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Laws in Physics

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This paper critically discusses different philosophical conceptions of laws of nature by examining how putative laws are treated in physical theorizing. These different conceptions are, first, views that take laws to be metaphysically basic; second, Humean views, which take laws to be reducible to patterns of instantiations of non-modal properties; and, third, a cluster of conventionalist or instrumentalist views that understand laws as part of the epistemic toolkit for building models and a reflection of a particular perspective of investigation. I argue that scientific practice best supports a moderate version of the third view: while the laws of physics do not form a single tightly organized axiomatic structure and there exists a multiplicity of frameworks in which putative laws are justified by their predictive use and relevance in a particular context, general overarching principles nevertheless play an important role in physics and provide some integration of different domains.

1. Introduction

During much of the eighteenth and nineteenth centuries, Newton's laws of motion were taken to be the paradigm of scientific laws, thought to constitute universal and necessary eternal truths. But since the turn of the twentieth century we know that Newton's laws are not universally valid. Does this mean that their status as laws of physics has changed? Have we discovered that the principles, which were once thought to be laws of nature, are not in fact laws? Or have we merely learned that the domain of application of Newton's laws is more restricted than we once thought, while the laws' role within their proper domain is unaffected by this discovery? What is more, with the demise of Newtonian physics as universal theory the entire paradigm of lawful predictability appears to have reached its limits – not only with the discovery of quantum probabilities but also with the emergence of the physics of nonlinear and complex systems, for which the notions of determinism and predictability come apart. How do these developments affect our philosophical conception of laws of nature? Are the laws of nature the (perhaps probabilistic) determinants of how the world evolves? Or are they rather our best predictive tools? That is, are the laws of nature fully objective and context-independent fundamental features of the world to be discovered by us, or is what the laws are at least partly also a reflection of our human cognitive capacities and of particular contexts of investigation? In this paper I want to make progress towards a philosophical understanding of the role of laws in physics – arguably our most fundamental science – by closely examining a number of features of how putative laws are treated in physical theorizing.

In the next section I will distinguish three broad philosophical conceptions of laws that play a particularly prominent role in contemporary philosophical discussions of laws of nature. These are, first, views that take laws to be metaphysically basic, including 'governing conceptions' that treat laws as metaphysically fundamental drivers of the temporal evolution of the world; second, Humean views, that take laws to be reducible to patterns of instantiations of non-modal properties; and, third, a cluster of conventionalist or even instrumentalist views that understand laws at least partly as a reflection of a particular perspective of investigation and as part of the epistemic toolkit for building models, which represent aspects of the world from a particular and partial perspective, relative to certain goals and interests.

Often, philosophical discussions of laws of nature are situated at some remove from examinations of the actual use of putative laws in physics, taking as their starting points purely philosophical reflections on the nature of laws, with only tenuous support from actual scientific practice. By contrast, here I want to approach the issue from the other end, as it were, by first examining several features that I take to be characteristic of laws in physics (in each case taking methodological reflections of eminent physicists as a cue) and then asking to what extent these features are compatible with various philosophical conceptions of laws. The three features of physical theorizing on which I will focus concern the place of axiomatization in physics; the relation between dynamics, kinematics, and initial conditions; and the role of older and in some sense superseded theories, such as classical mechanics, in contemporary physics. To anticipate somewhat, there is a conventional and context-dependent element in the way in which laws are treated in physics. Different sets of laws provide us with different perspectives from which to model or represent the phenomena, partly serving different purposes or answering different questions. And while laws at different levels are related in many and intricate ways, and hence there is little evidence for an image of physics as consisting of completely balkanized, disjoint groups of research activities, there is equally little evidence for a conception of physics as providing us with a single hierarchical and uniquely axiomatized structure. Thus, I will argue that even within physics there is support for a view of laws that is more frequently associated with the so-called 'special sciences', according to which laws function as domain- and context-specific generalizations.[1]

2. The Metaphysics of Laws

Laws of nature, according to one common philosophical understanding of that notion, are universal and necessary truths. The necessity in question is taken to be distinct from logical necessity and sometimes also from (other brands of) metaphysical necessity. We can distinguish broadly two ways of further fleshing out the view that laws are universal truths.[2] According to the first conception, nomological necessities are metaphysically fundamental – they are part of the basic inventory of the world. Some proponents of this

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conception hold that metaphysical necessity resides in the fundamental quantities themselves and they hold, for example, that it is an essential property of mass that it attracts other masses.[3] The laws of physics are then thought to be a consequence of the *physical essences* of things. Other proponents of the conception take the laws themselves to be fundamental and to constrain the patterns of instantiations of accidental or categorical properties in the world. On the latter view, the so-called *governing-law conception*, the laws of nature govern how the world evolves from one moment to another.[4]

Views that nomological necessities are part of the basic inventory of the world contrast with Humean conceptions of laws, named after the Scottish philosopher David Hume, according to which laws and nomological necessity supervene on the totality of particular non-modal matters of fact. Nomological claims, according to the Humean, are true in virtue of certain patterns of fundamental properties being instantiated. One way to spell this out further is the account associated with the names of John Stuart Mill, Frank Ramsey and David Lewis (MRL).[5] According to the MRL-account, laws provide us with that summary of the mosaic of particular matters of fact that best balances simplicity and strength. The MRL-account asks us to consider different ways of organizing statements about particular matters of fact into deductive systems. The strength of a system is a measure of how many truths the deductive system allows us to derive, while a system's simplicity is both a measure of the system's number of axioms and of the axioms' syntactic complexity. The laws are the axioms of that deductive system that best combines simplicity and strength.

While the traditional Humean account, which identifies laws with the regularities exhibited by the 'Humean mosaic,' appears to offer a reductionist but fully objective account of laws, the MRL-account introduces a pragmatic element. As defenders of the view emphasize, *both* the criterion of simplicity itself *and* what the proper relative weighting of the criteria of simplicity and strength is cannot be spelled out in a purely objective manner: overall goodness ultimately is goodness *for us*. Thus, according to the MRL account, what the laws are depends at least partly on us and our cognitive capacities. Yet this does not mean that what the laws are is arbitrary.

Ron Giere and others have traced the history of the notion of scientific laws as universal and necessary truths to the idea of God as divine law-giver – an idea one can find for example in Newton.[6] The universality of the laws is a consequence of God's supreme power, which ensures that nature has to obey His laws everywhere and for all time. Independently of whether Giere's account accurately captures the history of the concept of law of nature, the image of God as law-giver can provide a useful illustration of the contrast between the governing and Humean conception of laws.[7] The difference between the governing-law conception and the Humean conception concerns the question of whether laws are metaphysically fundamental or whether what the laws are is reducible to – or supervenes on – the totality of particular matters of fact. According to the former conception, when God created the world he had two tasks: he had to decree what the fundamental laws of the world would be; and he had to specify what the initial state of the universe shall be. Nothing more was required of him. Once the initial state was created, the universe evolved forward in time governed by the laws of nature. At least this would be so, if we assumed that the laws are deterministic and contain no 'gaps'.

Yet even if we assumed complete but non-deterministic laws, the basic picture of the laws being responsible for how the world evolves would remain.

By contrast, the Humean God is not a law-giver but rather a pointillist painter, who set himself the rather more involved task of sprinkling the universe's four-dimensional space-time canvas with particular matters of fact. That is, the Humean God does not merely have to decree what the universe's initial state should be but has to paint all of space-time – that is, all of space throughout all times – with a mosaic of events. What the laws of nature are, is then given by the totality of particular matters of fact. According to the traditional Humean theory, the laws strictly supervene on the pattern of particular matters of fact. According to the MRL view, what the best way of summarizing the mosaic created by God might be *for us* also partly depends on our cognitive capacities.

The image of God as pointillist painter does not yet tell us how easily the patterns on the canvas can be summarized. Lewis's God and the God of the standard MRL account of laws appears to have been kind to physicists searching for universal regularities on his canvas: his painting contains global patterns, is systematic and highly organized so that we can justifiably hope to be able to summarize the goings-on on the entire canvas with the help of a relatively small number of relatively simple fundamental physical laws. But we can also imagine a less systematic painter – a messy and mad genius who painted different parts of the canvas in ways that resist being unified within a single simple framework. Any description of the goings-on on the mad genius's canvas that is both true and universal might be absurdly complex – so complex that our best strategy might be to hunt for small pockets of order that permit being summarized in terms of simple 'lawish' statements rather than aim for a single unified description. If God was messy and the world was 'dappled', we would have to lower our ambitions: instead of aiming for a single best system, we might have to rest content with a multiplicity of domain-specific and perhaps even interest-specific systems. Instead of hoping to discover universal laws, we would search for ways to summarize small pockets of regularities. And instead of hoping to discover laws that are strictly true, we might have to make due with 'lawish' statements that fit the patterns we observe reasonably well to a certain degree of approximation, and aim for domain-specific systems of laws that best combine simplicity, strength and fit.

As I have presented it, the third conception of laws is a variant of the MRL-account.[8–10] The conception replaces the idea of a single best system with that of a multiplicity of systems, reflecting different perspectives and interests, and instead of demanding that laws be true takes goodness of fit to be just one criterion by which to evaluate a system, to be jointly maximized together with the competing criteria of simplicity and strength. A closely related view insists, in addition, that the relationship between laws and the world is more indirect than the accounts surveyed so far would have it: the primary role of laws, some philosophers argue, is to aid us in the construction of models of the phenomena. The representational role of science, on this view, is ascribed not (or at least not primarily) to the laws but rather to the models constructed with the help of laws: laws are tools for model-building (see Refs 6 and 7). Instead of providing us with the uniquely correct fundamental underpinnings of how the world evolves, laws are taken to be part of 'expanded understandings of both the world and our representations of it as a rich, variegated, interdependent fabric of many levels and kinds of explanations that are integrated with one another to ground effective prediction and action,' as Mitchell (Ref. 1, p. 19) puts it.

This concludes my brief sketch of the conceptual landscape concerning laws of nature. Which of these three conceptions should we adopt? In what follows I want to describe three features of laws of physics, which can provide us with some clues towards an answer to this question.

3. The 'Babylonian' Conception of laws

The first feature that I want to discuss is what Richard Feynman calls the 'Babylonian' character of laws in physics. In *The Character of Physical Law*, Feynman discusses the mathematized statements at the core of physical theories and asks whether there is 'one set of statements that is more fundamental and one set of statements that is more consequential' (Ref. 11, p. 46). According to what Feynman calls the 'Euclidean tradition,' physics and the mathematized sciences should be thought of as having an axiomatic structure, similar to that of Euclidean geometry, in which the entire content of a theory is derivable from a simple set of fundamental axioms. That is, the Euclidean tradition takes the laws of physics to exhibit a context-independent hierarchical structure. Feynman contrasts the Euclidean view with what he calls the 'Babylonian tradition,' which instead of deriving theorems from a set of axioms works its way towards different theorems by doing a large number of examples. This does not mean that the theorems are taken to be disconnected from one another. Rather, a theory's theorems provide us with an interconnected (and over-connected) structure, which, however, allow no unique and context-independent way of singling out certain of its parts as the most fundamental. Thus, Feynman says, we could 'start with some particular ideas which are chosen by some kind of convention to be axioms' (Ref. 11, p. 47), but we could have chosen a different starting place as well. By contrast with the Euclidean conception, the Babylonian conception of science is non-hierarchical and less tightly organized:

> I happen to know this and I happen to know that, and maybe I happen to know that, and I work everything out from there. Tomorrow I may forget that this is true, but remember that something else is true, so I can reconstruct it all again. I am never quite sure of where I am supposed to begin or where I am supposed to end. I just remember enough all the time so that as the memory fades and some of the pieces fall out I can put the thing back together again every day. (Ref. 11, p. 47)

Feynman's own illustration of the Babylonian conception is the relation between Newton's three laws together with the law of gravity, on the one hand, and Kepler's second law and angular momentum conservation, on the other. As Newton himself showed, we can derive Kepler's law that equal areas are swept out by a planet in equal times from Newton's laws, which might suggest that the latter are more fundamental than the former. However, Kepler's area law can be thought of as a special case of the principle of angular momentum conservation and the latter applies much more broadly than just to gravitational forces. In fact, according to Noether's theorem, which establishes a connection between symmetries and conserved quantities, angular momentum conservation follows from the fact that the Lagrangian of a system is rotationally symmetric. Thus, one might think that the symmetry principle and angular momentum conservation is the more fundamental principle and should be an axiom instead of the gravitational law. Yet while this principle provides a constraint on the possible form forces between bodies might take, it does not entail Newton's inverse-square law: we cannot make due with the symmetry principle alone.

Another example of the phenomenon to which Feynman points is the relation between the Lorentz force law and the principle of energy-momentum conservation in classical electrodynamics. We can begin by postulating the Maxwell equations and the expression of the principle of energy-momentum conservation for electromagnetic systems and from these together derive the Lorentz force law. Alternatively, we can take the Maxwell equations and the Lorentz force law for continuous charge distributions as starting points to derive that electromagnetic energy and momentum are conserved, given the standard expression for the field energy and momentum. Finally, there is a third view point: we can posit the Maxwell equations together with the Lorentz force law and demand that energy-momentum ought to be conserved in electromagnetic interactions and use these assumptions together to define the electromagnetic field energy in terms of the electromagnetic field vectors. On the first two approaches we assume that we already know what the expression for the energy of an electromagnetic field is, while the third approach uses the demand of energy conservation to find what combination of electric and magnetic field strengths represents the energy contained in the field. Analogously to Feynman's own example, we are faced with the choice of either taking a general principle, such as the principle of energy conservation, as a fundamental starting point or beginning with the specific dynamical laws governing the phenomena, such as the Maxwell-Lorentz equations.

Feynman concludes from his discussion that there is no unique answer to the question of which of the different starting points is 'more important, more basic'. Rather, in order to understand physics 'one must always have a neat balance' (Ref. 11, p. 50) between the different possible starting points – in particular, we must balance an approach that begins with broad, general principles with one that focuses on the particulars of the dynamics for a system. Feynman's view echoes a view expressed by Hendrik A. Lorentz, more than half a century earlier, who maintained that approaching physical phenomena *both* from the perspective of broad and general principles, such as the principle of energy conservation, *and* from what Lorentz calls 'the mechanism of the appearances' – that is the particular dynamical laws, can be fruitful.[12,13] Like Feynman after him, Lorentz, too, stressed, that neither of the two approaches is privileged: 'there are multiple ways by which we try to understand natural phenomena […] Individual characteristics and inclinations determine the choice for each scientist'.[14]

Feynman also allows for the possibility that 'some day when physics is complete and we know all the laws,' there may be a privileged set of axioms (Ref. 11, p. 49). Thus, that current physics does not provide us with a uniquely axiomatizable interconnected structure does not yet imply that a 'final' physics would not provide us with a privileged Euclidean axiomatization. But if current physics does not fit the Euclidean conception, this raises the question of why one should believe that a 'final' physics will.

One might argue, *pace* Feynman, that we do not have to wait for the completion of physics and that physics already has a hierarchical, quasi-axiomatic structure. This argument could appeal to the role of symmetry and conservation principles and to the connection between the two, to argue for the following hierarchical picture: we begin with certain symmetry principles, such as time-translation invariance as meta-laws. These principles explain, via Noether's theorem, which posits a connection between symmetries and conserved quantities, the 'great conservation principles', as Feynman calls them. Since the symmetry principles have the status of meta-laws, all particular dynamics have to satisfy the conservation laws. Thus, we have an explanatory hierarchical scheme beginning from symmetries to conservation laws to particular fundamental dynamical laws.

Yet it is not obvious how one might reconstruct this scheme within the standard MRL view, for it seems that the general symmetry principles could not be among the axioms of the best system of a complete and final physics. A set of axioms consisting *only* of these principles would be much too weak, because it would not allow us to derive any specific dynamical laws. However, if we enlarge our set of axioms to include all the specific dynamical laws, the general principles become superfluous: the system including the dynamical laws would be less simple without any increase in deductive strength compared with a system consisting of the dynamical laws alone.

More importantly, even if organizing theories in this way – from symmetry principles to conservation laws to dynamical laws – clearly plays a role in physics, the 'anti-Babylonian' needs to establish that this scheme is privileged and not merely one among several, and it is not clear that this can be done.

First, Noether's theorem presupposes a Lagrangian formulation, but not all dynamical systems can be represented in this manner.[15,16] Second, where Noether's theorem does apply, it establishes an equivalence and not an explanatory priority of the symmetry principles. That is, in perfect Babylonian fashion one can take either symmetry or conservation principles as the starting point.[17] Third, we can in principle take two different viewpoints on the relation between, on the one hand, conservation and symmetry principles, and, on the other, particular dynamical laws. We could take the general principles to be more fundamental and provide a meta-nomological constraint on the form any dynamical law has to take. But one can also take the opposite viewpoint, as Harvey Brown and Peter Holland suggest: 'the real physics is in the Euler-Lagrange equations of motion for the fields, from which the existence of dynamical symmetries and conservation principles, if any, jointly spring.'[15] It is compatible with this second viewpoint that we adopt the general principles as heuristic guides in our search for new dynamical laws, without treating them as meta-nomological constraints. Again, the coexistence of these two viewpoints (even if it is not always peaceful) supports Feynman's Babylonian conception.

I want to end this section by pointing to an area of physics that provides additional support for a Babylonian conception: non-linear and complex systems. The physics of complex systems concerns the aggregation of smaller objects into higher-level systems with a very large number of degrees of freedom that can exhibit new types of behavior not present at the lower level. Complex systems exhibit a certain robust organization that arises out of the interplay of underlying randomness and interactions of many elements that result in the higher-order structure.[18] The emergence of new properties in these macroscopically-ordered structures involves the breaking of symmetries of the underlying micro-dynamics, which can be characterized as a phase change.[19–22]

According to one notion, complex systems are systems whose behavior cannot be algorithmically predicted from the micro-dynamical equations governing the system. An example of this is fluid turbulence, which can be modeled at a higher level of description by the so-called 'Burgers equation', an equation that can be solved exactly for arbitrary initial conditions. At a more fundamental level, fluids are governed by the Navier-Stokes equation. Yet turbulent behavior cannot be predicted by integrating the Navier-Stokes equation, since turbulence involves the interactions of different features at different length scales – of big whirls, little whirls and lesser whirls, as the applied mathematician Lewis Richardson has put it – and the locations and times at which these features emerge is sensitive to the precise microscopic initial conditions.[23] That is, complex chaotic phenomena, such as fluid turbulence, pose an entirely new challenge for Laplace's demon in his attempt to predict the universe's evolution: not only does he have to have unlimited computational power, but he also would have to know *exactly* what the universe's *precise* micro-state at some time was, since approximate knowledge of the state, however ever close to the actual state, could result in arbitrarily large divergences in his predictions for the future.

This means that independently of the question whether complex systems might be *ontologically* reducible to their constituents, they are in general not *epistemically* or *explanatorily* reducible and a description of the higher-level patterns exhibited by the system in terms of higher-level theories is essential. We can be committed to the view that complex systems are in principle governed by the fundamental micro-dynamical laws, yet due to non-linearity, sensitivity to initial conditions, the existence of feedback effects, and the overall computational complexity of the problem, we cannot derive higher-level patterns and laws from the micro-dynamics.

From the perspective of an underlying micro-theory, higher-level descriptions will involve abstractions and idealizations. Nevertheless, to the extent that higher-level features and patterns are robust, have explanatory power and are predictive reliable, they can be thought of as real.[24,25] Even if nature were hierarchically organized, this does not entail an explanatory reductionism and a uniquely hierarchical structure of the laws of nature. The physicist Philip Anderson, echoing Feynman's Babylonian conception, expresses this hierarchical yet non-reductionist view as follows:

> The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. […] The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of simple extrapolations of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. (Ref. 19, p. 393)

What consequences does the Babylonian character of physics have for the philosophical accounts of laws we distinguished above? Feynman's view is obviously incompatible with

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any account that implies the existence of a uniquely privileged way of axiomatizing physical knowledge. Thus, the Babylonian conception is in tension with the standard MRL view. If Feynman's depiction of physics is accurate, there is no context- and interest-independent answer as to what the axioms of a best system and, thus, what the truly fundamental laws are. As Lewis himself acknowledged, how to aggregate the criteria of strength and simplicity is to some extent vague. His hope was that this vagueness would be inconsequential and that there would be one deductive system that would clearly and uncontroversially come out ahead. Feynman's discussion suggests that this hope might be in vain.

The Babylonian conception is also in tension both with the view that there exist truly fundamental laws that ultimately govern how the world evolves and with the view that the laws are consequences of the physical essences possessed by things. The problem for the latter view is that, according to the Babylonian conception, it is unclear which set of laws directly reflects the underlying essences. Is it, for example, part of the essence of massive objects to respond to forces, or is it rather in their essence to conserve energy and momentum or move along a path that minimizes the action (as a Lagrangian picture suggests)? Perhaps, however, adherents to a governing view of laws could hold that what governs the evolution of the world is the entire nomological structure of physics and that nomological necessities are located at multiple levels, while conceding that it might not be possible to differentiate between truly fundamental and truly derived laws within that structure.

Owing to their flexibility and their lowered ambitions, the revised MRL-view and the 'laws-as-tools'-view fare best. The role of general principles, whose usefulness in model-building extends far beyond the domain for which they were originally proposed presents a challenge, however, for more extreme patchwork accounts of laws. What is needed, in order to do justice to the Babylonian character of physics, is an account that can provide a role *both* for general, overarching principles *and* for highly domain specific modeling assumptions.

4. Dynamics, Kinematics, and Initial Conditions

In the previous section we saw that the distinction between fundamental and derived laws in physics is to some extent conventional or context-dependent. In this section I will suggest that conventionalist elements are also present in the distinction between dynamics, kinematics, and initial conditions. In a series of lectures, the physicist David Gross presented 25 questions on the future of physics. Question 13 was whether 'dynamics, kinematics and initial conditions can be separated'.[26] Gross's answer was that perhaps they cannot be disentangled. As Gross characterizes the distinction, kinematics constitutes 'the framework for physics and its interpretation' while dynamics provides the 'specific laws of nature.' Kinematics, that is, specifies the formal framework within which specific dynamical interactions take place. The initial conditions are the values of those quantities specified in the kinematical framework that need to be given as input to obtain solutions to the dynamical laws.

Gross suggests that the distinction comes under pressure in contemporary physics and says: 'I suspect that, as we learn to understand string theory and explore the nature of

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space-time, the distinction between kinematics and dynamics will be blurred.' Arguably, however, that the distinction is partly conventional is already a feature of established physics as the following example suggests. Instead of representing the evolution of a mechanical system of Newtonian particles in terms of Newton's laws and the forces acting between the particles, one can use the Lagrangian or Hamiltonian framework. The basic variables in the Hamiltonian framework are generalized position and momenta coordinates. By introducing generalized coordinates, the framework can be extended even to systems that cannot readily be represented in terms ordinary space-time coordinates. The state of a system consisting of n particles is represented in a $6n$-dimensional phase space, where a system's instantaneous state is given by the values of $6n$ variables representing the six linearly independent position and momentum coordinates for each of the n particles. We can think of phase space as the framework for representing the space of possibilities associated with a theory.[27] This space is the space initial data for the equations of the theory, representing possible instantaneous states allowed by the theory, which nomically determine the evolution of a system. Each state can further be assigned a kinetic energy T and potential energy V, which together encode all the physics of the problem. Hamilton's equations are equivalent to Newton's equations, but while Newton's equations represent the evolution of a system as the result of forces acting between particles, the Hamiltonian framework represents the system in terms of potentials to which a particle's motion responds.

The arena for Lagrangian mechanics is the $3n$-dimensional configuration space, corresponding to the $3n$ degrees of freedom of a system of n particles (assuming that there are no constraints reducing the number of independent variables). In the Lagrangian framework the starting point for deriving the evolution of a system is a variational principle, such as Hamilton's principle, according to which the action between two times is stationary along its actual path. (The Lagrangian L of a system is the difference between kinetic and potential energies: $L = T–V$. The action is defined as the time-integral of the Lagrangian between two times. That the action is stationary along the path means that it is a minimum, a maximum or a saddle point.) That is, in the Lagrangian framework, the evolution of a system is derived from the state at two times and a constraint the system satisfies at times in between. While the Newtonian formulation naturally suggests a causal picture of particles being pushed and pulled around by locally acting forces, and the Hamiltonian formulation is one of particles responding to the local value of a potential, the Lagrangian formulation might seem to suggest a teleological explanation of a system's evolution, since the path of a system is represented as depending not only on its initial state but on its final state as well: as Feynman puts it, the system's particles 'in some grand fashion [smell] all the curves, all the possibilities, and decide which one to take' (Ref. 11, p. 52).

A striking difference between the Hamiltonian and Lagrangian frameworks concerns the relation between the dynamical laws and the respective kinematic frameworks. Hamilton's equations provide first-order constraints on phase space and the equations determine the evolution of a system given the initial state of the system at a single time. By contrast, the variational principle from which the Lagrange equations are derived consider possible paths between the states at two times. Moreover, the Lagrange equations provide second-order constraints on the evolution of instantaneous configurations characterized only in terms of (generalized) positions. Thus, the space of possibilities in the Lagrangian framework is not given by the space of instantaneous states in configuration space, but by pairs of such states or by the space of solutions to the theory.[28]

For systems of gravitating particles the Lagrangian, Hamiltonian and Newtonian frameworks are mathematically equivalent. Differences between the frameworks can at most concern possible extensions to other domains and here it is unclear that one of the frameworks is clearly overall superior to the other two. Thus, in this case too, it seems that the physics would support a conventionalist approach, which, depending on the context, allows us to pick any of the different frameworks – the Lagrangian, the Hamiltonian, or one involving (broadly Newtonian) forces – as the appropriate one. Yet if the choice between Lagrangian and Hamiltonian frameworks is conventional, then so is, at least partly, the choice of kinematic background framework and of dynamical laws. According to the Hamiltonian framework, the state of a system at one time nomologically determines the entire history of the system. According to the Lagrangian framework, the state at one time is *not* sufficient to determine the temporal evolution of the system. The physicist Eugene Wigner proposed that the distinction between laws and initial conditions is a human artifact in our aim to distinguish a realm of regularities from one of randomness.[29] Comparing Lagrangian with Hamiltonian formulations of physics suggests that there is a certain amount of leeway in how we want to carve up the territory into contingent initial states and nomological constraints.

Let me briefly mention three other examples of the conventionality of the choice of background framework and of dynamical laws. First, gravitational effects are classically modeled in terms of forces, as in Newtonian gravitational theory. Alternatively, one can treat gravity as a geometric effect even non-relativistically, as is done in the Newton-Cartan theory.[30] The second example concerns the treatment of spin degrees of freedom in Bohmian mechanics, a specific version of quantum mechanics. According to Bohmian mechanics, particles follow classical trajectories, guided by a non-classical 'pilot wave' that satisfies the Schrödinger equation. Spin degrees of freedom can be introduced in Bohm's theory by modeling the particle as having additional internal degrees of freedom or by taking the wave function to be a multiple-component spinor wave-function. And, finally, systems governed by a stochastic dynamics can be alternatively represented in terms of a deterministic dynamics, where the system is modeled as interacting with an additional (hidden) noisy source.[31]

To the extent that the distinction between dynamical laws, on the one hand, and the kinematic framework within which the dynamics takes place, on the other, is blurred, this puts pressure on any account of laws that sees the distinction between nomological necessity and contingency as metaphysical basic. Indeed, any attempt to read off the essences of things from the different frameworks would presumably result in conflicting answers. Is it in the nature of quantum particles with spin to possess additional internal degrees of freedom or is it part of their essence to be guided by a spinor-valued wave function? Is it part of the essence of material particles to follow geodesics in the absence of non-gravitational forces or do material particles essentially exert gravitational forces? And, to return to our main example, is it in the nature of particles to respond to local forces or rather to local potentials? Or is it in the essence of a system to satisfy a global variational principle? It is unclear whether physics itself can provide unambiguous answers to these questions.[32]

There is an additional problem for a governing conception of laws, which sees the laws as being responsible for, or as producing, the temporal evolution of the state of a system: the governing conception appears to have difficulties accommodating the Lagrangian framework, since, as we have seen, the variational principle takes both initial and final states as given and the initial state in configuration space is simply not rich enough for the laws to uniquely determine the state's future evolution. Of course, it is open to defenders of the governing conception to argue that the Lagrangian variational principle is merely a by-product of more fundamental forces acting along infinitesimal parts of a system's path.[33] But such an argument would presumably have to invoke extra-physical or metaphysical reasons for preferring a Newtonian framework.

Humeans appear to have fewer problems with accepting that the distinction between instantaneous initial conditions and regularities is to some extent conventional. The view that laws merely summarize the Humean mosaic is compatible with the idea that there might be multiple ways to distinguish regularities from randomness in the mosaic. But traditional MRL-theorists might again face the problem of not being able to decide which of several different axiomatizations is clearly superior to its rivals and so provides us with *the* best system.

5. Established Theories

The third issue I want to discuss is the status of established theories of physics, which are not also our most fundamental theories. The philosopher Thomas Kuhn has famously claimed that the history of physics consists of a series of periods of normal science, in which a framework for doing physics, a 'disciplinary matrix' or, to use Kuhn's original term, a 'paradigm' is worked out in ever greater detail and expanded.[34] These periods of normal science are punctuated by scientific revolutions, in which a prior framework is abandoned and replaced by a new one. The acceptance of the theory of relativity and of quantum mechanics, according to Kuhn, constituted two such revolutions in which both classical mechanics and classical electrodynamics were replaced. In a critical review of Kuhn's work, the physicist Stephen Weinberg has argued, however, that Kuhn's image of science ignores an important distinction: the distinction between theories that are eventually rejected as dead-ends and are truly abandoned, and theories that, like Newtonian physics or classical electrodynamics, have remained an important part of physics, even after the development of quantum mechanics as its putative replacement.[35] As Weinberg puts it: 'After our theories reach their mature forms, their hard parts represent permanent accomplishments. If you have bought one of those T-shirts with Maxwell's equations on the front, you may have to worry about its going out of style, but not about its becoming false. We will go on teaching Maxwellian electrodynamics as long as there are scientists.'[36]

Yet if the Maxwell equations are permanent accomplishments, how did our attitude toward the theory change as a result of the quantum revolution? Weinberg's remarks suggest a picture of theory change and acceptance that has been more fully developed by the physicist Fritz Rohrlich together with Larry Hardin.[37] Rohrlich and Hardin distinguish mature theories from established theories. A mature theory, according to them, is one that has a mathematical structure, is predictively powerful, empirically well-supported, and coheres well with other theories. An established theory is a mature theory that, in addition, has known validity limits imposed on the theory by a superseding theory, to which the earlier theory is related through some limiting procedure. As example of an established theory they cite Newtonian classical mechanics, which they say 'has the validity limits "$(v/c)^2 << 1$" from special relativity and the validity limits "(number of quanta) $>> 1$" from quantum mechanics' (Ref. 37, p. 608). Prior to the development of quantum mechanics, classical electrodynamics was thought to have universal scope and problems for the theory such as black-body radiation and the ultra-violet catastrophe had the status of Kuhnian puzzles. With the development of quantum theory it became clear that black-body radiation was a phenomenon outside of the domain of the classical theory. The significance of receiving validity limits is that through such limits an established theory can be closed off from future refutation. This is what justifies Weinberg's confidence that the Maxwell equations are a permanent accomplishment of physics.

While Rohrlich and Hardin stress the importance of limiting relations between an established theory and its successor, it is also a consequence of their view that established theories retain an important and to a significant extent independent role in physics after their validity limits have been established. For one, the limiting relations are often not precise enough to allow the older theory to be strictly reducible to its successor, as they emphasize: 'The limiting process involved can be very complicated as well as very subtle. Some of the limiting processes have so far not been carried out in a mathematically satisfactory way, but far enough to satisfy the intuitive expectations of the physicist' (Ref. 37, p. 605, fn.3). An oft-cited example of the subtlety of the relations is the derivation of thermodynamic phase transitions from statistical mechanics. Phase transitions only emerge in the thermodynamic limit of the number of particles in a system tending toward infinity, even though real systems exhibiting phase transitions, of course, consist of a finite number of particles.

Established theories are not fully subsumed under their successor theories but play an independent explanatory role in physics. In order to see why this is so, consider the following. That the Maxwell equations are part of an established theory does not require that quantum electrodynamics will also be an established or even mature theory. That is, that we will go on teaching classical electrodynamics does not depend on whether we will go on teaching present-day quantum electrodynamics. Indeed, when classical electrodynamics transformed from a mature into an established theory – that is, when its validity limits were established by the new quantum theory, the latter theory was not yet mature, let alone established. Quantum mechanics was still very much in the process of being developed, yet this presented no threat to the status of classical electrodynamics as an established, permanent accomplishment of physics.

We can contrast the relation between classical electrodynamics and quantum theory with that between Galileo's law of free fall and Newtonian physics. The law of free fall has been fully subsumed under Newtonian physics. Moreover, had we been forced at some point to fully abandon Newton's theory (rather than to restrict its domain of validity), the law of free fall would have lost its putative explanation and we would have had to search for a new explanation. By contrast, despite the existence of a limiting process relating QED to classical electrodynamics, the latter has not been fully subsumed under the former and the classical theory does not crucially depend on the quantum theory as providing an explanation for it. Without the Newtonian framework (or a general relativistic replacement), the law of free fall would appear puzzling and in need of an explanation. By contrast, even though it is an interesting question to explore possible explanations of the Maxwell equations from quantum and group theoretic assumptions, the equations can stand on their own as providing the foundations of classical electrodynamics.

Thus, a better image of the relation among different established theories and their successor theories than that of a hierarchical structure with the most fundamental theories at the bottom is one of different pillars, some perhaps driven into the ground more deeply than others, interconnected by a network of bridges of varying strengths.

6. Conclusion

My aim in this paper was to survey several features of laws in physics and ask to what extent these features are compatible with different philosophical accounts of laws of nature. These features are the following. (i) Laws in physics form a 'Babylonian' interlocking set of 'theorems' among which we can choose different theorems as starting points or 'axioms', depending on the context, and which are connected by an interlocking web of more or less tight derivations. (ii) There are mathematically equivalent ways of carving up the phenomena into kinematic background framework and dynamical laws. Thus, the kinematics-dynamics distinction is to some extent conventional. (iii) Different established theories of physics are to some extent independent of one another and from putatively more fundamental theories.

These features put pressure on any philosophical account of laws that presupposes that the laws of physics have a unique quasi-axiomatic structure – foremost the traditional MRL account, but also metaphysical accounts that assume that there is a privileged metaphysical and explanatory hierarchy from meta-nomological symmetry principles to conservations laws, which constrain dynamical laws. The existence of multiple kinematical frameworks for modeling systems also undermines any attempt to try to read off a unique underlying metaphysical ontology of essences from our physical theories.

Due to its flexibility, a pragmatic revised MRL-account that allows for context-or perspective-dependent multiple best systems fares best in accounting for the features we have discussed. This, however, does not mean that the practice of physics supports a subjectivism about laws. What the laws are, within a certain context of investigation and for a certain domain of phenomena, is not up to us to decide. Moreover, the role of general meta-theoretic symmetry and conservation principles as heuristic guides shows that stressing the disunified character of modeling in physics can also be taken too far. While the laws of physics do not form a single tightly organized axiomatic structure and there exists a multiplicity of frameworks in which laws are justified by their predictive use, consistency, robustness, and relevance in a particular context,[1] general overarching principles nevertheless play an important role in physics and provide some integration of different domains.

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there seems to be no conceptually fully coherent way of applying the theory to discrete charged particles, such as an electron. See M. Frisch (2005) *Inconsistency, Asymmetry, and Non-Locality: A Philosophical Investigation of Classical Electrodynamics* (New York: Oxford University Press) . The reason for this is that the self-field of a charge either leads to infinities (if the charge is modeled as point particle) or the charged particle ought to explode due to repulsive forces among its different parts (if it is modeled as an extended particle). Nevertheless, the Maxwell equations and the Lorentz force law can successfully be used to model the interaction between charged particles and fields in a domain where quantum effects are unimportant.

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