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Dispositions and the Least Action Principle

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Abstract
This work deals with obstacles hindering a metaphysics of laws of nature in terms of dispositions, i.e., of fundamental properties that are causal powers. A recent analysis of the principle of least action has put into question the viability of dispositionalism in the case of classical mechanics, generally seen as the physical theory most easily amenable to a dispositional ontology. Here, a proper consideration of the framework role played by the least action principle within the classical image of the world allows us to build a consistent metaphysics of dispositions as charges of interactions. In doing so we develop a general approach that opens the way towards an ontology of dispositions for fundamental physics also beyond classical mechanics.

Keywords
classical mechanics; dispositionalism; laws of nature; least action principle; scientific metaphysics

1 Introduction

Within the context of scientific (or naturalist) metaphysics, it is usually assumed that the properties defined by our fundamental theories serve as a stepping stone towards a metaphysics of natural laws. In an example that constitutes the main focus of this work, if fundamental properties as described by our best theories are taken to be *dispositions*, and therefore totally specified by their causal profiles, then the laws of nature could be considered to supervene on these fundamental dispositions.

The causal theory of properties is a modern take on dispositionalism originating in the 1980s (see notably Shoemaker 1980 and also Bird 2005, 2007 and Bird et al. 2013). According to this view, fundamental physical properties are dispositions or powers to produce certain specific effects. This view is especially attractive when compounded by current physical theories, as fundamental dispositions can be identified with the charges of fundamental interactions, which are intimately related to the causal explanations that our theories can provide.

To be a disposition would not be a property that certain properties fulfil: in this approach, fundamental properties just are dispositions. To strengthen the proposal one can make the additional assumption that fundamental dispositions are *permanently manifest*, i.e., that no stimulus is necessary to activate a disposition (see Esfeld & Sachse 2011). This allows for a grounding of the laws of nature in terms of causal powers that avoids commitment to the causal efficacy of abstract entities such as ideals, while at the same time providing an answer as to the origin of the regularities described by science.

These virtues notwithstanding, there have been several challenges raised against dispositional views, both from pure metaphysics and from specific scientific theories. One of the most famous metaphysical criticisms to dispositionalism comes from what is known as Moliere's critique: it is not explanatory to state that opium puts people to sleep because it 'has a dormitive virtue'. As Maudlin (2007) points out, in a productive explanation the explanans must be ontologically distinct from the explanandum. Thus, it is usually assumed that there must be something other than the disposition that causally explains its manifestation, or in other words that every disposition must have a distinct 'causal basis'. Another well-known issue with dispositions appears when considering purported different dispositions of the same object that are arguably connected, raising questions about the relations between different dispositions behind the same phenomena (the fragility of glass as opposed to the electrostatic attraction of its molecules, for example).

Nonetheless, when considering the properties characterizing fundamental pieces of matter, it is possible to avoid both of these issues by conceiving 'bare' fundamental dispositions (McKitrick 2003), dispositional properties that are identical to their causal basis and that manifest at the fundamental level of reality. In other words: opium puts people to sleep because it has chemical components that affect certain neurotransmitters in the brain, and this works because of molecular bonding, which works via electrostatic forces of charged particles such as electrons, which have a negative electric charge, which is to act in such-and-such a way when in the proximity of other electric charges. This is the notion of dispositions that seems most suitable for a metaphysics of our fundamental laws, and the one we take in this work.

Perhaps more troubling for the naturalist, there are also criticisms stemming from science. Most notably, quantum mechanics is difficult to combine with a dispositionalist ontology based on intrinsic properties because of phenomena like entanglement, which seems incompatible with the adjudication of intrinsic properties to independent components of matter. Shortly stated, the holistic behaviour we encounter in phenomena such as quantum entanglement implies that at least some physical properties of quantum systems do not supervene on the properties of its component parts (Dorato & Esfeld 2015).

There is little agreement about the metaphysics of quantum mechanics, and in some interpretations of the theory, the difficulties for dispositions can be dissolved (see e.g., Dorato & Esfeld 2010, for such an analysis in the case of the GRW interpretation). However, avoiding quantum systems as too complicated for the task does not totally shield dispositions, as issues have been claimed to exist already within classical mechanics. Namely, there is an ongoing debate in the literature about the compatibility of the Principle of Least Action (PLA)—also known as Hamilton's principle—with a metaphysics of laws as dispositions. In a nutshell, Katzav (2004) rises challenges to a dispositionalist view of laws based on a critical analysis of the PLA (some of Katzav's arguments are reproduced in what follows). Subsequently, Ellis (2005) makes a defence of dispositionalism in response to Katzav's challenges in terms of a 'sophisticated dispositionalism' that takes into account natural kinds of hierarchies. Katzav presents his disagreement with Ellis's arguments in Katzav 2005. Smart & Thébault (2015) take part in the discussion by defending the viability of a dispositions even if admitting the pitfalls in Ellis' defence. More recently, Livanios (2018) highlights that although dispositionalism might respond to Katzav's argument, the compatibility between PLA and dispositions is still not established; whereas Terekhovich (2018) suggests reconciling the PLA with dispositional essentialism based on a modal interpretation of the PLA, assuming that each object's possible history in PLA possesses its own dispositions, which arguably leads to a metaphysics that is too onerous for a naturalist.

In this work we provide a reassessment of this alleged incompatibility, proposing an approach that saves the causal powers behind interactions, and makes them compatible with Hamilton's principle in a metaphysically parsimonious fashion when compared with previous attempts. For this, we exploit a distinction of scientific theories in two separate classes, which following Flores (1999), we call framework and interaction theories. We claim that each kind of theory requires different metaphysical commitments and that therein lays a road for a refined dispositionalism, one that preserves the spirit if not the letter of the causal theory of properties.

The interest in exploring this classical case goes beyond the ongoing debate. By studying classical mechanics one can achieve more conceptual clarity than with quantum mechanics or other modern theories that also lack metaphysical transparency. We argue that our solution, when properly transposed, also allows for a metaphysics of dispositions in more general contexts, something that will be further explored in a separate work.

This article is organised as follows: section 2 discusses the apparent issues between local dispositions and the PLA formalism for classical mechanics. In section 3 we present the framework / interaction classification and its metaphysical implications. In section 4 we present a dispositionalist strategy for the PLA by following the framework / interaction theory divide. We present our conclusions in section 5.

2 Least action principle and dispositions

The PLA states that the dynamics of a physical system is determined by a calculus of variations for a functional, the action, which depends on the behaviour of a single function, the Lagrangian L, which contains all the physical information concerning the system. The action functional along a path $\mathcal{P}$, parametrised as $\mathcal{P}(t) = q(t)$ (with $q(t)$ a generalised position coordinate) computed between times t_0 and t_1, is defined as

$$S[\mathcal{P}, t_0, t_1] = \int_{t0}^{t1} dt\ L(q(t),\ \tfrac{dq}{dt}(t)) \tag{1}$$

The variational problem is then to choose the path along which the action is minimal. It can be shown that this is equivalent to, and allows for the derivation of the classical equations of motion. The way interactions act in this approach is by assigning weights to different trajectories the system could take. The shape these weights take depend on the specific interactions at play in the system.

As Feynman says in his famed lectures on physics (Feynman et al. 2011)

> In other words, the laws of Newton could be stated not in the form $F = ma$ but in the form: the average kinetic energy less the average potential energy [the Lagrangian function, in the case of simple systems] is as little as possible for the path of an object going from one point to another.

The main argument appearing in Katzav (2004) is that the application of the PLA presupposes that the action of any physical system could metaphysically have taken different values. This means that the sequence of states of the physical system would be metaphysically contingent, which in turn would mean that the system cannot have the metaphysical disposition to act in any given way. Thus, the argument goes, massive bodies cannot have the disposition of accelerating towards each other, as there are system paths with non-extreme action where this disposition does not seem to exist.

Another way to describe the same issue is to say that, in non-extremal (and therefore non-actual) paths the properties of mass, charge, etc., do not seem to be identical to the dispositions to attract bodies, repel charges and so on. This would represent a blow for dispositionalism. In Katzav's view, the PLA cannot be grounded in the dispositional properties of objects, which Katzav argues is something that the thesis of dispositionalism requires.

If dispositions fail to provide a consistent metaphysics of natural laws, then two main alternatives exist in the modern literature, each with its own set of issues. The first, as in Maudlin (2007), is to take laws as primitive abstract entities, not analyzable in terms of more fundamental metaphysical categories. These laws would be the producers of physical change, and account for causality in the world. This is a heavy-duty form of primitive modality, which gives causal powers to (something like) platonic universals, and constitutes a strong metaphysical assumption, which can be uncomfortable for naturalists.

On the other extreme we find the Humean approaches, starting with Lewis (1986), and refined in the last years (see Esfeld & Deckert 2017), where there is no place at all for primitive modality. In this view, laws of nature are associated with the theorems of what is known as the best system, the formal system of theories describing phenomena which finds the best balance between simplicity and accuracy. Causality would not actually exist as a relation in the world, there being only regularities that we observe and describe. Humean views have the disadvantage of being too bare bones, having difficulties to differentiate the properties of our fundamental theories—given that these properties are defined by their casual profile. Electric charge is defined by its action on other charges; in a world without causality, the intrinsic nature of electric charge is metaphysically very opaque.

In this context, dispositions seem like an interesting middle way, worthy of being defended. To do that, the road we take in this work is to shield dispositionalism from Katzav's critic by denying that dispositions must ground the PLA. We show that Katzav's claims only work against a certain class of dispositional properties, but not in general. Dispositions that encode causal mechanisms participate in the PLA in an indirect way, and are at work in every one of the paths that are considered when minimising the action. Conversely, dispositional properties that deal with structural constraints, such as e.g. inertial mass, do not escape Katzav's conclusions. This still leaves the door open for dispositions to operate in the world, and for a metaphysics of dispositions for many well-known scientific laws.

In order to ground such a discrimination between different kinds of dispositions, we stand on Flores' distinction of natural laws between two classes. In a nutshell, we claim that dispositions are properties possessed by interacting objects, whereas the PLA is a general framework principle that does not involve objects or dispositions in any way. Before detailing this view, we introduce the classification of fundamental laws which plays a central role for our argument.

3 Framework and interaction theories

The framework / interaction classification was proposed by Flores (1999) as an improvement and generalisation on the classification made by Einstein (1919) between what he originally called principle and constructive theories. Flores claims that Einstein's original characterization includes three different dimensions, namely the epistemic, ontological and functional roles that a theory plays within our scientific image of the world. Flores proposes to focus on the functional role in order to achieve a clear-cut distinction between theories.

Interaction theories describe the behavior of specific interactions between objects in the world, such as would be the case for Maxwell's electrodynamics, while framework theories provide general constraints valid for any interaction, special relativity being a clear example. Classical mechanics as defined by Newton's three laws can also be seen as an example of a framework theory, as the forces that enter these laws play the role of empty placeholders, to be further specified by detailed interaction laws, as would be the case of the law of universal gravitation, or phenomenological force laws.

The functional role serves thus as a key for classifying scientific laws, but the information stemming from the epistemic and ontological roles that different theories play in our scientific picture of the world should not be minimised. In this we follow Romero-Maltrana et al. (2018), who argue that the ontological aspect of the description is useful at the time of assigning ontological commitments to objects and properties in our theories, as interaction laws assume the existence of interacting objects, whereas framework theories are in principle fully structural and compatible with empty worlds. The epistemic facet is also a source of relevant information. Whereas interaction laws explain phenomena in a bottom-up fashion, by means of causal mechanisms, framework laws explain phenomena structurally (see Dorato 2017, Felline 2018).

The distinction is especially fruitful when approached from the perspective of scientific realism, the claim that successful scientific theories must have a certain correspondence with reality. The framework / interaction classification can guide our ontological commitments to the different laws, objects and properties of theories in each class, so that we can better discern which elements of our theories have which kind of correlates in the world.

Consider first the case of interaction theories. These theories explain phenomena in a bottom-up way, by means of causal mechanisms—the 'interactions' at play. What is central for this discussion is that every (fundamental) interaction theory involves a type of charge, a property that induces or generates said interaction. For gravitation this property is mass, for electromagnetism it is electric charge. These interaction charges are defined by their dispositional aspects: an electric charge is defined by the changes it enacts in the behaviour of other charges and so on. When these charges are considered to be dispositions, they convey a transparent metaphysics of causality in the physical world.

Instead of dealing with objects and their properties, framework theories deal with structures. Generally speaking, framework laws are not mechanistic but work as general constraints, in a way reminiscent to the meta-laws of Lange (2007, 2016). There is no causal mechanism behind translation invariance, as there is no causal mechanism behind the speed of light being an absolute speed limit.[1] Because of this, it is trivially the case that dispositions cannot account for frameworks laws: their whole metaphysical role is that of linking the objects in our theories and the chains of causes and effects that we observe in the world. Framework laws lay beyond the scope of dispositions.

As argued above, rejecting dispositions leaves two options for a metaphysics of laws. Framework laws, as in Maudlin (2007), could then be primitive abstract entities. The problem with this view of framework laws is that framework laws do not carry any causal power. They cannot thus play the role that Maudlin assigns to them, that of producers of changes in the configuration of matter. Change in the world is the product of interactions. A Humean approach would then constitute a more natural route for the ontology of framework laws (on this see Hicks 2019). These laws can be considered as emergent regularities, without

[1] Here and throughout we equate causality with *mechanistic* causality, which is the relevant type for scientific explanations (see e.g., Psillos & Ioannidis 2019, Williamson 2011).

primitive modality.

Now, the fact that framework laws and interaction laws carry different modalities does not in principle imply that framework laws have no modal strength whatsoever (see Lange 2016, for a take in which the modality of meta-laws is *stronger* than that of mechanistic laws). The crucial argument for this is to equate physical modality with causation—to deny the need for any further modality on grounds of parsimony. Once causation is accounted for by means of interaction laws, all further general regularities an be regarded as an emergent state of affairs in the Humean spirit. Indeed, scientific observations and theory-testing can only be made by interacting with physical systems (for this see Dretske 1981, Kosso 2012, Shapere 1982) so that any probe into the nature of framework laws can only be indirectly made using interaction laws. To give supra-causal modal strength to such indirectly established laws seems unwarranted within a parsimonious and naturalistic metaphysics.

Conversely, if we take such a Humean stance only with respect to framework laws we avoid to fall into the usual pitfalls of Humeanism. Indeed, issues with the definition and individuation of intrinsic properties without linking them to their causal profile (Lewis 2009) do not appear here, as the fundamental properties are those dispositions associated with our interaction theories, and are indeed defined by their causal profile. These notions are close to—and also flesh out—Demarest's (2017) proposal for a dual metaphysics of laws.

Interaction generating dispositions embedded in Humean frameworks minimize the metaphysical cost of laws of nature, while at the same time preserving a notion of causality and a metaphysical grounding for the regularities described by science within our interaction laws. By sharing the load of a metaphysics of laws between dispositional and Humean approaches for interaction and framework theories we overcome the key issues that each of these approaches has by itself.

4 Hamilton's principle as a framework

In criticising Katzav's work, Smart & Thébault (2015) observe that it is not necessarily the case that the system performs a metaphysical evaluation of possible paths, but that this evaluation can instead only be a logical one. This beckons a framework structure: to give metaphysical weight to the emergent action functional is, in the approach to realism we advocate here, a confusion.

In fact, to conclude that dispositionalism does not work based on the framework of the PLA is a categorical mistake with respect to where is that dispositions reside: if a metaphysics of laws as dispositions is a true description of the world, these dispositions are carried by the objects in the world. These objects, in turn, are best associated to interaction theories, as their dispositions involve their powers to interact.

Otherwise said, dispositions were never supposed to describe the modality of framework laws such as the PLA. The only modality that can be legitimately explained by dispositions is the one associated with causation. There is no causation in framework theories, only structure. The makers of difference and change in our scientific theories are always interactions, mediated in every case by local charges, and structurally constrained in a non-local way.

In the case at hand, dispositions enter the metaphysics of classical mechanics by the interaction theories embedded within the framework of the PLA. The specific interactions at play in each physical system modify the form of the Lagrangian, and thus affect the computation of the action. In this way, dispositions *are active for each and all the paths* in the optimisation procedure that leads to the correct solution for classical movement. Differently put, the weights of the paths in the action functional are all evaluated using the dispositional properties carried by the objects in the system, as encoded in the system-specific Lagrangian function. Dispositions are at play in the PLA every time we actually use it.

Meanwhile, properties associated with the framework of classical mechanics, such as the inertial mass, cannot be assigned causal powers and therefore are not to be seen as dispositional. Inertial movement is a structural (in this case geometrical) property that is not localised within matter but can be considered instead a property of space and time themselves. One could imagine such global structural properties as some kind of global noncausal dispositions (such as in Bigelow et al. 1992), but this is once again heavy metaphysical machinery that does not seem justified from our best science.

Instead, adopting a Humean posture with respect to non-causal modality, the quantities related with framework laws (such as inertial mass, or kinetic energy) are always to be considered as relational, emergent properties (Benitez et al. 2022). They are not located in the individual objects that constitute matter but are assigned to them based on the relations into which they enter. Within the PLA formalism, the action functional defines the energetic cost of the different possible paths the system could take. To follow the path of least action is nothing more than the inertial movement of matter, once we consider how interactions between different physical objects modify their definition of shortest path.

By taking seriously the distinction of laws of nature between frameworks and interactions we can find an answer to Katzav's challenge. Katzav (2004) concludes by stating:

> This is not to say that we ought to reject dispositionalism. Whether we ought to do so depends, among other things, on our view of the PLA itself. We might, for example, try to maintain dispositionalism by combining an instrumentalist view of the PLA with a realist view of equations of motion. (2004: 214)

Our approach justifies something akin to this stance, while still being compatible with scientific realism. By adopting a half-Humean, half-dispositional approach to the laws of nature we are able to have our metaphysical cake and eat it too.

5 Conclusions

In this work we show how the principle of least action is compatible with a metaphysics of dispositions, once we account for the separation of the elements of our physical theories into those that directly model interactions and those that describe general frameworks valid for every interaction. The framework of the principle of least action only provides a complete description of a classical physical system when it is applied to a specific Lagrangian functional, which depends on the interactions at play. These interaction are governed by specific interaction laws embedded within the framework of classical mechanics.

It is in these specific interactions laws that dispositions can play a central role. The charges associated with our fundamental interaction theories are compatible with a metaphysics of dispositions in a permanent state of manifestation, dispositions that are identical to the interaction charges in the property-instantiation sense.

In our approach, only interaction laws are dispositional. From this point of view, the framework Hamilton's principle is either a brute fact about our world or an emergent law in the Humean sense of a best system explanation—a regularity with no modal weight. This poses no problem for scientific explanations: causal explanations are governed by interaction theories, whereas framework theories provide structural / unificationist explanations. We only need to give room to causal mechanisms in our metaphysics for theories in the former group, something which dispositions accomplish by construction.

Our approach is general: the framework / interaction distinction transverses fundamental physics, including quantum mechanics, a theory that has also been proposed as incompatible with dispositionalism. In the same way as the principle of least action, quantum mechanics is a framework which is empty until interactions are explicitly included, as would be the case of the electromagnetic interaction when considering atomic physics.

We believe our approach constitutes real progress in the metaphysics of laws of nature. In future works we plan to extend it to the analysis of state-of-the-art fundamental science.

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