only does

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[3] For details concerning this distinction, see Cartwright (1983, pp. 1-2 and 160); and Cartwright (1999, pp. 23 and ff., and pp. 35-36)

[4] I think of *Romeo and Juliet*, Act 2, Scene 2, where Juliet says: "What's in a name? That which we call a rose / by any other name would smell as sweet," implying that Romeo would keep his excellence if called by another name. Regarding my argument, I suggest the concern of whether scientific laws would keep their character if called differently.

science teach us about laws, but it also informs us about equations, principles, postulates, symmetries, and so forth. Let me mention a few examples:

i. *Laws*: The Ohm law for acoustics; the conservation laws; the laws of thermodynamics; the law of gravitation.

ii. *Principles*: The principle of least action; Heisenberg uncertainty principle; Pauli exclusion principle.

iii. *Equations*: Einstein field equations in general theory of relativity; Maxwell's equations of classical electromagnetism; the Schrödinger equation.

iv. *Postulates*: The first postulate of special relativity (the speed of light is constant).[5]

In what follows, I suggest employing the expression *scientific law* (or just *law*) as a generic label that encompasses them all. No rigour has been achieved in practice regarding the ways in which research communities name scientific laws. As observed above, some laws are called principles, others are called equations, and a few others are named postulates. Some laws are labelled symmetries in view of the fact that they pick out symmetric features of theory or reality (or both), whereas others are termed laws *simpliciter*, as though they were the proper laws of scientific endeavour.[6] Science has its folklore too. Some laws are christened after the names of those who discovered them, whereas others are categorised by reference to their physical targets. For the most part, this lack of rigour seems to be the natural result of the general unimportance of naming practices in view of scientific interests.

One moral that can be derived from the argument thus far is that the boundaries of what counts as a scientific law and what does not are blurry. On the one hand, there appears to be no principled (*a priori* or otherwise) distinction among specific laws, principles, equations, symmetries, and postulates. On the other, we do find in each particular case a difference in the physical generalisations that mathematics-based law statements express, thereby having specific nomic scopes related to the regions of reality they intend to describe or explain. Some of them, as the Kepler laws, address only a small number of planets and employ basic mathematics (equations relating

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[5] Note that the second postulate of special relativity states that the laws of physics are the same in all inertial frames, without having by itself a standard mathematical formulation.

[6] Although with different purposes from those that I have in mind here, Similar analyses of the naming practices of laws in science can be found in Mumford (2004, p. 134) and Holton and Brush (2006, pp. 187 and ff.)

geometrical properties of the orbit of a body), whereas other laws can be applied to any physical system throughout the space-time universe in terms of high-level abstract mathematical theorising (group theory, Hilbert spaces, etc.). Additionally, it is not easy to find out a difference between those abstract mathematical statements that scientists call laws and those that, by contrast, are similarly abstract and mathematical, but do not bear a law-like status in inferential practices.

2 From full-blown metaphysics of laws to nomological eliminativism

In this section, I show that proposals in the philosophy of science arena go from full-blown metaphysical views of laws of nature (3.1) to sophisticated versions of the anti-metaphysical nomological eliminativism (3.2). I shall succinctly highlight the shortcomings of these proposals and point out the main issues regarding which the physico-mathematical approach adopts a different stance.

2.1 The metaphysical strategy: *laws of nature* and *scientific laws*

To attempt to offer a single definition of laws of nature as they are conceived of in the metaphysical debate would not do justice to the variety of accounts that we find throughout this philosophical trend.[7] Yet, a common feature of these approaches is the main question they raise, namely: what is the nature of the laws of nature? To some extent, such question assumes that there is a metaphysical story to tell in this respect. The following is a first characterisation of the laws of nature from a metaphysical perspective:

i. *Universality*. Laws of nature universally govern their regions of reality. The law statements expressing them are universal in scope regarding

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[7] Philosophical approaches to laws of nature are standardly categorised as follows: on the one hand, we find various Humean accounts, with variations in supervenience theories and the best system account; whereas, on the other, there are various metaphysical takes, such as the natural necessity approach, including several versions of the Dretske-Tooley-Armstrong theory, and dispositional and essentialist theories grounding laws in a specific conception of properties (see Carroll 2004). To engage in critical analysis of these views would distract me from the goals of this article. It should be observed that the literature also includes less metaphysical approaches granting a central role to counterfactual analysis (Lange 2000 and 2009), measurements (Roberts 2008 and 2013), invariance (Woordward 2003, 2013, 2017 and 2018) and models (Cartwright 1983 and 1999). Likewise, in section 4, I shall examine approaches to laws of nature that highlight their mathematical character, such as Dorato (2005a, 2005b and 2005c) and Feynman (1965).

the parcel of reality they quantify over. They may take the following conditional form: *for all x, if Fx then Gx*.

ii. *Necessity*. For something to be a law of nature of the kind *Fx/Gx*, it must necessarily be the case that *Fx/Gx*. Thus, if *Fx/Gx* is a law of nature, *x having the property F necessitates x having the property G*.

iii. *Truth*. What makes a law statement true is the law of nature it describes. There are no true or false laws of nature, but only true or false law statements.

iv. *Objectivity*. Epistemically, law statements are objectively true or false in virtue of the laws of nature they describe. Ontologically, the existence of specific laws of nature is an objective, mind-independent fact about the way reality is. (ARMSTRONG 2012)

The metaphysical view partakes of the general account of science that we find in recent defences of scientific realism, usually constituting one section of the larger project of elaborating a metaphysics for this doctrine. Advocates of this view maintain that science is in the business of achieving approximately true theories of reality, typically succeeding to do so. Hence, those who work on the metaphysical foundations of scientific realism go a step further and claim that some of our best scientific theories do uncover laws of nature, being a task for metaphysicians to account for the metaphysical underpinnings of such laws.

The metaphysics of scientific essentialism exemplifies this strategy. As Ellis claims (2001, p. 222; emphasis added), "the *causal laws of nature* are *objective* and describe the *essential natures* of the *basic kinds* of *causal processes* occurring in nature". This shows that scientific essentialism relies on the postulation of a heavy metaphysical baggage that includes essential properties, powers, capacities, and propensities; kinds of causal processes; a natural-kind structure of reality; truth-makers; and the laws of nature that emerge from the necessary relations instantiated by members of the natural kinds depending on their essential constitution. Consequently, laws of nature are universal in the sense that they quantify over every member of the natural kinds that fall under the formulation of the law, describing the sorts of processes that must take place among them given their essential properties.

Considering this metaphysical construction of the laws of nature, we now ask: does the metaphysical approach to the laws of nature make sense of the scientific laws that we find in science? Sections 41-43 shall suggest reasons to think that it does not. For the moment, we can consider the purported distinction between *laws of nature* and *scientific laws* suggested by the metaphysical approach. Swartz (2009 and 2003, section one) makes explicit this assumption, claiming that "[l]aws of nature are to be distinguished from scientific laws": the latter are inaccurate or mere approximate truths when compared to the former. This invites the idea that scientific practice fails to achieve knowledge of the laws of nature, since it does not thoroughly fulfil criteria (i-iv) abovementioned. Additionally, this is taken to be what makes the metaphysical investigation of the laws of nature worth pursuing, granted that such criteria set a speculative conceptual framework for lawhood, operating as a heuristic for empirical inquiry into scientific laws. Whereas scientific laws correspond to mere contingent generalisations achieved by empirical and mathematical means, they would be grounded in the laws of nature that are a subject matter to be articulated by metaphysicians.

A corollary of this is that metaphysics should not defer to science questions regarding the nature and reality of laws of nature, since –so the argument goes– science does not provide an account of what it is for something to be a law of nature. Furthermore, it is assumed that metaphysics has a distinctive approach to problems such as what laws of nature there are and what exists overall (MUMFORD 2004). Having a proper method in examining the reality of laws of nature, metaphysics occupies a fundamental place in relation to scientific disciplines. In its full-blown fashion, the metaphysical view contends that science is limited to finding out truths about the world, "but it is far from clear that those sought truths are truths about laws in the world" (MUMFORD 2004, p. 128).

The physico-mathematical view rejects the metaphysical approach and proposes to develop a minimalist conception of laws that is closer to scientific practice. A literal reading of current best scientific theories, I shall argue, does not support the distinction between laws of nature and scientific laws. In fact, theories inform us about mathematics-based law statements only. Their ontology is yet to be the subject of a piecemeal investigation. I shall aim to show that we should rather defer to scientific theorising questions about laws, taking it to be the primary source of information about the character of laws, their mathematical formulation and the scope of their physical generalizations.

2.2 SHOULD WE DO AWAY WITH LAWS ALTOGETHER?

We also find in the literature sophisticated versions of what I call *nomological eliminativism*. This view holds the no-laws thesis, initially proposing the idea that there are no laws of nature. It finds an interesting defence in the works of van Fraassen (1989) and Giere (1999). Both of them, however, go beyond this, claiming that we should dispense with laws altogether in our construal of science.

The first argument for nomological eliminativism is historical. Descartes and Newton spoke of the laws of nature in their writings on natural philosophy, and in different passages they refer to God as the lawgiver. The expression is thus a metaphor that derives from an analogy to the laws of God in Christianity. Moreover, still within the early-modern tradition, this understanding of laws of nature finds inspiration in the deductive rigour of Euclidean geometry as well, being a manner of speaking that was used for brevity's sake to refer to those theories that occupy the place of principles prescribing how things must behave. Although useful in the 17th and 18th centuries, van Fraassen (1989, pp. 1-2 and 8) claims that the talk of laws of nature ceased to be necessary for our account of science, hence its persistent appearance in philosophical discourse amounting to an anachronism.

At this point, I see no problem with embracing the historical argument. Abundant historical evidence persuasively demonstrates that the origin of the expression *law of nature*, as it took place in early modern science, derives as a metaphor whose basis are both religious and moral laws and the axiomatic structure of Euclidean geometry. Ruby (1986) compellingly gathers evidence for these contentions. Accordingly, if not plainly old-fashioned, such a conception calls for substantial amendments and reformulations.

A second argument that nomological eliminativism puts forward has to do with the set of criteria of adequacy for philosophical accounts of laws. To the criteria (i-iv) above, van Fraassen adds (v) delivering a theory of explanation; (vi) a theory of confirmation, (vii) an explanation of necessity, and (viii) a way of understanding the aim and structure of science.[8] As we shall see below, this comes to be particularly relevant since van Fraassen maintains that symmetries and models, rather than laws, are better equipped to successfully accomplish tasks (v-viii).

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[8] Other criteria of adequacy are inference; intensionality; necessity bestowed; necessity inherited; prediction and confirmation; and counterfactuals and objectivity (van Fraassen 1989, chapter 2, section 4).

First of all, concerning symmetries, nomological eliminativism moves from the claim that *there are no laws of nature* to the claim that *we need not laws, but only symmetries, in order to account for scientific practice*. In this picture, science is in search of symmetries rather than laws, where symmetries are transformations that leave all relevant structures the same. Examples of symmetry are the various isometries we find in gravity; the symmetries in Galilean relativity; space-time symmetries in general relativity; the symmetries of the conservation laws; and the invariance of certain physical constants and laws across the Lorentz transformations. This move appears attractive so long as it makes sense of those occasions where the pre-theoretical assumption of a symmetric world has paid off in theory construction and explains scenarios in which symmetry considerations led scientists to achieve new theoretical findings.

Second, regarding models, nomological eliminativism appeals to the semantic view in order to claim that scientific theories are collections of models. If there are any laws in science, they are mere descriptions of the relationships among the different elements constituting such models. Understood as the basic principles of the theory or the fundamental mathematical equations, laws would be restricted to describe what must take place in the ideal systems that models represent. Additional developments of this view purport to show that the laws that we find in science do not always meet criteria (i-iv) above. Rather than laws in this sense, what we find in the structure of scientific theorising are principles expressing restricted generalisations that are not to be interpreted as statements about reality, in which case they would be plainly false, but as rules for the construction of models (GIERE 1999, pp. 6 and 86). Likewise, if they bear any truth, that truth is not about the world, but about the working of abstract models.

A concern nevertheless emerges at this point. Nomological eliminativism ends up rejecting both the metaphysical understanding of laws of nature, on the one hand, and the concept of law in scientific practice, on the other. Hence, granted its revisionary stance, an examination of this view suggests the question of whether it could be considered a live option if it forces us to dispense with the notion of law in standard scientific practice overall. Facts would speak against doing this, since it can be easily pointed out that *we do find several laws in current best science*. As I understand the expression *scientific law* (see section 2 above), symmetries represent one example, whereas others are the various principles, equations and postulates that play specific roles in delivering physical generalisations. Therefore, an account of scientific practice by reference to the investigation of symmetries only –as van Fraassen submits–, which in other respects overlooks the investigation of scientific laws overall, would be largely insufficient.

Earman (1993, p. 414) nicely helps us state this point:

> To be concrete, consider gravitational physics from Newton to Einstein to the present day. Is it possible to understand the history of this field without construing the scientific activity as being in large part a search for the laws of gravitation and an attempt to understand their implications? Is the use of the notion of law in this field so muddled that both working scientists and philosophers seeking to understand the methodology and foundations of science would be better off dropping the notion altogether?

As shall be argued in sections 4.1-4.3, the physico-mathematical view advances a negative answer to both questions: the history of science is better construed as at least partly being a search for laws, and the concept of law is a live category currently in use in scientific theorising.

In brief, although interesting, nomological eliminativism falls apart given the limitations it imposes on the scope of laws understood as mere descriptions of the working of abstract models that are restricted to inform us about ideal systems. As such, it makes scientific laws appear devoid of empirical content, thereby threatening to hinder a proper understanding of this element of science. To claim that scientific laws are laws of abstract models does not do justice to the place they occupy in scientific practice and the roles they help to perform.

3 A MINIMAL CHARACTERISATION OF SCIENTIFIC LAWS

Having in mind our remarks on laws in section 2, I outline below the physico-mathematical account addressing (4.1) the mathematical character of laws, (4.2) Dorato's appraisal of the software theory of the universe, and (4.3) the scope of laws' physical generalisations.

3.1 MATHEMATICS' CONTRIBUTION TO PHYSICAL LAWS

The claim I defend in this section is that scientific laws are routinely expressed in terms of more or less complex, abstract mathematical statements.

This contention becomes important once the distinction between the laws of nature and the laws of science has blurred. The best access we have to the laws of the physical realm is provided by more or less complex, abstract mathematical statements, usually differential equations of various sorts. This should come as no surprise, though, especially if one focuses the analysis on physics, where most laws are written down in mathematical language[9].

Nevertheless, if one moves to other areas of science, things are different, since we find laws that are not expressed in mathematical terms. Examples of the latter sort taken from chemistry are the periodic law, which states that the chemical properties of the elements vary periodically according to their atomic number; and the law of definite composition, which states that a compound is composed of two or more elements chemically combined in a defined ratio by weight. I mention these two laws since although they are not mathematically expressed, they are nonetheless basic for current chemistry. Likewise, a similar example concerning the biological realm would be the laws of evolutionary theory that resist a precise mathematical formulation, leading some to deny them a law-like status.

In brief, to claim that most laws in physics are mathematical statements only means that such scientific laws are *best expressed in mathematical terms*. Importantly, it should not be interpreted as involving the claims that all laws across different scientific fields are mathematical, as abovementioned; or that those laws that are not best formulated in mathematical terms should not be granted a law-like status.

Let us return to the first point. The contention that most laws in physics are more or less complex, abstract mathematical statements has had disparate luck in the philosophy of science arena. One exception is the work of Dorato (2005a, 2005b and 2005c) on the contribution of mathematics to the formulation of laws in science. I shall return to this below. However, apart from that, philosophers have only recently come to fully recognise the philosophical import of this fact. In a tangential manner, Ellis (2012) and Armstrong (2012) highlight that scientific laws are standardly formulated in mathematical terms, but they do not explain why this is the case, nor what relevant consequences can be derived from this for our understanding of laws.

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[9] For a detailed analysis of mathematics' contributions to the articulation of physical laws, see Soto (2020), where I address Wigner's reflections on the effectiveness of mathematics, along with standard characterisations of the interplay between physics and mathematics.

Instead, they pursue metaphysical considerations attempting to ground laws in essential properties and universals, respectively.

The situation is slightly different in the scientific literature. Physics textbooks confirm that most laws in this field are best formulated in mathematical terms. Scientists themselves have observed that an important use of mathematics takes part in the formulation of scientific laws. An example is Feynman (1965, p. 39), who claims that "[…] the more laws we find, and the deeper we penetrate nature, the more this disease persists. Every one of our laws is a purely mathematical statement". He analyses the Newtonian law of universal gravitation:

$$F_{grav} = Gm1m2/R^2$$

Here, $m1$ and $m2$ are the masses of two bodies, R^2 is the square of the distance between their centres, G is the gravitational constant, and F_{grav} is the resultant force of gravity. The law of gravitation tells us that any two bodies, $m1$ and $m2$, exert a force upon each other that is directly proportional to the product of their masses and varies inversely as the square of the distance between them, R^2. This mathematical formula, which has been provided a physical interpretation in terms of forces, masses and distances, states a constant correlation between certain mathematical variables that represent the outcomes of measurement procedures applied to specific physical systems. I return to this in 4.3 below.

Among the aspects of the law of gravitation, we find that it is mathematical in character, but also that it is not exact. By the end of the 18th and beginning of the 19th century, Cavendish carried out a series of experiments in order to determine in a more precise manner the value of G. Although he succeeded to do so, the Newtonian law of gravitation came later on to be corrected by Einstein's general relativity theory. In brief, mathematics was useful for the formulation of this law from the very beginning, given that large numbers were involved in the description of complex physical situations, but it did not guarantee by itself the precision of the correlation established.

Scientists formulate laws in mathematical terms. Mathematical notation and operational rules convey some of the best models available to perform the task of expressing laws with certain precision. Feynman, however, speculates that physics may ultimately not need mathematics at all in the formulation of physical theories, “that in the end the machinery will be revealed” (1965, p. 58).[10] From a philosophical perspective, some still wonder whether the mathematical character of laws opens the door to ontological arguments suggesting the idea that reality is at once physical and mathematical. Indeed, some are inclined to explain the contribution of mathematics to laws in physics arguing that reality is at bottom both physical and mathematical (Psillos 2012); or even that reality is an all-encompassing mathematical structure (TEGMARK 2014). Yet, we can avoid going down the metaphysical slippery slope by adopting epistemic and pragmatic takes on this issue, namely: the applicability of mathematics to the formulation of laws is of epistemological concern insofar as the mathematics involved enables scientists to achieve explanations and understanding of phenomena; and it is, in turn, pragmatic, since the mathematics involved in the articulation of law statements facilitates the expression of large physical quantities and physical relations in a few symbols (SOTO 2019). The applicability of mathematics to the formulation of laws in physics may be largely due to “[…] the speed with which the mathematical symbols convey information” (FEYNMAN 1965, p. 36). No ontological addendum is required here.

At face value, some scientific laws are expressed in terms of differential equations, such as Newton’s law of universal gravitation. Other parcels of mathematics contribute to express the laws of specific regions of reality, as in the case of group theory, which enabled scientists to formulate the symmetries that hold across various physical systems in the standard model of particle physics. Similarly, the mathematics of Hilbert spaces facilitated the formulation of laws in quantum mechanics, providing a rigorous account of vector spaces (STEINER 1998, pp. 38-44). This all contributes to show the epistemic and pragmatic purport of mathematics in the articulation of physical laws.

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[10] Pincock puts forward a similar view. Thinking of Maxwell’s classical electromagnetism, he visualises the following strategy: “The epistemic proposal is consistent with the prospect of eliminating mathematics in some ideal end of science. This would occur if the scientific community was gradually able to zero in on the underlying causal mechanisms by first isolating stable larger scale mathematical structures and then proceeding to consider possible smaller scale underlying mechanisms” (Pincock 2011, p. 73). See Soto and Romero (forthcoming) for an analysis of the mathematics in the transition from classical to quantum electrodynamics.

3.2 AN EXERCISE: DORATO'S APPRAISAL OF THE SOFTWARE OF THE UNIVERSE

Some may be inclined to believe that the examination of the mathematical dimension of laws only delivers a formal understanding of lawhood. This, however, is not the case. The mathematical character of scientific laws also makes sense of the fact that laws are instruments of calculations that facilitate the construction of explanations, predictions and representations of physical systems. Let me briefly look at this point in some further detail. Scientists can track the probability of one physical system passing from one physical state to another by means of applying the correct law to measurements of specific properties of phenomena (see 4.3 below). This is what the *software theory of the universe* attempts to demonstrate (DORATO 2005a, 2005b, 2005c). Some scientific laws can be interpreted as algorithms that constitute the software of reality, analogous to the computer software that operates on different computer hardware. Dorato (2005b, p. 61) further develops his view appealing to Whewell's characterisation of the three components of scientific laws:

i. The algorithmic structure, given by the mathematical formula (differential equations, and the like) that prescribes the law properly speaking;
ii. The initial or boundary conditions, i.e., the initial numeric data to which we apply the law; and,
iii. The constant quantities left unchanged by the application of the algorithm, i.e., the constants of nature.

Think again of Newton's law of universal gravitation. The arrangement of symbols F_{grav}, G, $m1$, $m2$ and R^2 corresponds to element *i*, viz., the algorithmic structure of the mathematical equation. Yet, the algorithmic structure is to be filled with element *ii*, which corresponds to the measurement outcomes (physical data, physical quantities, and so forth) to which the law is applied. Lastly, concerning *iii*, G introduces the mathematical variable which stands for a physical constant that holds for two massive bodies across reality and which is left unchanged in the algorithm that tracks the relevant physical process.

The physico-mathematical approach is largely in agreement with Dorato's software theory, whose core claim is that scientific laws express in mathematical terms the best physical generalisations achieved by science.[11]

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[11] See Soto and Bueno (forthcoming) for further analyses of the software view and alternative takes on the ways some mathematics get to be applied to the relevant structure of physical domains.

However, it should be noted that the software/hardware metaphor involves some pitfalls. One is the suggestion of taking scientific laws as algorithms that bear a structure that suitably accounts for laws of succession, but not for laws of simultaneity (Dorato 2005a, p. 142). A second drawback is that it implies that physical systems behave as if they were computing their next physical state. The metaphor of the software entails the idea that physical systems carry out this computation of their next physical state by means of causing it. A problem would arise at this point if there are non-computable mathematical equations in current scientific and mathematical practice to which the algorithmic view would not apply.

3.3 On the scope of physical generalisations expressed by laws

I turn to the second aspect of the physico-mathematical approach, which is that laws are at least in principle intended to inform us about features of physical systems. Importantly, this firstly implies that laws are not to be understood as abstract mathematical statements that solely describe the structure of abstract models, as nomological eliminativism claims. Secondly, it also entails that laws inform us about those features of physical systems that are the target of empirical enquiry, and not about the supposedly fundamental metaphysical dimension of reality, as the metaphysical approach would contend.

Recall the distinction between fundamental and phenomenological laws aforementioned (section 2 above) in order to illustrate the scope of physical generalisations expressed by laws. We can refine the fundamental/phenomenological distinction highlighting the various scopes of lawlike physical generalisations that we find in physics. To determine its scope, the crucial step consists in assessing the relevant target system in each case. For instance, the scope of physical generalisations expressed by the laws of general relativity is determined by gravitational phenomena that in principle take place across the universe as a whole. Such generalisations are explained in terms of the geometric features of the four-dimensional space-time. At a different scale, the Planck constant contributes to the formulation of laws in quantum mechanics and describes a physical generalisation about a certain force of action of phenomena at the quantum level, viz., the quantum of action, which can equally be applied to every physical system at such scale throughout the universe. By contrast, the scope of other laws in physics is radically restricted, taking place only under certain conditions. An example of the latter is the Fourier's law of heat conduction, which provides a physical generalisation about the rate of heat flow through a homogenous solid that is directly proportional to the area. And so forth.[12]

A refinement to my statement regarding the physical scope of laws is in order. Scientific laws refer to only those features of phenomena whose salience and stability are relevant for certain scientific tasks (WOODWARD 2003, pp. 239 and ff.). Hence, good scientific laws need not necessarily yield exhaustive, minutely detailed descriptions of physical systems. The example of the Newton's law of universal gravitation helps us illustrate this, particularly since such law takes into consideration a restricted number of features of the objects to which it applies in particular scenarios. Scientists measure the force of gravity resulting from the attraction in the Sun-Earth system, filling the variables of the equation in question with numeric data about measurements of the masses of the physical systems and the distance between their centres. To these factors, the law adds the determination of the force of gravity in specific, concrete scenarios. However, the law does not account for other aspects of the Sun-Earth system, such as the physical constitution of both massive bodies, which may be salient and relevant for other scientific tasks.

The concepts of *measurements* and *models* allow provide a better understanding of the inherent partiality of laws. Being aware that these are big issues in the philosophy of science, I confine my remarks to clarify their intertwining with the physico-mathematical view of laws only. Concerning measurements, scientists detect the salience and stability of phenomena by performing measurement procedures that employ quantitative treatment of data (Roberts 2008). Measurements enable us to identify relevant and salient properties of phenomena along with the structural relations among them. In turn, laws describe such properties and structural elements instantiated by target systems. To be sure, not every aspect of phenomena is salient and stable in the right sort of way. This is decided by considering the interests at stake, the availability of technology, and the problems under examination, among other things. Likewise, phenomena that lack relevant salience are usually not quantified over by the mathematical variables of laws, and those which do not bear any sort of stability are hardly tractable by means of measurements that are required to fulfil repeatability conditions. In the case of Newton's law

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[12] An analysis of physical generalisation is fully developed by Soto and Rodríguez (2019) from the perspective of an experimental dispositionalism about capacities and phenomenological laws.

of gravitation, the availability of measurement outcomes allows scientists to specify the mass of physical systems *m1* and *m2*, the distance R^2 between them and the value of the constant *G* that applies to a specific physical scenario, thereby facilitating the identification of the relevant salience and stability of specific aspects of phenomena (ROBERTS 2013, p. 29-34; WOODWARD 2013, p. 48).[13]

Models, on the other hand, help us understand the relationship between abstract mathematical structures expressing laws and the outcomes of measurement procedures (SOTO AND ARMENDÁRIZ forthcoming). In some cases, models are built in order to provide a lower-level abstract representation whose structure suffices to bridge the transition from high-level abstract mathematical structures to concrete physical systems. In some cases, models bear a structure that enables scientists to draw representational relations of partial homomorphisms, partial isomorphisms, or similarities between the mathematical structure expressing a law and the structure of its intended target physical system. In this regard, models bridge the transition from more or less complex, abstract mathematical statements and the physical world.

Likewise, such models serve as guides to designing measurement procedures, presenting a blueprint of how we believe the intended target system should look like in a particular scenario. Morrison (2015) shows that this was indeed the case of the employment of various models and computer simulation in the construction of the Large Hadron Collider with the goal of detecting the banging of subatomic particles, among them the Higgs boson. In this latter case, not only did models play a central role bridging theory and reality, but also in guiding the construction of the experimental conditions and laboratory design. The expected results of measurement procedures in this case were outlined by models and computer simulations providing a framework for understanding the gathering and reading of data that worked as evidence for the reality of this subatomic particle, hence probing the theoretical laws stated by the standard model of particle physics.

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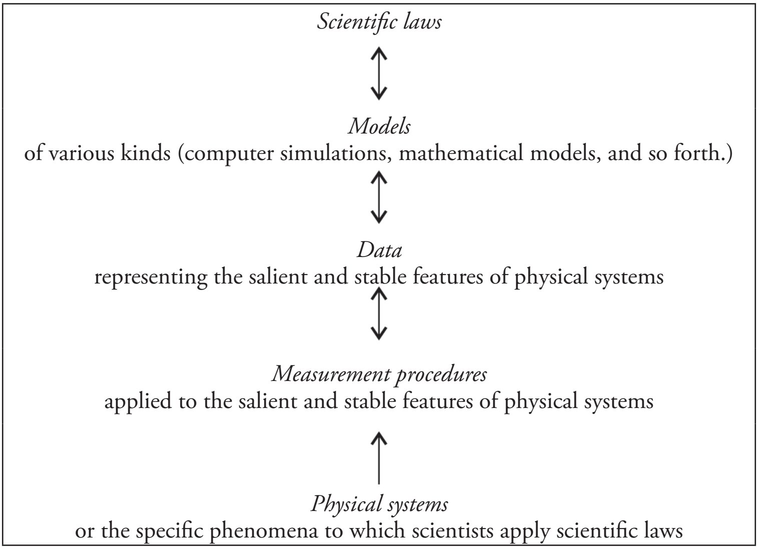
[13] Note that Roberts (2008, 2013) and Dorato (2005b) argue that measurements grant a nomic status to law statements. For the time being, the physico-mathematical account need not commit to such a claim, even though it embraces the role of measurement procedures in the articulation of laws. The physico-mathematical view aims at putting forward a conceptual framework for understanding the character of mathematics-based law statements in science, without providing a (metaphysical) account of what grants certain statements in science a nomic status.

Contrary to advocates of nomological eliminativism, the physico-mathematical account advocates the view that laws play a role in scientific practice, at least in principle being intended to inform us about aspects of reality. Certainly, they may fail to do so, or the transition from high-level abstract mathematical structures to concrete physical structures may be hard to visualise. What models do for laws is mainly to fill the gap between abstract mathematical statements expressing laws and their intended physical target systems revealed through measurements of various kinds. In performing this task, what we expect from models is to bear enough structural complexity and flexibility so as to accommodate specific mathematical structures to well-defined parcels of reality.

Let me summarise and organise the elements outlined thus far as follows:



A further point that emerges concerning the physical scope of laws is whether they inform us about properties (causal powers, capacities or necessities) in the world (SOTO AND RODRÍGUEZ, 2019). As far as our outline goes, laws seek to refer to properties that are uncovered through detection processes. This, nevertheless, does not commit the physico-mathematical view to heavy metaphysical accounts of properties. By contrast, we can deflate such notion as follows: properties are any quantities revealed to us through the application of reliable measurement procedures. In this respect, measurements can teach us that certain physical systems possess specific natures, where this means no more than they have a determinate physical constitution. For instance, current best descriptions of the properties of electrons correctly include quantitative features such as their electric charge, mass, and spin. To our best knowledge, the nature of the nucleus of a hydrogen atom is correctly described in particle physics as being composed of a single positively charge proton and a single negatively charged electron, which are bound to the nucleus by the Coulomb force. Detection processes may fail us, however. when it comes to the decomposition of a single positively charged proton, which includes two up quarks and one down quark. And so forth.

CONCLUDING REMARKS: MINIMALISM AND THE PHYSICO-MATHEMATICAL VIEW OF LAWS

Various consequences can be derived from the physico-mathematical view outlined in this article. On the negative side, what has been said so far should suffice to show that we need not pursue heavy-loaded metaphysical accounts of the laws of nature as if they were grounding the laws that we find in science; nor do we need to dispense with laws in science altogether, as various forms of nomological eliminativism claim. In particular, the task seems to be that of finding out a construal of laws that adequately accounts for the laws that we find in scientific practice. In this, the physico-mathematical view pays more attention to scientific detail than to philosophical preconceptions of lawhood.

On the positive side, the argument outlined in this article remains minimalist enough, encompassing several relevant elements that partake in the construction of laws in scientific practice in a coherent picture. Rather than postulating metaphysical presuppositions, we can appeal to the contribution of mathematics to the formulation of scientific laws; to the role of models in scientific theorising; or to the role of measurement procedures in the identification of the relevant salience and stability of target physical systems. Scientific laws in physics may result from the systematic interplay of mathematics, modelling and measurement procedures, among other tasks.

In a well-known passage, Feynman (1965, p. 13) metaphorically describes the character of scientific laws as follows: “[t]here is also a rhythm and a pattern between the phenomena of nature which […] we call Physical Laws”. To the eyes of metaphysicians, this description may not be satisfactory, since –they would argue– laws of nature are not mere rhythms and patterns (MUMFORD 2004, pp. 11-12). Yet, the physico-mathematical view has no ontological quarrel in conceiving of laws in these terms, granting that at least part of the scientific endeavour appears to be in search of mathematical descriptions of such rhythms and patterns in phenomena. Furthermore, this leaves room for the fallibility of our knowledge of laws, since nothing in principle prohibits that scientists fail to track the relevant rhythms and patterns, and so forth.

Needless to be said, more is required to fully account for the role of mathematics in the construction of laws. I have attempted to do so elsewhere looking at the pragmatic and epistemic indispensability of mathematics in scientific theorising, at an empiricist ontology of dispositions, at the inferential conception of the application of mathematics, and at the intertwining of models and laws. Further work is yet to come from other perspectives, such as the invariance-based account of laws (Woodward 2017 and 2018). Be that as it may, the argument above suffices to position the physico-mathematical view of laws as a live alternative in current debates on laws of nature.

SOTO, C. Algunas consecuencias de la concepción físico-matemática de las leyes científicas. *Trans/form/ação*, Marília, v. 43, n. 4, p. 65-88, Out./Dez., 2020.

Resumen: Este artículo examina consecuencias de la concepción físico-matemática de las leyes científicas y de su lugar en el debate filosófico sobre leyes de la naturaleza. Tras ofrecer algunas consideraciones sobre la expresión ley científica, que aparece en la práctica científica bajo diferentes nombres, tales como leyes, principios, ecuaciones, simetrías y postulados, evalúo brevemente dos posiciones extremas opuestas, la concepción metafísica radical de las leyes de la naturaleza, que distingue tales leyes de las otras leyes más mundanas que encontramos en la ciencia; y la tesis de la ciencia sin leyes, que en definitiva sostiene que tenemos que eliminar las leyes de la ciencia sin más. Argumentaré que ambas posiciones no se hacen cargo de las leyes que encontramos en la práctica científica. Para ello, desarrollo las siguientes dos tesis: primero, gran parte de las leyes en física son enunciados matemáticos abstractos; y segundo, ellas expresan algunas de las mejores generalizaciones físicas obtenidas en esta rama de la ciencia. Entendidas de esta manera, una comprensión minimalista de las leyes sugiere que ellas se encuentran en principio orientadas a referir a aquellos aspectos de los fenómenos cuya saliencia y estabilidad son relevantes para tareas científicas específicas.

Palabras clave: Leyes científicas. Leyes de la naturaliza. Matemáticas. Metafísica. Sistemas físicos.

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Recebido: 15/6/2017

Aceito: 27/12/2019