Is the Best System Account of laws of nature really compatible with scientific practice?

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Abstract Do laws of nature govern physical reality? Proponents of the so-called Best System approach give a negative answer to this question. At the same time, they do not reject the existence of laws of nature altogether. Instead, on this view, laws are axioms of a deductive system whose true theorems describe the physical world with the best balance between simplicity and strength—hence the name 'the Best System.' How does the Best System relate to scientific practice? Many philosophers have argued that, in comparison with rival accounts of the laws of nature, it reflects scientific practice particularly well. Not only does it capture the fact that science aims to develop theories that are simple yet strong (for instance, in terms of explanatory power), but it also refrains from invoking metaphysical categories such as powers or dispositions, which are not recalled in contemporary scientific discourse. However, what is missing from the literature on the Best System approach and scientific practice is the observation that scientific laws—at least in physics since the modern era—are largely formulated in the language of equations, such as Maxwell's equations of electromagnetism or Einstein's field equations. In this paper, I argue that the Best System approach runs into a number of novel problems when applied to laws of physics expressed in the form of equations, including problems concerning approximations and idealisations, the role of units, and the lack of perfectly isolated systems. I further argue that, once such laws are taken into account, traditional objections to the Best System—such as the problem of immanent inter-system comparisons—take on a new form. I conclude with some brief considerations as to whether, in light of these arguments, the Best System should be rejected entirely, or whether some of its core postulates could be preserved.

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1. Introduction

Laws of nature lie at the centre of interest both for philosophers of science, who seek to answer the question of what laws of nature are (or are not), and for scientists themselves, who in fields such as physics typically regard their work as aiming to discover and systematise such laws.

Indeed, a criterion for assessing accounts of laws of nature based on their compatibility with scientific practice has been invoked in the philosophical literature by a number of authors (such as Cohen and Callender 2009, Woodward 2014, Jaag and Loew 2020, Loewer 1996, Earman 1993, p. 418, Friend 2022); even those skeptical of the laws have recognised the need of acknowledging scientific theorising in formulating philosophical views on this topic (cf. Cartwright 1983, p. 144).

Most of these authors argued that the account which best corresponds to the scientific practice is the Best System Account (BSA), also called MRL after its founders: John Stuart Mill (1843), Frank Ramsey (1928), and David Lewis (1973, 1994). On this account, laws are theorems of the deductive system that describe physical world with the best balance between simplicity and strength—hence, called 'the Best System.' Among the arguments in favour of BSA over other philosophical accounts of the lawhood one can find an observation that seeking the most simple yet powerful laws does well reflect what scientists' strive for unified theories and that this account does not employ such categories as dispositions or powers, which are foregin to the contemporary science.

However, what is missing from this literature on compatibility of the Best System Account with the scientific practice is an observation that, at least in physics from modern era onwards, an overwhelming majority of laws is expressed in the form of equations, such as Newton's laws of dynamics or Einstein's field equations—and, perhaps, some would even argue that laws of nature exclusively take a form of such equations (cf. Heller et al. (2010) on 'mathematical universe').

Given the extent to which scientific practice—hereafter with a particular focus on physics from the modern period onwards—centrally involves the derivation, formulation, systematisation, or transformation of laws expressed in the form of equations, the aim of this article is to explore whether the Best System Account also qualifies them as laws of nature. The answer is negative. I suggest several examples of laws employed by contemporary physicists and demonstrate that they are not laws according to the BSA. I therefore conclude that this account is not compatible with scientific practice.

The structure of this paper is as follows. In Section 2, I introduce the landscape of views about laws of nature, including the Best System Account. In Section 3, I recall several arguments in favour of the appeal of the BSA from the perspective of scientific practice. Section 4 is concerned with what I refer to as a special instance of 'scientific practice'—that is, the use of laws of nature in the form of equations. In Section 5, I present several problems concerning the Best System Account and the practice of physics, including both new versions of standard objections to this account that arise in the context of laws expressed as equations, as well as some novel objections. I also show why some revisionary versions of the BSA, which successfully address some of the standard concerns, fail to resolve these new versions of the problems. I conclude in Section 6 by arguing that the Best System Account fails to accommodate laws expressed as equations.

2. The landscape of views and the Best System Account

Contemporary views on the laws of nature can be divided into three main classes. First, philosophers such as van Fraassen (1989), Cartwright (1980, 1983), or Giere (1999) entirely deny the existence of laws. They might agree that there are entities such as causes or symmetries, but they would reject laws of nature. Second, supporters of the governing view argue that laws of nature not only exist, but also play an active role in governing and producing events in the physical world. Among supporters of such a view one can enumerate Dretske (1977), Maudlin (2007), Armstrong (1983), Tooley (1977), Swoyer (1982), Bird (2005), or Shoemaker (1998). Finally, according to the non-governing approach, although there are some laws of nature, they do not govern or create events. The most popular version of the non-governing view is the Best System Account (BSA).

Historically, the earliest account of the Best System Account may be found in *A System of Logic* by John Stuart Mill, published in 1843 (bk II, chs IV, XII, and XIII). A similar conception of the laws of nature was also suggested by Frank Ramsey in *Foundations* (1928). Their intuitions were taken up and developed by Lewis, the modern architect of BSA. He formulated this view in terms of the deducibility of information about the so-called Humean mosaic—that is, local matters of particular fact about the physical world. The Humean mosaic is based on "[...] the doctrine that all there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another" (Lewis 1986, p. ix). Thus, on Lewis's view, this mosaic exhausts the fundamental ontology of the world: physical reality consists solely of local matters of facts and laws of nature do not belong to this fundamental level. Rather, they arise as part of the best deductive system that provides the most efficient systematisation of the mosaic, according to the following recipe:

> Take all deductive systems whose theorems are true. Some are simpler, better systematized than others. Some are stronger, more informative than others. These virtues compete: An uninformative system can be very simple, an unsystematized compendium of miscellaneous information can be very informative. The best system is the one that strikes as good a balance as truth will allow between simplicity and strength. How good a balance that is will depend on how kind nature is. A regularity is a law iff it is a theorem of the best system.[1] (1994, p. 478)

Therefore, before deciding which of the deductive systems (namely, 'deductively closed, axiomatizable sets of true sentences' (Lewis 1973, p. 73)) is the Best System, one should examine their simplicity and strength and check which of them strikes the best balance of them. The strength of a deductive system might be understood in terms of the number of truths about the world—both among its postulated axioms and its derived consequences. At the same time, systems that are simpler have fewer independent theorems or shorter ones. Simplicity and strength compete. It is easy to find a stronger system that is not simple, such as one that takes all true sentences as its axioms. At the same time, by sacrificing strength one can obtain an extremely simple system in which, for instance, there are no axioms at all. The theorems of deductive systems with the best combination of simplicity and strength are the laws of nature. For example, assuming that our current theories are systems of true propositions, then Schrödinger's equation would count as a law, since a deductive system lacking it would be inferior either in strength (leaving many truths about quantum reality unknown that might be deduced from the Schrödinger equation) or in simplicity (if these truths were postulated in such systems as independent theorems).

The Best System Account as defined above[2] remains a topic of critical analysis in the

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[1] In *Counterfactuals* Lewis gives a slightly different formulation of this definition. He writes: 'A contingent generalization is a Law of Nature if and only if it appears as a theorem (or axiom) in each of the true deductive systems that achieves a best combination of simplicity and strength.' (Lewis 1973, p. 73). I will not analyse the difference between these two definitions, but just note that due to Lewis' intention, one can use terms 'a theorem' and 'an axiom' interchangeably.

[2] This 'basic' version of the Best System Account is sometimes referred to in the literature

contemporary literature (see e.g. Beebee and Mele 2002; Friend 2016; 2022; Hicks 2018; 2019; Hicks et al. 2023). Some versions of this account introduce significant modifications that respond to objections raised against Lewis's original formulation. Notable examples include the Better Best System approach proposed by Cohen and Callender (2009) which, *inter alia*, incorporates epistemic limitations into the construction of candidate systems of laws. Similar ideas also appear in later pragmatic approaches developed by authors such as Hall (2015), Hicks et al. (2023), and Friend (2022). Crucially, however, the core of the Best System Account—namely the search for a balance between simplicity and strength in deductive systems of true propositions, together with the claim that laws supervene, at least in part, on the Humean mosaic—remains present even in these more recent versions of the view.

3. The apparent appeal of the BSA for scientific practice

While the question of what laws of nature are is a matter of philosophical debate, it is scientists who are engaged in the discovery of such laws and who employ them to articulate and systematise their scientific theories. It therefore seems plausible that metaphysical accounts of laws of nature should be compatible with scientific practice.

Indeed, many philosophers have acknowledged the need to deliver and account of laws of nature that would reflect the practice of scientists. For instance, Cohen and Callender cite the following passage from Feynman's introduction to his celebrated *Lectures in Physics*: ...it is possible to condense the enormous mass of results to a large extent – that is to find laws which summarize... (Feynman 1963, p. 1; after Cohen and Callender 2009, p. 3). Indeed, the Best System Account does have certain advantages from the perspective of scientific practice. For instance, this account does not postulate the existence of empirically inaccessible entities that play a causal role, such as powers or dispositions (cf. Loewer 1996, p. 103). Of course, scientists may privately believe in the existence of such metaphysical entities; but even if they do, the scientific language they employ does not make reference to them. For example, a contemporary physicist will say that a body fell to the ground because it is in the Earth's gravitational field, rather than because it has a disposition to long for the centre of the Earth, as was believed, for instance, by Aristotle.

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as the Fundamental Best System Approach, to distinguish it from more recent variations of this view.

Moreover, it has been argued that the founding premise of the Best System—that is, striking the balance between strength and simplicity—reflects the efforts of scientists to consolidate 'small sets of basic principles' (cf. Cohen and Callender 2009, p. 3). Indeed, these efforts can be seen in attempts to unify theories; for example, one of the results of formulating a theory of quantum gravity (although certainly not the primary motivation for pursuing such a theory) would be the replacement of two theories—quantum field theory and general relativity—with one, thereby simplifying physics in this sense. Historical attempts to find the simplest forms or ways of expressing the laws of nature by introducing novel notations likewise support the intuitions behind the Best System Account; one can recall Maxwell's laws of electromagnetism, which originally consisted of more than a dozen equations written explicitly with derivatives with respect to x, y, and z, whereas today they are expressed as just four laws in a concise form using the curl and divergence operators.

What is more, the machinery of the Best System has been extensively discussed in the context of quantum mechanics (Ladyman and Ross 2007, chs. 2–5; Maudlin 2007, pp. 51–64; Esfeld 2014), giving rise to sophisticated debates concerning the reconciliation of contemporary physics with Humeanism. It is also worth emphasising recent attempts by authors such as Hicks (2019), Duguid (2023), or Friend (2024) to develop Humean accounts of symmetries—an important pursuit, given that symmetries constitute one of the fundamental tools of modern physics. In addition, attention should be paid to the recent pragmatist turn within the Best System Account (e.g. Hall 2015, Hicks et al. 2023, Friend 2022), which likewise stems from a desire to render this account of lawhood more plausible from the perspective of scientific practice. In particular, this turn aims to accommodate the fact that some principles historically regarded as laws—though no longer accepted as such—should nevertheless have counted as laws within the Best System at the time they were employed by scientists. A familiar example is phlogiston, which lay at the core of the dominant theory of combustion until its abandonment following the discovery of oxygen.

Other general advantages of the Best System Account include distinguishing laws from accidental true generalisations, accounting for counterfactuals, and its connection with objective probabilities (cf. Loewer 1996). In that, the Best System performs better than other non-Governing views, such as naïve regularity analysis (Swartz 1995), which *inter alia* falls into the problem of accidental regularities, or projectivism (e.g. Goodman 1983 or Ayer 1956), which struggles with scientific realism.

4. A new perspective on the BSA and scientific practice

It therefore seems that the Best System Approach offers several advantages from the perspective of scientific practice and beyond. *Inter alia*, it reflects scientists' striving for theories that are simple yet powerful, and it does not posit categories foreign to contemporary physics—such as dispositions or powers. Moreover, I believe that it offers a further advantage that has not been sufficiently emphasised in the literature: namely, that on this account laws share the same *genus proximus* as the laws employed in physics. Rather than being dispositions, powers, or some primitive metaphysical entities, laws in the BSA are propositions. Why might this be appealing from the perspective of scientific practice? Because, at least since modern era, physicists generally make use of laws formulated in form of equations, such as the second law of dynamics $F = \mathbf{a}m$ or Einstein's famous equation $E = mc^2$—to give just two out of endless examples. This fact is widely acknowledged by the physicists themselves; or instance, only a few lines below the quotation from Feynman cited above by Cohen and Callender (2009), he explicitly emphasises the need for mathematical expertise in order to state the laws of nature in physics (not to mention the fact that the subsequent hundreds of pages of his lectures are devoted primarily to the analysis and derivation of equations, a feature characteristic of basically all contemporary handbooks, textbooks, and research articles in physics):

> …the correct statement of the laws of physics involves some very unfamiliar ideas which require advanced mathematics for their description. (Feynman 1963, p. 1).

What is interesting is that, despite the voluminous literature advocating the Best System Account—also in the context of scientific practice and often drawing on examples from physics—a careful analysis of laws of this kind within the framework of this account of the laws of nature has largely been missing.[3] The remainder of this paper develops such an analysis. Specifically, in this article I will consider examples of actual laws that are used by physicists and, since Lewis defines the laws of nature as theorems of deductive

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[3] For an exception, see Friend (2016), who briefly acknowledges that the laws of nature employed in physics often take the form of equations. In particular, in his development of a general strategy for reformulating laws as conditionals ('all Fs are Gs', cf. Dretske 1977), he uses examples in which the consequent takes the form of an equation. However, Friend does not consider any of the problems discussed in this paper, as addressing them is not the aim of his article. Moreover, in the present paper I treat equations themselves as examples of laws, rather than their reformulations as conditionals, since physicists in their practice rely on equations rather than conditional statements.

systems, which are true in virtue of describing local matters of fact that constitute the Humean mosaic, I will analyse whether, in fact, the BSA classifies these laws used by physicists as laws of nature.

In other words, the titular ‘scientific practice’ in this paper is understood as the consideration of laws of nature in the form in which they appear in scientific publications in physics or in textbooks. The choice to frame this debate in terms of scientific practice stems from a very specific reason. In the next section, each problem will be formulated according to the same schema, namely: selecting a law of nature in the form of an equation that is commonly used by physicists, showing that the BSA does not classify it as a law of nature, and concluding—more or less explicitly—that this is problematic, since the initial law is widely used by scientists, has strong predictive power, and so on. Without appealing to scientific practice, we would not only lack a justification for why a given expression should count as a law of nature, but we would also be committed to the assumption that laws are equations. In its present form, my argument does not rely on this assumption; one can still believe that laws at some more fundamental level are not propositional at all—and physicists merely write (at least some of) them down in the form of equations. Thus, I am far from endorsing the view that all laws of nature—whether those discussed by physicists or those posited in the special sciences—are expressible in the form of equations. On the contrary, I take this to be a nontrivial question requiring further analysis. The considerations presented in this article are instead motivated by the observation that, insofar as the Best System Account is presented as attractive from the perspective of scientific practice, and insofar as scientific practice itself relies heavily on equations, it is important to carefully examine whether applying the Best System Account to laws formulated as equations gives rise to new difficulties for the account.

Are laws of nature in the form of equations, then, compatible with the Best System Account?

5. Problems with the Best System Account

We are already familiar with some reasons why the Best System Account may be appealing with respect to scientific practice. In this section, however, I will argue that considering such laws raises a number of challenges for the Best System Account—some of which are new variants of well-known difficulties faced by this account, while others are entirely novel.

5.1. Idealisations

Consider the ideal gas law:

$$pV = nRT \tag{1}$$

where P is pressure, V is volume, n is the number of moles of the gas, R is the ideal gas constant, and T is temperature. This law describes the relation between macroscopic thermodynamical properties of the so-called ideal gas; that is, a gas that consists of point-like particles which are not subject to intermolecular forces, and whose collisions are perfectly elastic.

Obviously, no real gas can satisfy these assumptions; for instance, all particles in the physical world, including those that constitute real gases, have a finite size, meaning that they cannot be point-like. Moreover, Benoît Paul Émile Clapeyron, who formulated this law in 1834 as a combination of other empirical laws describing relations between pressure, volume, and temperature, was already aware of these limitations. Thus, equation (1), by its very design, is not meant to describe the properties of any particular real gas. This is why an ideal gas is a canonical example of an idealisation: a system distinct from the target physical system, designed such that some of its properties are an inexact description of the target system in question (as defined by Norton 2012, p. 290). Here, the target system is some real gas, and such properties of an ideal gas as the point-like size of its particles are an inexact description of the real gas.

What does the Best System Account say about such defined idealisations and the laws that describe such systems?

Crucially, the ideal gas does not exist in the physical world—just as no other idealisation exists—since idealisations, by their very definition by Norton (2012), are systems distinct from the target physical systems that do exist in the physical world. Consequently, equation (1) does not describe local matters of fact and therefore cannot be an element of any axiomatic system that systematises the Humean mosaic. In particular, this formula cannot appear in the Best System—nor, for the same reason, can any other equation that describes an idealised system.

Of course, one need not appeal to laws expressed as equations in order to argue that the Best System Account fails to account for idealisations. Nevertheless, by considering this particular equation—widely employed, for example, in engineering and chemistry with great success—one can see how far-reaching the problem is that a proponent of the Best System account would be unable to include it among their set of laws. Given that there are many other instances of idealisation in science—indeed, some authors even argue that most, if not all of science is fundamentally based on idealisations—such cases pose a serious challenge to the Best System account when assessed against scientific practice. Obviously, there exist many other accounts of idealisation (e.g. Elgin 2017; Potochnik 2019; Weisberg 2007). The reason for adopting Norton's definition in particular will become clearer in the next section: his account distinguishes idealisations from approximations which, as we shall see, also fail to count as laws according to the BSA, but for a different reason. Notably, however, on all alternative accounts the ideal gas (or the ideal gas law) would still count as an idealisation.

In fact, the problem of idealisation in Humeanism has been raised by Friend (2023)[4] who makes a similar observation: namely, that there are no candidate laws concerning idealised systems, since there are no local matters of fact corresponding to such idealised systems. His proposed solution is based on the observation that for every idealised law there exists a corresponding *super law* (following terminology by Cartwright (1983, p. 70)) which, first, provides a more accurate description of the actual physical system and, second, reduces to the idealised law under appropriate substitutions. For example, the super-law corresponding to the ideal gas law is the van der Waals equation:

$$\left(p + a\frac{n^2}{V^2}\right)(V - nb) = nRT, \tag{2}$$

where a accounts for intermolecular attractive forces between gas particles and b accounts for the finite volume of gas molecules. Notably, as required by a definition of a super law, one can easily check that the van der Waals equation (2) mathematically reduces to the ideal gas law (1) under conditions $a = 0$, $b = 0$. Friend therefore concludes that laws such as the ideal gas law are *meta-ised*: they do not describe the Humean mosaic itself. Instead, idealised laws merely state what is the case in another, more fundamental system.

This way of addressing idealisation laws within the Best System Account is, however, problematic, particularly from the perspective of scientific practice, which does not dis-

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[4] Note that Friend (2023) does not follow the distinction between idealisations and approximations by Norton (2012), and therefore at certain points it is unclear which of these categories his arguments concern. In the discussion below I only recall arguments that are relevant to my understanding of idealisations.

tinguish between idealised laws and super-laws. Scientists treat them on a par, using both to describe and predict the behaviour of physical systems in our world. On Friend's account it is difficult to explain why scientists treat both of them as laws, given that only super-laws are elements of the Best System, as only they describe Humean mosaic.

Moreover, there is no guarantee that for every idealised law there exists a corresponding super-law. Consider the case of laws concerning a black body, an idealised physical object that absorbs all incident electromagnetic radiation. The most general law in this category is Planck's law, which describes the emission of electromagnetic radiation by a black body in thermodynamic equilibrium at a given temperature. Following Friend's argument, one would expect there to exist some super-law that reduces to Planck's law under appropriate conditions; however, no such law is currently known to physics. While Friend (2016, p. 165) acknowledges that we may not even have epistemic access to such super-laws, this answer is problematic from the perspective of scientific practice—it would imply that scientists employ only meta-ised laws, which are not themselves laws, while the super-laws that justify why idealised laws may be used in scientific research are not known to scientists.

Last but certainly not least, a proponent of this meta-approach may face difficulties in explaining the empirical success of meta-ised laws, given that they do not describe local matters of fact, but rather facts about a meta-system. Of course, one could attempt to construct an account of explanation across meta-systems and the Best System, but such an account would appear overly complicated and would appear an *ad hoc* defence of Humeanism—especially given that both laws are used in physics.

For these reasons, Friend's solution does not seem compelling in light of scientific practice, and idealised laws continue to pose a challenge for Humeanism.

5.2. Approximations

Another class of laws frequently employed in scientific practice consists of laws based on approximations—that is, inexact descriptions of target systems. As argued by Norton (2012), approximations differ from idealisations in an important respect. Approximations are propositional and aim, in principle, to describe physical systems accurately. Idealizations, by contrast, are systems rather than propositions and, by their very design, they aim to accurately capture only selected properties of their target systems in the physical world.

Although this distinction may appear subtle, approximations do not fall into the same problem with the Best System Account as idealisations do. This is because in the case of idealisations, BSA does not classify equations as (1) as laws, since they describe systems that, in virtue of being idealisations, fail to provide local matters of fact—simply because such systems do not exist in the physical world. Approximations, by contrast, aim to accurately describe target systems that are a part of physical reality, and therefore cannot be dismissed as candidate laws on the same grounds as idealisations.

As we shall see, however, this does not mean that approximations qualify as candidate laws according to the BSA. To see this problem, consider the following example of Einstein's equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{3}$$

where $G_{\mu\nu}$ – Einstein's tensor, $T_{\mu\nu}$ – energy-momentum tensor, G – gravitational constant, c – the speed of light. Now, consider the so-called Newtonian limit, that is, a case in which the gravitational field is weak. In this regime, the spacetime metric $g_{\mu\nu}$ that in General Relativity can be, in general, curved can be written as a flat Minkowski metric $\eta_{\mu\nu}$ perturbated by a small factor $|h_{\mu\nu}| \ll 1$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{4}$$

Moreover, we assume that all relevant velocities are much smaller than the speed of light and that the gravitational field is approximately static. Under these assumptions, Einstein's field equations can be 'linearised', which is a standard calculation in physics textbooks (e.g. Wald 2012), resulting in recovering the equations familiar from Newtonian physics:

$$\nabla^2 \Phi \approx 4\pi G \rho \tag{5}$$

and

$$\frac{d^2\mathbf{x}}{dt^2} \approx -\nabla \Phi \tag{6}$$

(first is the Poisson equation, which describes the Newtonian gravitational potential Φ sourced by the mass density ρ, and second is Newton's second law). In this form, these equations are approximations, that is, propositions that provide inexact descriptions of the physical system. Are approximations, then, candidate laws according to the Best System Account?

Unfortunately, this is not the case. This is because approximations, mathematically represented in equations (5, 6) using '$\approx$', do not describe local matters of fact—not by stipulation, as in the case of idealisations which are by definition different to target systems, but because no physical system satisfies such equations exactly; an approximation of an equation is not the equation itself. Standard formulations of the Best System Account, however, only accommodate propositions that describe local matters of fact, rather than their approximations.

Needless to say, such a conclusion poses serious problems for the Best System in light of scientific practice. Not only do the assumptions underlying the Newtonian limit approximately describe the physical world of everyday experience—since we move at non-relativistic speeds and gravitational effects are typically negligible—but the resulting equations are also widely employed by scientists or engineers. Thus, failing to qualify approximations as candidate laws poses a problem for the Best System account in light of scientific practice.

5.3. Absence of isolated systems

In fact, the Best System Account faces difficulties not only in accounting for approximations and idealisations, but also with equations that are regarded by physicists as exactly correct and as describing actual physical systems. To see just one example, consider Newton's second law of motion (assuming that it is exactly correct), which describes the relation between the force $\mathbf{F}$ applied to a certain body and its acceleration $\mathbf{a}$:

$$\mathbf{F} = m\mathbf{a}. \tag{7}$$

However, in the actual world bodies move in some medium that has resistance, such as air, water, glass, or a vacuum, which is not perfectly empty. Consequently, there are no systems that exactly satisfy the equation (7). In other words, in the actual physical world, there are no perfectly isolated physical systems—that is, every physical body is subject to some external phenomena: interactions with other systems and various forces, such as friction, air resistance, intermolecular interactions, or quantum effects, to name only a few. It therefore seems plausible that even allegedly correct laws, such as Newton's second law (7) or Einstein's field equations (3) do not function as theorems in the sense required by the systems introduced within the Best System Account.

In fact, a similar observation has been discussed in the philosophical literature in context of Newton's first law of motion, due to which all bodies in inertial frames have no acceleration. However, according to some philosophers, such bodies do not exist in the actual physical world, precisely because all bodies move with acceleration. The question of whether the first law of motion should be considered a law in such a case would divide philosophers into two groups. For example, Brown would say that this is a law of nature—since it is approximately non-vacuous—while Friedman would deny it (cf. Brown 2005). Therefore, the first of them might have a problem with the Best System Account. However, for those who deny that vacuous laws should be considered proper laws of nature, this feature of BSA would be a great advantage.

The problem of the absence of isolated systems, which is based on the observation that there are no systems that exactly satisfy a given equation-law, has already been noted in the literature in a somewhat different form—namely, starting from the observation that some laws (in particular, laws of the special sciences) are only approximately satisfied in the actual world. Our case is, however, slightly different. For if we were to have a perfectly isolated system, then, according to the laws of physics, a body moving within it under the action of a force would satisfy $F = ma$ exactly. Notably, this is not an idealised system in the sense discussed in this paper, since such a system would exist if it were perfectly isolated; by contrast, an ideal gas would still not exist by its very definition. In the case of the special sciences, it is moreover unclear whether, in any isolated system (whatever that might mean, for example, in the context of biology), laws such as Cope's law would in fact be exactly satisfied.

Although the problem that certain laws are not exactly satisfied by local matters of fact may have different sources—some of which I have discussed above—one might attempt to apply the same solution to all of them. If successful, this solution could also be extended to the earlier problem concerning approximation laws.

This solution is based on the so-called 'lossy systems,' according to which a Humean can be more relaxed about laws that are not exactly instantiated in the mosaic but rather only approximately (Braddon-Mitchell 2001, Backmann and Reutlinger 2014). Such a solution, however, faces serious difficulties. In particular, there is no clear criterion for separating what should count as an admissible approximation. This problem becomes especially vivid in the case of laws formulated in the form of equations, which seem to demand the specification of a an exact number value for permissible error. For instance, suppose we have a body of mass $m = 1\,\mathrm{kg}$ on which a force of $1\,\mathrm{N}$ acts at a given moment, yet the body accelerates at $a = 1.2\,\mathrm{m/s^2}$. Does this still constitute a local matter of fact that provides grounds for Newton's second law? And what if $a = 1.02\,\mathrm{m/s^2}$?

Someone with experience in laboratory work might respond that such vagueness is hardly surprising. When conducting experiments—for example, testing Newton's second law for a fixed mass m and plotting the results as points, leading to an $a(F)$ graph—one never obtains a perfectly straight line. Instead, for each measurement point one calculates a measurement uncertainty and an error, and only then fits a line that goes through these error bars rather than through the points. As in the case of the lossy-systems solution, there is no single, unique standard of uncertainty (such as a particular equation defining an error); moreover, some points that deviate radically from the others are excluded from the fitting procedure.

Of course, the fact that not all measurement points lie exactly on a straight line is due primarily to our epistemic limitations—such as the inaccuracy of measuring equipment—rather than merely to the absence of isolated systems. Still, one might argue that the overall pattern is the same as in the problem with the lack of isolated systems: despite the lack of a single standard for measurement error, we are able to recover Newton's second law from the data. Similarly, one might suggest that it should be possible to recover Newton's second law from a deductive system describing local matters of fact that only approximately satisfy such a law.

The problem, however, is that behind such data analysis ultimately stands a human agent who knows what kind of relation to look for—for example, a straight line—and who is able to assess this 'by eye' and to evaluate the fit proposed by an algorithm. In some cases, the search for a relation may proceed without exact knowledge what the relation is, but even then one still fits one of a familiar family of functions, such as a quadratic, a square root, or a logarithm. The Best System, however, which is merely a deductive system, has no such mechanism built into it. If it contains only propositions of the form 'A body of mass 1 kg accelerates at $1.2\,\mathrm{m/s^2}$ under a force of 1 N, there is nothing that would allow one to generalise these descriptions of local matters of fact into a relation that is, as it were, 'estimated by eye' and corresponds to Newton's second law. For this reason, it seems that the problem of no isolated system remains a problem for the Best System account.

5.4. A new type of vagueness

The problems mentioned above are relatively new to the Best System literature. We will now see that even the most commonly discussed objections to this view—such as vagueness and immanent inter-system comparisons (Loewer 1996)—take on a new form when one considers laws of nature formulated as equations.

Let us begin with the objection concerning the vagueness of simplicity, strength, and the balance between them, with a special focus on simplicity. The contested issue is how one ought to quantify the measures of simplicity and strength of a given deductive system. A *prima facie* reasonable criterion might be to count the number of theorems (as a measure of simplicity) and the number of propositions generated by these axioms that provide novel information about the world (as a measure of strength). In practice, however, this is far from straightforward, especially once one considers examples of laws formulated in the form of equations.

Let us take the example of Gauss's law. One of its more popular formulations, that are considered by the physicists to be the same law but wrote using different notation, is the following:

$$\nabla \cdot \mathbf{E} = 4\pi\rho, \tag{8}$$

$$\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = 4\pi\rho, \tag{9}$$

where $\mathbf{E}$ denotes the electric field and ρ is electric charge density. Imagine that we have two deductive systems: one of which includes a theorem (8) and the other includes (9), which are perfectly identical otherwise. It seems that the difference between these systems lays purely on the level of notation. However, in order to prove their equivalence, one has to equip the system that includes the first one with the definition of the divergence operator: $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$. Therefore, the system that contains (8) postulates one more rule and is less simple than the second one—at least according to the naïve criterion of simplicity as the number of axioms.

However, in general, this is not a plausible conclusion. One could think about simplicity, for example, in terms of syntactic length, which is measured as the number of symbols in a formula. In such a case, equation (8) is shorter than (9) and, for this reason, is simpler in terms of its syntactic length. Moreover, it is intuitively plausible to believe that in the complete deductive system corresponding to our world there would be many regularities similar to (9) that might be written in a more convenient, shorter form using divergence. However, since the definition of divergence is an independent axiom that has to be postulated, according to the BSA the Best System will contain laws in the longer form similar to (8).

Thus, the Best System Account fails to provide standards of simplicity that would facilitate comparison of systems with laws in the form of equations that are mathematically equivalent, yet expressed in various ways.

5.5. Immanent inter-system comparisons

A second, frequently discussed problem of the Best System Account, which assumes a new form when considered in the context of scientific practice, stems from the recognition that simplicity is relative to the language in which the system's theorems are formulated (see e.g. Loewer 1996; Carroll 2016; Cohen and Callender 2009). As a result, a proposition that is simple in one language might be complex in another. This problem can be expressed using the categories of immanent and transcendent quantities introduced by Quine (1970). The first group is defined relative to some system of predicates, while the second is independent of them. Simplicity is immanent: in order to compare the simplicity of two deductive systems, they have to be formulated in the same language, the language of natural kinds. Therefore, the worry about picking the correct language is often referred to as the problem of immanent comparisons.

To illustrate this problem, philosophers often employ an example known as the riddle of induction that is based on predicates 'grue' and 'bleen' (cf. Goodman 1983). An object is grue if and only if it is observed before the year 2026 and is green, or else is not observed and is blue; an analogous definition holds for 'bleen'. If, in a language, the predicates 'grue' and 'bleen' are simple (e.g. the predicates 'green' and 'blue' are defined in these terms), then the sentence 'All emeralds are green' formulated in this language will be more complex than in our natural language, where 'green' and 'blue' are simple. It might be the case that preferring theories with the predicate 'green' rather than 'grue' is a consequence of human psychology rather than of the real structure of the physical world. Therefore, the lesson from the example of the riddle of induction should remain the same: namely, that there is no known way to justify the preference of one language over another.

A good example of immanent comparisons from scientific practice might be contemporary theories of quantum mechanics, e.g. the Everettian and pilot-wave theories. The discussion of which of them is included in the Best System is meaningless because, on some reading, they are both formulated relative to very different systems of basic kinds (e.g. supporters of the de Broglie theory believe in the existence of particles that Everettians do not need in their interpretation). This means that one cannot compare the simplicity and strength of these two systems and, as a consequence, judge which one represents the laws of nature of our world—for instance, whether our Best System contains the so-called guiding equation that is present only in the de Broglie theory and not in the Everettian interpretation. It is important to emphasise that this is not only an epistemic problem illustrating a lack of knowledge concerning which combination of simplicity and strength is the best, but also the impossibility of making inter-system comparisons of immanent quantities. This means that even if one has complete knowledge of all axioms of the Everettian interpretation and the de Broglie theory and knows which of the systems has the best balance of simplicity and strength within these two theories, one cannot judge which of them is the Best System of quantum mechanics.

The problem of immanent comparisons is widely regarded as one of the most serious threats to the Best System account, and a number of attempts have been made to address it. Before turning to one such proposal, however, let us consider the form this problem takes in the case of laws expressed as equations. To this end, let us reconsider equations (8) and (9). In discussing this new type of vagueness, I suggested that a system including (8) must also include a definition of the divergence operator. However, there does not exist any criterion determining which mathematical symbols are more fundamental than the others and, as such, whether their definitions should be included in the Best System. In particular, one could argue that the definition of divergence should be added to the system with formula (9) rather than (8), as I suggested before.

Of course, a physicist would immediately note that equations (8) and (9) are equivalent, and thus express the same law. However, this observation does not resolve the problem of immanent comparisons, for the Best System account insists on choosing one system over another—and at the same time BSA does not provide objective, transcendent criteria for determining which language—the one employing the divergence operator or the one formulated in terms of explicit derivatives—is more fundamental.

5.6. Natural kinds without predicates

This problem of immanent comparisons can be resolved by accepting some universal language in which all theories should be formulated and compared. This raises the question of the criterion for the choice of the correct language. Such a worry was already noted by

Lewis (1983), who suggested that simplicity should be understood within a language in which every predicate has an extension to the class of objects that are grouped by some natural criterion, e.g. the class of stars.

In the contemporary literature, a candidate class of such objects are natural kinds, and can be defined for instance in the following way:[5] To say that a kind is natural is to say that it corresponds to a grouping that reflects the structure of the natural world rather than the interests and actions of human beings. (Bird and Tobin 2018) Referring to natural kinds may appear to be a plausible solution to the problem of the choice of the correct language, especially in the context of scientific practice. Although among natural kinds one can probably find such objects as cats, trees, or leaves and construct some regularities that take advantage of them, they should be excluded from being laws of nature by the criterion of the balance between simplicity and strength. For example, adding the proposition 'all trees have leaves' takes away some simplicity from our system but does not add much information. Moreover, many believe that the list of basic natural kinds includes, in particular, all fundamental physical entities, e.g. particles. In such a case they can automatically get rid of many true generalisations that we intuitively do not want to consider to be laws of nature—such as that 'all trees have leaves'. On this view, such statements can be derived from the basic axioms of the Best System that includes predicates referring to fundamental physical properties.

The main worry with the solution that refers to natural kinds is the problem of deciding what should count as natural kinds. In particular, one of the criteria for being a natural kind mentioned in a further part of an article by Bird and Tobin (2018) is that "natural kinds should participate in laws of nature". Therefore, the supporter of Lewis might be committed to a vicious circle in his argumentation. A possible answer to avoid this objection would be to accept natural properties as primitive or to give a definition of natural kinds or properties that does not refer to laws of nature. However, this raises an epistemic worry: since natural kinds are primitive notions and they determine the language in which we should formulate the Best System, there is no epistemic access to knowledge about which regularities are in fact laws of nature.

In fact, it is not clear whether looking for an account of natural kinds is at all compatible

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[5] For more in-depth discussion about natural kinds see e.g. Quine 1969. Check also Lewis 1983, 1999 for the description of perfectly natural properties.

with our scientific practice. Let us consider the integral formulation of Gauss's law:

$$\iint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = 4\pi \iiint_{\Omega} \rho \, dV, \tag{10}$$

where dS is the differential vector element of the surface area S and $\partial\Omega$ is a closed boundary surface of a fixed volume Ω. How can one rewrite this equation in the language of natural properties or natural kinds? This would probably require us to consider an electric field to be a natural property or a natural kind.[6] However, physical fields are mathematically described functions ascribing vectors to particular spatiotemporal points. It is not clear whether it is possible to provide an adequate predicate that represents a natural property corresponding to some field.[7]

Further, even if this is possible, it is not guaranteed that the natural properties in the Humean mosaic really correspond to all natural properties that appear in equations used by physicists. For instance, it is in principle possible that the physical world is built in such a way that there are simply no natural properties that correspond to the electric field—in which case (10) is not even a candidate law, even if syntactically it would be plausible from the perspective of the balance of strength and simplicity.

What is more, it is not clear at all how one should approach translating such equations as (10) into valid propositions of deductive systems formulated in the language of natural properties or kinds. 'dV' is not a property but is equally problematic. It is an infinitesimal part of a given volume, and even if one considers such a tiny piece of an object in the world, it cannot be qualified as a natural property or kind because there is no grouping that reflects the structure of the natural world to which it belongs. It is even less clear on how to understand a closed boundary surface $\partial\Omega$ as a candidate for a natural property or kind.

A similar problem is faced by integrals and by differential equations. Most laws of nature in the form of equations contain them, but it is entirely unclear which natural

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[6] Concerns described in this section could be shared also by Ladyman and Ross (2007) who argue against the belief that physics should be interpreted in terms of 'object-oriented', subject-predicate ontology.

[7] Note that every function can be replaced by the predicate, i.e. n-ary function $f(x_1, x_2, \ldots, x_n) = y$ can be transformed into $(n+1)$-ary relation $R(x_1, x_2, \ldots, x_n, y)$, which represents some predicate. However, in the case of laws of physics it is not enough, since such entities as fields refers to vectors, that cannot be easily transformed to predicates corresponding to natural kinds.

properties or kinds they would correspond to. Perhaps one possibility would be to develop a notion of a natural operator or a natural operation; however, at present it is not clear what such a notion would look like. This observation drives the BSA approach very far from contemporary scientific practice because the majority of the most fundamental laws have the form of differential equations or integrals.

5.7. Units

One more interesting point can be made against BSA in context of laws taken as equations. Consider another formulation of Gaussian law that differs from (8) only in the choice of units:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}. \tag{11}$$

Assume that we have correct deductive systems that include equations (8) and (11), which take charge density, distributed capacitance of the vacuum[8] and electric field to be natural predicates. This means that both are formulated in the same language. However, there is no good reason to choose one rather than the other to be our Best System, since both are equally simple and strong.

An interesting attempt of solving this worry is by invoking the fact that scientists sometimes use the term ‘natural units’. Therefore one may postulate that as the language of our deductive systems should use predicates corresponding to natural kinds, then analogously our regularities should be formulated in the natural units. This is an interesting point, however it requires the argument that would show that the usage of the term ‘natural’ for both ‘kinds’ and ‘units’ is not a mere coincidence—and such argument has not yet been provided.[9] Moreover, a belief that there exists a class of ‘natural’ units somehow distinguished by the natural world—whatever that would mean—would again leave us with an epistemic worry, as we do not have an epistemic access to which of the units from our equations are truly ‘natural’.

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[8] The distributed capacitance of the vacuum ε_0 is not strictly a constant, but it is defined as the inverse of the product of magnetic constant and squared light velocity. However, written in the form (11) it does have units other than (8), which is the point of the argument.

[9] On absolute units see Dewar (2019)—but whether they can count as candidates for ‘natural’ units requires further analysis.

5.8. Mathematical representation

As it has been already noted, the vast majority of propositions that are considered to be laws of nature in scientific practice are captured in the form of equations. On the other hand, when considering Lewis's account, authors, in general, give examples of axioms of a deductive system that are written in the language of logic; in other words, on this account, the Best Systems are chosen from deductive systems that have theorems and axioms formalised in logic. The problem of choosing correct predicates for such theorems has already been discussed before However, even assuming that it is possible to find predicates that would be adequate to translate our physical theories into the language of first- or higher-order logic, there remains a question about the technical possibility of doing this reduction.

Prima facie, it is possible, since one can obtain first-order versions of arithmetic, analysis, and set theory by replacing the second-order axioms with schemes (e.g. first-order arithmetic consists of successor, addition, and multiplication axioms and the axiom scheme of induction). I used a similar observation at the beginning of this article to argue that laws expressed as equations are in principle compatible with the Best System Account. However, it turns out that these theories are not finitely axiomatisable (see Shapiro 2000, p. 110). This means that it even though it might be possible to translate a huge part of contemporary physics into first-order logic and then apply the standard Best System approach to it, the infinite axiomatisation of these theories would kill the requirement of simplicity.

Moreover, first-order formalisations of calculus do not provide accounts of such notions as the smoothness of functions and are in general problematic. This can be addressed by moving to second-order logic. However, the attempt to obtain the axiomatisation described above in second-order logic would result in losing completeness. In such a situation the system is not complete: there exist local matters of fact that are not theorems of the system. In that case, the laws of nature are not the best description of the whole mosaic, but only of a fragment of it.

Therefore, it is possible that none of our contemporary physical theories can be finitely and completely axiomatised as finite deductive systems. While this does not lead to a final refutation of the Best System in the context of laws as equations, since one might attempt to construct deductive systems that are not formulated in first- or higher-order logic, it contradicts how contemporary authors usually read Lewis and moreover this conclusion leads to potential implausibilities related to incompleteness.

Setting these concerns aside, one should acknowledge that there already exist sophisticated accounts of how algebraic or differential expressions employed by physicists can be translated into the language of logic. For instance, Madarász et al. (2007) developed a robust first-order reformulation of relativity theories (see also Andréka et al. 2007). Similarly, Montague (2010, ch. 11) translated, at least partially, classical mechanics into first-order logic. These examples show that at least some physical theories, including laws formulated in the form of equations within these theories, not only can be expressed in the language of logic, but also that such translations are actively pursued and strongly motivated; for instance, Madarász *et al.* argue that a formalisation of relativity of this kind would benefit logic by offering a new perspective on the relationship between geometry and logic.

Finally, it should be noted that the definition of a deductive system as consisting of theorems and rules of inference does not exclude the possibility that such a system may include algebraic or differential equations—for deductive systems are well-defined for all formal languages, not only logic. In this sense, the problem with mathematical representation flagged above does not apply to the original work by Lewis (1973, 1983) but rather to contemporary supporters of BSA, who use examples of laws in the language of logic in their considerations. Thus, while there remains a question of whether such branches of mathematics as, say, calculus, are really formal languages, this objection can be refuted.

6. Outlook

In this paper, I have raised eight problems for the Best System Account that arise when considering laws in the form of equations. Is this a complete list of such problems? Probably not. Does this imply, then, that the Best System Account should be abandoned altogether in favour of, say, governing views of laws?

If someone agrees that, first, laws of nature have to be compatible with scientific practice and, second, that scientific practice requires the employment of laws in the form of equations, then it follows that the Best System Account should indeed be rejected. This is because, even if someone rejects all but one problem mentioned in this paper, this one counterexample is enough to reject the entire view. What is more, if one were to reject all arguments mentioned here, it seems that one can propose other problems in a similar vein, because the language-based account of the laws of nature developed by Lewis—while works well for examples from first- and higher-order logics, which are widely used in the philosophical literature—seems to be too poor to account for the complexities of contemporary mathematics, which employs calculus, differential geometry, and so on. Furthermore, even if one were to present a complete formalisation of all of contemporary physics in the language of logic, some familiar problems will remain—such as the problem of immanent inter-system comparisons. Of course, as we have seen, one can try to address these and similar problems by developing novel versions of the Best System Approach; however, in order to address all of the problems proposed here, one would have to combine different accounts into one (e.g. Friend's meta-ised view with Braddon-Mitchell's 'lossy' account), and there is no guarantee that such an account would be coherent—and moreover, the number of required 'patches' raises the question of why one needs such a complicated philosophical account to capture laws of nature, which, from the perspective of scientific practice, are not so diverse.

On the other hand, as I indicated at the beginning, the Best System Account has some advantages with respect to scientific practice, specifically understood as considering laws in the form of equations: such as not employing metaphysically rich notions that are foreign to contemporary science, such as powers or dispositions.

Thus, it is worth noting that a significant part of the problems mentioned here is related not to Lewis's view that laws of nature supervene on the Humean mosaic, but rather to the requirement that laws are theorems of deductive systems that strike the best balance between strength and simplicity. Accordingly, someone who is strongly committed to the virtues of the Humean mosaic could reject the latter requirement and attempt to develop a new account of the laws of nature that would still employ Humean supervenience. At present, however, it is not clear what such an account would look like and, what is important for the argument in this paper, such an account would no longer be the Best System Account.

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