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Why metrical properties are not powers

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Abstract What has the dispositional analysis of properties and laws (e.g. Molnar, Powers, Oxford University Press, Oxford, 2003; Mumford, Laws in nature, Routledge, London, 2004; Bird, Nature's metaphysics, Clarendon Press, Oxford, 2007) to offer to the scientific understanding of physical properties?—The article provides an answer to this question for the case of spacetime points and their metrical properties in General Relativity. The analysis shows that metrical properties are not 'powers', i.e. they cannot be understood as producing the effects of spacetime on matter with metaphysical necessity. Instead they possess categorical characteristics which, in connection with specific laws, explain those effects. Thus, the properties of spacetime do not favor the metaphysics of powers with respect to properties and laws.

Keywords Dispositions · Powers · Metrical properties · General relativity · Spacetime points · Laws

1 Introduction

In metaphysical theories of dispositions (e.g. Molnar 2003; Mumford 2004; Bird 2007) it is commonly assumed that fundamental properties of physics are paradigmatic examples of dispositions in nature. Dispositions, on the basis of their local and causal (and thus productive) nature, are thought to be suitable truth-makers for law statements (Bird 2007) or even *Ersatz-entities* suited to occupy the place that has traditionally been assigned to the supposed 'laws of nature' (Mumford 2004). Now, if there were no dispositions at the basic levels of physics, then this would largely undermine the plausibility of the claim that properties of nature can be analyzed as dispositions.

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Since spacetime points are, according to General Relativity, absolutely basic entities which are not composed of any other more fundamental constituents, there should be a dispositional analysis of their characteristic metrical properties which is at least compatible with spacetime physics. I shall argue that metrical properties of spacetime points, according to General Relativity, are indeed local and causal (and thus productive) properties, and thus possess dispositional character (Sects. 4 and 5). But they cannot be conceived of as 'powers', i.e. they do not cause their gravitational effects on matter with metaphysical necessity (Sect. 6). Instead they are grounded in a categorical basis that, in connection with contingent laws, explains those effects. Therefore, the case of spacetime points supports neutral monism of dispositions proposed in Mumford (1998), but fails to exemplify any theory of powers, either in the version of dispositional essentialism (Bird 2007) or in the version of elementary modal properties (Mumford 2004). The metrical properties of spacetime points do not determine the dynamical laws, according to which they interact with matter; thus the laws cannot be *reduced* to the metrical properties. Laws of nature stand out against a background of physical possibilities, hence they are contingent. But this fact does not rule out the possibility to give dispositional analyses of their content (Sect. 7).

2 Is the physical world based on powers: a quick answer?

On the face of it, fundamental properties of physics like charge, gravitational mass, spin, or the metrical properties of spacetime points seem to be individuated by causal dispositions. The charge of a particle, for instance, may be characterized as its ability to produce an electromagnetic field around itself. On the other hand, there are many such causal dispositions connected to charge, for instance, the ability of free charges to 'react' by acceleration to a change of the magnetic field in their surroundings. Thus, there is a multitude of dispositions or powers connected to a physical property like charge. We then probably have to admit that the property is to be identified with a cluster of powers (Mumford 2004, p. 173). This, at once, leads to the problem that each possible kind of causal manifestation of a property may be taken as being grounded in a different power.[1]

Furthermore, there are characteristics of charge that have nothing to do with causal dispositions, for instance, the fact that a charge of classical electrodynamics is represented by a scalar, not by a vector. Such a mathematical and categorical characteristic is as much an 'essential' one as the causal characteristics of the property. Thus, it seems that the case for the dispositional nature of charge cannot be easily decided to the positive. To the contrary, charge seems to be partly characterized by causal dispositions and partly in a categorical way. I shall not follow this example further, but will be content with the result that the dispositional nature of physical properties cannot

[1] Mumford (2004, p. 172) thinks that fundamental physical properties entail a single power. But examples like charge and mass raise doubts that one single power could provide for the different sorts of manifestations of these properties. Concerning 'higher-level' properties, Mumford proposes to reduce the multitude of powers constituting them by identifying causal manifestations that can be conceived of as tests of a single power. But there seems to be no clear-cut criterion distinguishing the case of different tests for a single power from the case where manifestations of different powers occur.

be disclosed by a surface analysis. In the following, I focus on the metrical properties of spacetime points and discuss (a) whether metrical properties are dispositions and (b) what concept of disposition they may exemplify.

3 The dynamical nature of spacetime

It is a common view that spacetime plays a dynamical role in General Relativity. The principle of covariance forbids *absolute objects* (Anderson 1967, 191f.; Friedman 1983, p. 214), i.e. objects not interacting causally with other objects. Spacetime points therefore have to be characterized exclusively by their metrical properties determining how they interact with matter, and not by any other causally inert intrinsic properties.[2] This suggests that spacetime structure which has been paradigmatic for categorical properties within classical physics, must be conceived of as causal and dispositional in General Relativity. For instance, Bird claims that:

> Each spacetime point is characterized by its dynamical properties, i.e. its dispositions to affect the kinetic properties of an object at that point, captured in the gravitational field tensor at that point. The mass of each object is its disposition to change the curvature of spacetime, that is to change the dynamical properties of each spacetime point. Hence all the relevant explanatory properties in this set-up may be characterized dispositionally.[3]

The inertial motion of physical bodies seems to confirm the dispositional nature of spacetime. Water drops are stretched in vertical direction and compressed in horizontal direction during free fall as a result of the activity of tidal forces occurring in an inhomogeneous gravitational field.[4] These empirical facts clearly seem to support the view that spacetime causally acts on physical objects.[5]

But is the dynamical behavior of the metrical field really causal? Probably it is sufficient to describe the observed deformation of water drops in the gravitational field as the total result of the changes of relative displacement between the trajectories of the material points of the drop. As a result of their geodesic motion the distances between the points change in such a way that the drop takes on ellipsoid shape. It depends on the concept of causality employed whether the free fall of the drop counts as a

2 In the 'Lochbetrachtung' in 1913 Einstein had become aware that the covariance principle was not compatible with the Mach-principle, according to which the distribution of matter should uniquely determine spacetime structure. The metrical structures can be shifted against a background of spacetime points, such that the theory cannot determine which metrical properties have to be ascribed to which spacetime point. After a period of despair, Einstein finally found the solution in 1915. It has been a mistake, Einstein recognized, to conceive of metrical structure as something that can be shifted against a background of spacetime points. The physical points have no identity independently from the metrical structure. They are nothing else but occurrences of specific values of the metric—constituents of a particular physical field, the metrical field.

3 Bird (2007, p. 166). A causal, dispositional view of the properties of spacetime points has also been proposed by Esfeld (2009).

4 cf., for instance, Ohanian (1976, p. 34).

5 Other evidence for the independent causal role of spacetime is the existence of vacuum solutions of the field equations, demonstrating that the geodesic structure exists autonomously.

causal or a non-causal process.[6] I shall postpone this point to Sect. 5, where it will be discussed whether the metrical properties of spacetime points are really dispositional properties. In the following, I shall use a rather naïve concept of causality assuming that the metrical properties of spacetime as occurring in the geodesic structure are indeed causal properties.

4 Are metrical properties local properties?

In Newtonian spacetime metrical properties are relational and categorical properties of manifold points. A spacetime point p has its distance from another point q *not independently* from the existence of q, even if it is possible to *ascribe* the property of being in a distance d from q to p.[7] In the Riemannian metric of General Relativity, things are different. The metric tensor at a point p is defined for an *infinitesimal* neighbourhood of that point, and it is thus not identical with the classical relational property determining the distance structure between finitely distant points. Instead, it is defined by a bilinear real-valued function on the tangential space determining the length of each tangent vector of the tangential space.[8] Lam and Esfeld (manuscript, forthcoming) claim that "since it involves infinitesimally neighbouring points through the notion of tangent space on which it is defined, the metric tensor should be conceived as an extrinsic or relational but local property." Since I do not argue here for or against some notion of 'intrinsic' as opposed to 'extrinsic', I accept the foregoing characterization of the metric tensor as representing an 'extrinsic' property. What is far more important with respect to the dispositional character of the metric is whether the metric tensor represents a *local* property. About this point, I agree with Lam and Esfeld, that the metric tensor is indeed a local property, following the definition of 'local' as given by Butterfield (2006): "… a mathematical object (structure) is local if it is associated with a point by being determined (defined) by the mathematical structures defined on any neighbourhood, no matter how small, of the point."[9] Indeed, the metric tensor at point p is determined by the metric field in any arbitrarily small neighbourhood of p.

The local character of the metric tensor implies that the metrical properties at some point p can be spatiotemporally separated from the metrical properties at any finitely distant point q; it is always possible to find mutually non-overlapping neighbourhoods of p and q such that the metrical properties of p and q are completely defined by the metric field on these neighbourhoods. Thus, the metrical properties at p do not counterfactually depend on the metrical properties at q, except by possible causal signals

[6] For instance, according to a transfer concept of causality (cf. Dowe 2000), the process should count as a causal one. The gravitational field has energy content and it transfers some amount of energy to the drop which is consumed as deformation energy. The problem is that, in general, there exists no definite covariant expression for the energy content of the gravitational field (Misner et al. 1973, 969ff.). Thus, the case for a causal interpretation according to the transfer theory can only be made precise for highly idealized situations (cf. Bondi et al. 1962).

[7] cf. Esfeld (2008, p. 179).

[8] cf. Friedman (1983, 40f.).

[9] Butterfield (2006, p. 187).

connecting p and q. The metrical properties of Riemannian spacetime thus fulfill the *locality* requirement for dispositional properties.

5 Are metrical properties causal properties?

The Riemannian curvature tensor follows directly from the metric tensor und its first and second derivatives. It is local in the same sense as the metric tensor itself.[10] Since it expresses the contribution of a spacetime point for the measurable tidal forces which are, according to the received view, causal effects of the metric field, it seems to be natural to conceive the Riemann tensor as representing 'causal properties': It expresses dispositions of spacetime points manifesting themselves in (contributions to) measurable local forces. Instead of speaking of curvature (or tidal force) properties of spacetime points in addition to their metrical properties, it is more convenient to ascribe to spacetime points only one sort of properties, namely the metrical properties. By determining the curvature properties, metrical properties, then, would be causal properties manifesting themselves through the occurrence of tidal forces.

There are two sorts of general objections against the claim that metrical properties of spacetime points play a causal role. Livanios (2008), for example, has argued that the field equations of General Relativity do not describe how matter distribution co-varies with spacetime structure within one world, but how matter distribution and spacetime structure correspond to each other across worlds.[11] Thus, changing the matter distribution does not bring about a change in spacetime structure within the same world, but represents another possible world. The answer to this objection is that the field equations can be used indeed to describe local variations in matter distribution, as for instance the gravitational collapse of a massive star, which leads to drastic changes in the local spacetime structure. Livanios' second objection is that "even granting that matter brings about certain changes in spacetime structure … spacetime does not *causally* affect material bodies".[12] The reason for this objection is, according to Livanios, that the affection of matter by spacetime is mediated by metrical (or affine) structure, not by forces which are the paradigmatic causes in classical physics. The answer to this objection is that, in General Relativity, metrical (affine) structure is the means by which the gravitational field couples to matter. Spacetime affects matter not by means of classical forces, but by means of its metrical (and affine) structure which brings about tidal forces producing paradigmatic causal effects like spatial deformations of material bodies.

Thus, the claim maintaining a causally active role of metrical properties can be defended against general objections (what precise notion of causation may capture this causal role will be discussed in the second part of this section).

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10 The components of the curvature tensor are, in contrast to the components of the metric tensor, measurable quantities—just as the electric and magnetic field strength in electrodynamics are measurable quantities, while the vector potential is not measurable.

11 cf. Livanios (2008, p. 389).

12 cf. Livanios (2008, p. 389).

According to Mumford (1998, p. 135) properties are dispositional if they are characterized by their playing a specific causal role. The metrical properties of space–time points are, according to that view, dispositional, because they play a specific causal role by contributing to the tidal forces in a region of space–time. In particular, they are dispositional properties of a kind which does not need any stimuli in order to produce their manifestations. Tidal forces also occur in vacuum solutions with their well defined geodesic structure although there are no test particles in such solutions *by definition*. The dispositional character of metrical properties can thus be expressed following Bird (1998, p. 233)[13] (as explained before, stimuli can be omitted):
The metrical property g of a spacetime point p is a dispositional property because

(i) g is a local[14] property of p
(ii) g is a p-complete cause of G (tidal forces)

The p-completeness of g means that g entails all of the local properties which contribute to G.

The foregoing argumentation was based on some common intuitive notion of 'cause' and 'causation'. Is there any more precise notion of causality, according to which causal and thus dispositional status could be ascribed to metrical properties?

As I have already mentioned in Sect. 3 (Footnote 6), the ontological transfer approach to causation cannot be made precise for gravitational field/matter interaction. Thus, I switch to an epistemic theory of causation, the counterfactual approach proposed by Woodward (2000, 2005). As we will see in the following, this is no 'second choice', because it will provide us with a transparent frame for evaluating the modal status of the causal relation between g and G.

Causal relations, according to Woodward's counterfactual approach, are patterns of counterfactual dependence, where the counterfactual variation takes place for variables which appear in some invariant generalization (cf. Woodward 2000). For the special case, in which the place of the invariant generalization is occupied by a law of nature, this approach comes out to turn into the older logical-empiricist *nomological dependence* conception of causal explanation. The nomological dependence approach has its notorious shortcomings. For instance, it provides a causal interpretation for the EPR-correlations and for cases in which physical variables are instantaneously dependent on each other. But since General Relativity neither confronts us with instantaneous dependencies nor with non-local correlations we can hope not to run into any of these shortcomings here.

Woodward's counterfactual approach can be applied to the relation between the metric g and the tidal forces G in the following way: The relation between g and G in standard General Relativity is determined by a special choice of the affine structure on the semi-Riemannian manifold, and this choice is represented by the 'geodesic

[13] This definition goes back to Lewis' 'reformed conditional analysis', in which the stimulus S has been omitted. Since the metric is an essential property of spacetime points, and the production of a gravitational field cannot be shielded by any other forces, problems with either a loss of the metrical property during the causal process as a result of finkish influences, or with 'antidotes' which could prevent the manifestation of the causal property, can be left aside as irrelevant in our case.

[14] In contrast to Bird's definition, the notion of "local" substitutes Bird's "intrinsic". I have discussed in Sect. 4 why this replacement is reasonable in the case of metrical properties.

hypothesis' that constitutes a part of the field equations of General Relativity requiring the 'compatibility' of the affine structure with the metrical structure.[15]

The affine structure represents the trajectories of particles in free fall. These paths of particles are observable, independent of any metrical structures. Now, General Relativity connects these independent structures, the affine and the metrical structure, by means of the geodesic hypothesis: "What GR does is to identify these physical paths with geodesics. But the class of geodesics, on the contrary, does depend entirely on the choice of geometry. Therefore, what the geodesic hypothesis does is to select out of the infinitely many possible geometric manifolds that particular one whose geodesics coincide exactly with the world lines of freely falling test particles, and to proclaim this is the real geometry of the space–time region."[16]

In mathematical terms, the affine connection determines how vectors change when shifted along a curve in the manifold; in particular, the connection determines what it means that a vector remains self-identical along a curve. The affine structure is then given by the class of curves for which it is true that the tangential vector at some point of a curve remains to be a tangential vector at every point of that curve if it is shifted along the curve in a self-identical way. The affine structure for the semi-Riemannian manifold of General Relativity is selected by its property that the curves characterizing the affine connection are, at the same time, geodesics in the metrical sense (timelike geodesics are extremal in the class of timelike curves, spacelike geodesics are extremal in the class of spacelike curves).

As mentioned before, the choice of this particular compatible affine connection represents a fundamental law of the theory. This law is the basis of the counterfactual dependence between g and G which is taken as defining the causal relation between g and G according to Woodward's approach: If the value of g would not have been the actual value, then G would not have its actual structure.

Since the production of tidal forces depends on the form of the affine connection, the occurrence of a certain metric tensor g at a spacetime point p cannot, therefore, by itself be sufficient for the production of certain tidal forces. Other choices with respect to the affine connection (for instance the choice of a non-symmetrical affine connection) would lead to other tidal forces and other observable phenomena in general. Therefore, the metrical properties do *not* produce certain tidal forces with metaphysical necessity; it depends on the chosen affine connection what tidal forces are actually produced by a certain metric tensor.[17] The only way open for the claim of a metaphysically necessary status for the causal relation between g and G would be to require a metaphysically necessary status for the geodesic hypothesis itself.

[15] cf. Friedman (1983, p. 180). This compatibility requirement can also be expressed by the condition that the covariant derivation of the metric tensor vanishes identically.

[16] Graves (1971, p. 171).

[17] The friend of powers could object in the following way: Metrical properties are powers playing a *generic* causal role for the tidal forces, whereas the determinate form of the tidal force field depends on contingent laws. But the claim defended in this article is not that metrical properties do not play a causal role; they are indeed dispositions for producing the tidal forces. The claim is, rather, that they are not powers, i.e. that their producing of these forces depends on contingent laws. I think that Hume was right when saying in the *Treatise* that powers, if they exist, have to *determine* their manifestations.

A possible objection is lurking here: There are conceptions of properties as powers in the literature attempting to do without metaphysical necessity (e.g. Handfield 2008; Schrenk 2010; Anjum and Mumford 2011). Could metrical properties not be construed according to such recipes as powers that act without metaphysical necessity?

Firstly, the main reason to be found in Schrenk (2010) and Anjum and Mumford (2011) for believing that powers fail to act with metaphysical necessity is the possible existence of antidotes which prevent or diminish the full production of a power's manifestation. Anjum and Mumford's example is the wind that 'selects the possibility' to blow us over—but we can resist the wind's power.[18] Now, in the case of metrical properties, the power producing a certain affine field cannot be resisted. True, a material body can be urged to deviate from geodesic motion by non-gravitational forces, but as long as the affine field and its tidal forces are concerned, there are no additional causes that could prevent their determinate production by the metric field (given the geodesic hypothesis). Thus, if metrical properties were powers, then there would be no particular reason to doubt that they act with metaphysical necessity.

Secondly, even if it is assumed that fundamental physical properties are powers acting without metaphysical necessity, the friend of powers has to concede that under ideal circumstances (in which additional forces are absent) those powers would produce their effects just by virtue of being that particular power (for instance the power of active gravitational mass in a material body would produce, under ideal circumstances, a determinate gravitational attraction upon some other body just by virtue of being that particular power). It is exactly this claim, I argue against in this article. Metrical properties produce their effects, under all circumstances, only in connection with a law, the geodesic hypothesis.

To summarize what has become clear about the status of the relation between g and G up to this point: The relation is a causal one, according to a counterfactual dependence approach to causality. Whether this causal relation has a contingent or necessary metaphysical status depends on the metaphysical status which is attached to the mediating law, the geodesic hypothesis. If the law is contingent, then it mediates a contingent causal relation, i.e. a relation that would not hold in every possible world in which the particular metric occurs. In that case the metric would have a dispositional nature which is *grounded* in categorical features that determine, together with a contingent law, its actual world manifestations (the tidal forces). If the law is necessary, i.e. if it ascribes a *power* to the metrical properties to produce a certain affine structure, and thus determined tidal forces, then the causal relation is a metaphysically necessary one, i.e. the metric produces the same tidal forces that occur in the actual world in every possible world in which it occurs itself. In that case, the metrical disposition of a spacetime point would be pure or 'ungrounded'[19] and the geodesic hypothesis would itself be 'contained' in this disposition.

[18] Anjum and Mumford (2011, p. 392).

[19] cf. Mumford (1998, 167f.); Mumford (2004, 2006).

6 The categorical base of metrical properties

There are three possible competing conceptions of dispositional properties in general and of the dispositional character of metrical properties in particular. According to the first one, a dispositional property possesses its dispositional character *essentially* (i.e. for something having this property is to have this dispositional character), to the effect that systems having the property produce the manifestation of the disposition in every possible world (i.e. with metaphysical necessity). There might be also categorical features applying to the dispositional property, but these features are not relevant for explaining its dispositional character and thus do not 'ground' the dispositional property. Dispositional properties of this sort are called 'ungrounded dispositions'. According to the second one, a dispositional property has also non-dispositional features, which are not by themselves, but in connection with some laws, sufficient to produce the manifestation of the disposition. Dispositional properties of this sort are 'grounded' in their categorical features, but these categorical features do not constitute a 'causal base' distinct from the disposition. In contrast, dispositional and categorical features apply to the very same property (this is the claim of 'property monism'[20]). The third conception is the classical empiricist notion ('property dualism'), according to which the categorical features constitute a 'categorical base' distinct from the disposition.[21]

The question is now: Are metrical properties 'ungrounded' dispositions (dispositions of the first variety), or are they 'grounded' in categorical features according to either the second or the third notion of dispositional properties?

The answer clearly is that metrical properties are 'grounded' in categorical features—and I opt for the second, the property monist, way of understanding this fact. To be a measure for the length of tangent vectors of a tangential space is a mathematical feature which is conceptually connected neither with a certain affine structure nor with certain causal roles, in particular with the role of producing tidal forces. But at least some of those mathematical features of the metric tensor describe relevant *physical* properties of spacetime. For instance, it is a feature of the semi-Riemannian metric tensor that a coordinate system can be introduced in which locally the metric tensor is diagonal. In that representation one of the four diagonal elements will have a sign different from that of the other three.[22] This feature depicts the physical distinctness of space and time (ds^2 will be positive if the interval is spacelike, and negative if it is timelike). Thus, according to the definition proposed in Mumford (1998), the metric tensor represents physical properties that can be characterized by a categorical ascription:

> Disposition ascriptions are ascriptions of properties that occupy a particular functional role as a matter of conceptual necessity and have particular shape or structure characterizations only a posteriori. Categorical ascriptions are

20 cf. Mumford (1998, Chap. 7).

21 cf. Prior et al. (1982).

22 cf. Graves (1971, p. 157).

> ascriptions of shapes and structures which have particular functional roles only a posteriori.[23]

Following Mumford's neutral monism in Mumford (1998) concerning the duality of categorical and dispositional features, if we stick to the mathematical definition of the metric tensor, we ascribe (physical) metrical properties in a categorical way, while if we characterize metrical properties by their capacity to determine tidal forces, we characterize them by their causal role, and thus as dispositions.[24] If the relation between categorical and dispositional features is conceived in this way, then the disintegration of physical properties into their categorical and dispositional part is avoided. The metrical properties, for instance, do not split into a categorical and a dispositional part. Instead, what they are can be described in a categorical and in a dispositional way. The metric is categorical *and* dispositional, but this is not, because two different sorts of properties occur in conjunction, but because it can be described in two different ways.

The existence of a categorical base for metrical properties clearly does not involve the existence of some other more basic properties of spacetime points, on which base the metric emerges. Neither are spacetime points, according to General Relativity, complex entities that can be analyzed into more fundamental constituents, such that the metrical properties of spacetime points would be reducible to properties of those constituents. Rather, metrical properties have a categorical base in the sense that their physical realization involves the instantiation of their categorical (mathematical) characterization. They possess a categorical base, but they are not distinct from that base.[25]

Mumford's contention, in his later work (2004, 2006), that simple entities of physics (elementary particles, spacetime points) exemplify what he then calls ungrounded dispositions, seems to rest on his ignoring the distinction just established. Consider, for instance, his claim:

> …what of dispositions which allegedly have no categorical base? These, ungrounded' dispositions are commonly understood to be the fundamental powers of subatomic particles which … have a causal role but nothing which causes them to behave the way they do … There is no explanation of why they possess their dispositions; no underlying categorical explanation. They are more like powers in the old-fashioned sense ….[26]

The assumption, according to which properties of entities without an internal structure must be exemplifications of ungrounded dispositions, is a result of one-sidedness with respect to such cases in which the categorical base of some entities' properties is given by the properties of its micro-constituents. The causal role of charge, spin, the metric and other fundamental properties of physics, can indeed not be explained by recourse to some properties of possible micro-constituents. But, as argued before, the micro-constituents-model is not the only way to understand how some property can have a categorical base. There are categorical characterizations of fundamen-

[23] Mumford (1998, p. 77).

[24] cf. Mumford (1998, Chap. 7: property monism).

[25] Mumford (1998, p. 144).

[26] Mumford (1998, pp. 167–168).

tal physical properties that apply by virtue of the fact that these physical properties realize the mathematical structure of those characterizations and which have important explanatory import for the understanding of the causal roles of those properties. Metrical properties are an example of properties being categorical and dispositional at the same time.

7 Laws: contingency and dispositional analysis

The foregoing discussion has shown that a metaphysics endowing spacetime points with elementary metrical powers producing their causal effects with metaphysical necessity is not supported by the way General Relativity represents metrical properties. Metrical properties of spacetime points have a categorical basis, and their categorical basis is connected to their dispositional nature (the affine structure and the tidal forces) by means of the geodesic hypothesis. This law is *contingent* in the sense that its particular form is not necessary relative to a given metric tensor.

Similar considerations would apply to other favored examples used by metaphysicians of dispositions. It is also true for charge, mass and other fundamental physical properties that there is a categorical base, constituted by their mathematical characteristics fixing their identity within some physical theory. Each occurrence of those properties must be an instantiation of its respective categorical base. Their *dispositional* characteristics are then explained by means of contingent laws which specify how the categorical base is connected to dynamical relations.

The intuition that laws are contingent, in my view and contrary to Bird, is not grounded in the epistemic facts that “we can imagine the laws of nature to be otherwise” and that laws “come to be known a posteriori”.[27] The main reason for the contingency of laws is, instead, a *methodological* one: Natural properties are represented in physical theories by mathematical descriptions which do not uniquely determine the dynamical laws in which they figure. This is evidenced by the occurrence of coupling parameters[28] between law-like connected dynamical quantities the numerical values of which have to be *empirically* determined. At least those worlds that differ from the actual world solely by the numerical values of such parameters are treated in physics as *physical possibilities*. Since this methodological presupposition has a solid place in physics, it should be respected by a metaphysics that intends to be compatible with physics. Hence, these physical possibilities should also count as representing metaphysically possible worlds.

[27] cf. Bird (2007, p. 171). The example of ‘water = H_2O’ shows that, on the condition that Kripke’s theory of necessary identities is acceptable, both facts would indeed by themselves give no reason to believe that laws are contingent.

[28] This is also the case for the coupling between the metrical field and the affine connection. In standard General Relativity the chosen coupling determines that the length of vectors is not changed by parallel transport along a geodesic. Another physical possibility has been realized in Weyl’s unified theory of gravitational and electromagnetic field by making the length of vectors in parallel transport changeable. This possibility was later on eliminated for empirical reasons.

If it is accepted that fundamental laws like the law of affine connection cannot be reduced to fundamental dispositional properties, then this might be understood to imply a complete rejection of any dispositional analysis of laws of nature. But this impression is spurious. Galileo's law of free fall, for example, can be analyzed as describing a disposition of material bodies for free fall behavior. But this analysis should not imply that this disposition is supplied with the status of a *power* producing the free fall behavior described in Galileo's law with metaphysical necessity (what would make the law itself necessary relative to this disposition). Instead, the disposition is contingent relative to the bodies and their properties, since only the law itself determines how they couple to the gravitational field of the earth.

Galileo's law has been corrected by a more fundamental theory, Newton's theory of gravitation that entails a dynamical understanding of gravitational and inertial mass as the relevant properties of bodies determining their free fall behavior. In connection with this more fundamental law, the categorical ascription of gravitational and inertial mass then leads to an improved description of the free fall dispositions of bodies. Thus, a dispositional analysis of laws is compatible with the contingent status of laws, as far as the dispositions to which the analysis refers are not conceived as powers.

The same applies to the case discussed in this article: The geodesic hypothesis cannot be *reduced* to the (dispositionally understood) metrical properties. But it can be analyzed as *expressing* the dispositional nature of the (categorically ascribed) metrical properties.

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