Constructive theories and explanation by structural necessitation

Abstract

Einstein famously distinguished between constructive and principle theories. He believed only the former to be explanatory. Lange has recently argued that principle theories explain, too, by virtue of putting necessary constraints on the laws of physics. In this paper, I want to draw attention to the fact that constructive theories also offer explanations in terms of necessities: they represent contingent regularities as necessities. I call this feature 'structural necessitation' and the understanding afforded by it 'how-necessarily' understanding. In contrast to the necessities of Lange's explanations by constraint, structural necessitation can be brought about by causal mechanisms.

1 Introduction

Einstein, in a letter to the London *Times* in 1919, famously drew a distinction between two kinds of theories: constructive and principle theories. Constructive theories, according to Einstein, "attempt to build up a picture of the more complex phenomena out of the materials of a relatively simple formal scheme from which they start" (Einstein 1993/1932, 167-168). Principle theories, on the other hand, seek to deduce "necessary connections, which separate events have to satisfy" from "general characteristics [or principles] of natural processes", whereby these principles, in contrast to constructive theories, are "not hypothetically constructed but empirically discovered ones" (ibid.; added emphasis). Even though Einstein classified his own special theory of relativity as a principle theory, he characterized constructive theories as the "most important class of theories" and claimed that "when we say that we have succeeded in understanding a group of natural processes, we *invariably* mean that a constructive theory has been found which covers the processes in question" (ibid.; added emphasis).[1] Given Einstein's examples of constructive and principle theories (the kinetic theory of gases and classical thermodynamics, respectively), constructive theories have also been described as postulating models about the

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[1] Frisch (2005) points out that H. Lorentz made the relevant distinction already in 1900. In fact, it was made even much earlier than that by the physicist W. J. Rankine, who distinguished between hypothetical and 'abstractive' theories (Rankine 1855).

microphysical reality behind the phenomena (Balashov and Janssen 2003). Principle theories, which Einstein praised for their "logical perfection and security of the foundations" (Einstein 1993/1932), do not just describe the phenomena. Instead, a principle like the second law of thermodynamics, which postulates the impossibility of perpetual motion machines, Einstein treated as antecedently true and firmly believed that it "will never be overthrown" (cf. Klein 1967, Einstein 1993/1932).

Einstein's distinction has recently been hotly debated in the context of whether Einstein's special theory of relativity really explains the relativistic phenomena of length contraction and time-dilation. Taking Einstein's own classification of his theory as a principle theory for granted, Brown (2005) and Brown and Pooley (2006) deny this and suggest that an explanatorily more complete (constructive) theory will eventually have to explain why objects obey the Lorentz invariance of the dynamical laws in terms of objects' microproperties. Balashov and Janssen (2003) and Janssen (2009), on the other hand, believe that the special theory of relativity *already* provides a constructive explanation in terms of Minkowski spacetime; they reject Brown's view that the cause of a body's inertia remains unexplained within special relativity. Janssen (2009) also rejects Brown's assertion that Minkowski spacetime must be interpreted as an ontologically autonomous entity (a view also known as substantivalism) for it to qualify as a constructive theory. Frisch (2011) argues that much of the disagreement between the two sides of the debate turns out to be unsubstantial, once principle theories are understood to explain in virtue of constraining other laws.[2] The idea of explanation by constraint Frisch borrows from Lange (2007, 2011), who cashed out this idea in detail in his book *Because without Cause* (Lange 2016).[3]

The purpose of this paper is to shed further light on the prinicple / constructive theory distinction, and particularly on the kinds of explanations afforded by constructive theories. Although the motivation for the discussion of this paper springs partially from the just mentioned discussions concerning the explantory power of special relativity, the full consequences for this debate will have to spelt out elsewhere.

The structure of this paper is as follows. In Section 2, I will briefly review Lange's case for the explanatory power of principle theories in virtue of their provision of *necessary* constraints. In Section 3, I will argue that an important aspect of the explanatory power of Einstein's favorite example of a constructive theory, namely the kinetic theory of gases, is

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[2] In order to make this point, Frisch invokes a distinction by H. Lorentz (cf. fn. 1). Yet, contrary to what Frisch claims, Einstein's principle theories are not to be equated with being based on merely phenomenological regularities. See e.g. Flores (1999).

[3] For further discussion of the explanatory power of the special theory of relativity and Einstein's distinction see also Acuña (2016) and references therein.

its representation of empirical regularities as necessities. Thus, not only principle theories explain via necessity (if Lange is right), but explanation via necessity is also an important element of how constructive theories explain. I call this aspect of the explanation afforded by constructive theories *structural necessitation*. In Section 4, I will elaborate this notion and will provide further examples of constructive theories that explain by necessity. In Section 5, I will compare the necessities afforded by constructive theories to the necessities of principle theories. Section 6 concludes the paper.

2 How principle theories might explain

Lange (2016) has argued that principle theories, contrary to Einstein and those who have followed him in his characterisation, are explanatory after all. In particular, Lange has argued that principle theories explain by providing constraints for other laws of nature.

Lange's preferred example of an explanation by constraint is inspired by remarks by R. Feynman and concerns the explanation of why various force laws conserve energy. Why do electrical and gravitational forces, despite their different range, different strength and different objects they apply to, all conserve energy? Either this is a mere coincidence, or the forces all conserve energy *because* they obey the principle of conservation of energy. That is, either the forces conserve energy because *each* of the force laws *separatly* requires them to do so, for separate reasons, or those two kinds of interactions conserve energy *for the same reason*: because energy conservation requires them to do so (49-50). Another way of putting this point is in terms of 'explanatory priority': if it was a mere coincidence that various force laws conserved energy, then the various force laws would be explanatorily prior because they would be "partly responsible for its holding" (50). On the other hand, if energy conservation is prior to the force laws, it constrains *all* of them to have a certain feature (namely energy conservation), even though energy conservation does not entail any of the particular force laws there happen to be (50). Although Lange states that he does not want to committ to either view, he maintains that much of what scientists say does suggest that they view principles like energy conservation not as coincidences but as constraints (46).

For Lange, explanations by constraints are thoroughly non-causal: there is nothing about the forces themselves that would cause them to be such that they conserve energy. So by the virtue of what do they explain? Obviously, explanations by constraint unify: they give a common explanation to seemingly rather distinct phenomena. But that's not all. Explanations by constraint explain by virtue of 'natural necessity', which Lange also describes as physical or nomological necessity. By virtue of natural necessity, it is not only the case that extant force laws must conserve energy, but also any force laws that 'might have been' would have had to. As Lange puts it, explanation by constraint

> transcends the grubby, pedestrian details of the various particular force laws […] It does not depend on the kinds of forces there actually happen to be. Rather, it limits the kinds of forces there could have been […] certain kinds of forces that are not among the kinds there actually are nevertheless qualify as possible in virtue of satisfying these constraints, whereas others qualify as impossible […]. (51)

Likewise, Lange claims, energy conservation explains the fact that there is no law of nature that posits force fields that pop alternatively in and out of existence every other second, since that would imply that the potential energy of all bodies in a field would change while their kinetic energy stays the same, which would be inconsistent with energy conservation (57). On the coincidence view, there is no reason why no such force fields exist.[4] Thus, Lange concludes, "a constraint possesses a certain distinctive kind of invariance under counterfactual perturbations" (49). Since the relevant counterfactuals are those whose antecedant contains a 'natural impossibilty' Lange also refers to these kinds of counterfactuals as 'counterlegals' (74).

Despite what the 'invariance under counterfactual distubances' may suggest, Lange considers constraints to be inexplicable on a standard account of explanation (Woodward 2003), because constraints like conservation principles do not identify circumstances in which the explanandum (such as energy conservation) would have been different, nor do they identify *what* would have obtained in the actual explanandum's stead (49). It is thus hard to answer what-if-things-would-have-been-different questions, which are essential to Woodward's account of explanation.

Explanation by constraints, according to Lange, exhibit necessities similar to the ones to be found in mathematical explanations, such as his famous example of Mother failing to distribute 23 strawberries evenly among her 3 children because it is impossible to evenly divide 23 by 3. Yet, although Lange claims that the necessity of explanations by constraints is 'greater' than the necessity of 'ordinary' laws of nature, it is not as strong as the necessities of mathematical explanations (51). According to Lange, there is a metaphysical "pyramidial hierarchy" of necessities, whose levels can be determined on the basis of counterfactual conditionals, such as the ones considered above. If the counterfactual antecedant contains natural impossibilites, then the associated necessity is stronger than when the counterfactual antecedant contains just 'subnomical' facts.

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[4] Then again, one might add, a lot of things that do not exist are not explained by our theories.

According to Lange, the special theory of relativity, Einstein's own principle theory, is also a theory that explains by constraint. On that theory, the fact that the dynamical (force) laws are Lorentz-covariant (viz. invariant under Lorentz transformations), either is an accident or the dynamical laws must be Lorentz-covariant because the principles of the special theory of relativity (in particular, the principle of relativity) constrain the dynamical laws in such a way that they *have to be* that way (103). Just like energy conservation would have held if the forces had been different, Lorentz-covariance would have held in such circumstances too (109). Lorentz-covariance would thus inhabits a similar space on Lange's pyramidal hierachy as principles of conservation. Lange furthermore cites evidence that scientists actually believe that Lorentz covariance is of a stronger necessity than the force laws in this sense (106-107). With regards to the debate about the explanatory status of Einstein's theory, Lange sides with those who have affirmed that the theory is explanatory (Janssen 2009) and rejects Brown's view that genuine (constructive) explanation would require a microphysical and causal explanation of why rods contract and clocks retard.

I am persuaded by Lange's slightly provocative case for principles such as energy conservation – despite first appearances – actually being explanatory. Likewise, I do think that we can accept that principle theories give us *some* understanding of the target system. But how does the understanding principle theories give us compare to the understanding that constructive theories can bring about? In order to address this question, we need to know more about constructive theories and the way they explain.

3 How does the kinetic theory of gases explain?

Consider now the kinetic theory of gases (KT), Einstein's favorite example of constructive theories. KT's explanandum is the ideal-gas law (IGL). How does KT explain? Many leading philosophers of explanation have discussed this example. Hempel (1970) argues that KT explains IGL by offering bridge-laws that connect macro- with micro-variables. Salmon (1984) suggests KT explains IGL by correctly identifying the causal structure or mechanism underlying IGL. Friedman (1974) argues that that it is KT's unifying power that explains IGL (and other laws). Cushing (1991) claims that KT is explanatory because it provides us with a visualisable picture that underlies IGL. Elgin (2004, 2007) believes that IGL (that can be derived from KT's highly idealized assumptions) gives us understanding by virtue of misrepresenting the target. Woodward (2003), as we shall see in a moment, argues that there is a sense in which IGL is in fact more explanatory than KT.

In spite of the extent of philosophical engagement with KT and the plethora of views of its – largely undisputed – explanatory power, I believe that one important element of KT's explanation of IGL has been overlooked, namely the representation of IGL in KT as a necessity.

IGL is a summary of two empirical laws: Boyle's law and Gay-Lussac's law. The former states that the pressure of a gas is inversely proportional to the gas volume and the latter tells us that pressure is proportional to temperature. It is easy to see that these relations support Woodwardian counterfactuals: had we decreased (increased) the volume of a gas in a container, the pressure of the gas would have increased (decreased) (this is Boyle's law), and had we increased (decreased) the temperature, the pressure would have increased (this is Gay-Lussac's law). Woodward (2003) has pointed out that these relations give us understanding of causal dependencies between the relevant macro-variables (250ff.). But how does KT figure on his account, given that KT is normally taken to explain IGL? Curiously, Woodward has not much to say about this question, at least not much positive. Although he admits that since KT "provides information that allows us to answer what, in some respects, is a wider, more detailed range of w-questions" and that KT therefore gives us a sense of "deeper explanations" (223), he believes that the explanation offered by KT for IGL is deficient, as it "omits information that is crucial to an explanation" of changes in the values of macro-variables. For Woodward, it therefore "fail[s] to provide the explanation of the macroscopic behavior of the gas we are looking for" (232). More specifically, Woodward believes that KT fails to give us much understanding of IGL because for any particular value of a macrovariable such as pressure, there is not one determinate microstate, consisting of initial positions of molecules, their momenta and molecule trajectories. Because of that, there is no determinate answer to the question of what the value of the pressure-variable would have been, had the microstate been different, because, again, any macrostate is compatible with a multitude of microstates. Woodward concludes that IGL itself does a "better job" at explaining changes in macrovariables than KT (232). Woodward believes that this lesson is a general and that it is often the case that lower-level explanations do worse than upper-level explanations (233).

I believe Woodward does not do full justice to KT; at the very least, he is at odds with not only many philosophers studying explanation (see above), but also with the way in which KT is normally perceived amongst scientists, namely as explanatory of IGL.

Notice that, on a higher grain of abstraction, we *can* associate certain macrostates with certain microstates, contrary to Woodward's assertion. For example, a higher value in the pressure variable corresponds to an increase in the frequency of molecule-wall collisions, no matter what the initial conditions of the molecules might have been. Thus, contra Woodward, we *can* say how the pressure would have changed, had the frequency of the molecule-wall collisions have changed. More than that, we can say why the relation of the macrovariables summarized in IGL *has got to* be the way that it is. Let me explain.

IGL, as an empirically discovered relationship, is contingent. We came to know of it by investigating the world in which we actually live in. In a different world, the laws describing the behavior of gases might have been different. In another world, for example, it might have been the case that a decrease in gas volume would not result in an increase in pressure (as in our world) but in a *decrease*. So how come that in our world the gas macrovariables are related in the way they actually are? This is where KT comes in: it tells us that IGL *must* have the form that it does and that, for example, a gas's pressure *must* increase when the volume is decreased. It is *not possible*, within KT, to increase a gas's volume and thereby to decrease its pressure. How does KT manage this feat? Consider the following truncated partial derivation of IGL within KT.

The number of collisions of a molecule with the container wall per second for a molecule on a 'round trip' between opposite sides of the container wall is ${}^{v_x}/_{2l}$, where l = the distance between two opposite container walls and v_x = the molecule velocity along the x-axis. The total momentum change per second for all molecules (N) in the container with average speed $\overline{v_x}$ is $N\frac{m\overline{v_x}^2}{l}$. By Newton's second law, this is equivalent to the average force exerted by the molecules on a container wall per second. Since pressure is defined as the force exerted perpendicularly on an area (here: l^2), $P = N\frac{m\overline{v_x}^2}{l^3}$. Since l^3 is the volume of a cubical container, $P = \frac{Nm{v_x}^2}{V}$. Assuming that there is no preferred direction for the molecule's path, $P = \frac{1}{3}\frac{Nm\overline{v}^2}{V}$. Since the total kinetic energy of translation KE_{trans} of all molecules is $\frac{1}{2}m\overline{v^2}$, this gives us $P = \frac{2}{3V}KE_{trans}$. It is easy to see that the smaller (larger) the volume, the higher (lower) the gas pressure. It is also apparent from this derivation that this relationship is a necessity within KT: it is not possible for the pressure to rise when the volume decreases. This is explained qualitatively by the distances between the container walls which the molecules have to traverse before hitting the walls being shorter and the number of the molecule-container wall collisions per time interval thereby increasing. Conversely, it is not possible, in KT, for the gas pressure to *decrease* (rather than to increase) when the volume increases, because that would mean *fewer* molecule-wall collisions when there is actually more space for the molecules to travel in the container before hitting the wall, which is ruled out on KT. Analogous points hold for KT's explanation of Gay-Lussac's law. Tab. 1 summarizes KT's representation of IGL as structural necessities.

IGL regularity	Explanation in terms of structural necessitation in KT
$P \propto {}^{1}/_{V}$ (Boyle's law)	FC ∝ gas density *Not possible*: FC ∝ 1 / gas density
$P \propto T$ (Gay-Lussac's law)	FC ∝ speed of molecules *Not possible*: FC ∝ 1 / speed of molecules

Tab. 1: KT and Boyle's and Gay-Lussac's laws (as parts of IGL). In KT contingent regularities are represented as necessities. FC= frequency of molecule-wall collisions. KT presupposes the following relations between macro- and microvariables: P ∝ FC, V ∝ 1/gas density, and T ∝ molecular speed.

4 What kind of explanation, what kind of understanding?

The structural necessitation afforded by KT, Einstein's prime example of a constructive theory, tells us why an empirical law like IGL has the form that it does have. Without KT, we would only know *that* the relation between the relevant macrovariables would be as it is, but we wouldn't know *why*. So, although we can appreciate that IGL itself is in some sense explanatory (since it allows us to answer Woodwardian *w*-questions), KT provides a deeper explanation of IGL and of the relationship of macrovariables that it describes than we could have had by virtue of IGL alone. This seems very much in tune with how scientists themselves think about the relationship between KT and IGL.

The kind of understanding KT gives us of IGL is not just a 'how-actually' understanding, which has often been focused on by theorists of explanation (Salmon 1984), but also 'how-necessarily' understanding. Thus, KT helps us understand not only how it is that certain changes in, say, pressure, depend on changes in volume (because with a reduced volume the between-wall distances decrease and therefore the number of molecule-wall collisions per time increases, which in turn increases the pressure), but it also helps us understand why this *has to be* the case (because it cannot be the case that the distances become shorter with a volume reduction and nevertheless the pressure decreases).

KT is of course just one example of a constructive theory. Other examples I consider to be Dalton's explanation of the laws of constant proportion and Mendel's explanation of his three laws of inheritance. Dalton's atomism explains the laws of constant proportions, i.e., the law that chemical elements always combine in the same ratios (e.g. oxygen always making up 8/9 and hydrogen 1/9 of the mass of water), and the law of multiple proportions, i.e., the fact that whenever two elements form more than one compound, the ratio of those compounds will be multiples of each other (as in CO and CO_2, where a certain amount carbon combines with exactly twice as much oxygen in the first compound as in the second). Dalton's atomism explains not only the fact *that* we observe those ratios, but also why we do not observe any intermediate ratios (e.g., where carbon would combine with 1 ½ as much oxygen as in CO), as that is ruled out by the assumption of indivisible atoms. Mendel explained the laws he discovered in terms of genetic 'factors', as he called them, by showing that the crossing of pure white and purple flower peas will *have to* result in the fixed probability distributions of the colour traits in the daughter populations. Given the Mendelian model, it is for example impossible that a dominant and recessive trait such as white and purple flower colour will result in a 2:2 ratio in the first filial generation; it has *got to be* a 3:1 ratio.

The kind of explanation afforded by constructive theories via structural necessitation is what Salmon (1998) called 'modal' explanation, and which he contrasts with ontic explanations, which he himself is concerned with. Salmon has in mind mostly the classical DN model, which he rightly criticizes. I don't have the space here to comment on all of his concerns, but it is important to notice that the DN model is a model of explanations of *events*. The explananda I am concerned with here, though, are not events but regularities describing events. It is therefore no good criticism of structural necessitation to point out, as Salmon does, that there are many probabilistic explanations in science where the particular events are not necessitated by their explanantia. As the Mendel example illustrates, there may well be explanation of *regularities* by necessitation even when the events or particularities (the colour of *this* particular pea) is not necessitated at all.

5 What kind of necessities?

As we saw in Section 2, Lange distinguishes between various sorts of necessities that may be involved in the explanation of the phenomena. On the highest level of his pyramidal hierarchy of necessities, we find mathematical necessities involved in explaining why Mother cannot divide 23 strawberries evenly among her 3 kids. On a lower rung of his hierarchy, we find explanations by constraint, such as conservation laws, which explain why the (actual and potential) force laws *have to* conserve energy. On a yet lower rung we find regular laws of nature (such as the force laws). Each level in Lange's hierarchy, as we saw, is individuated by counterfactuals. For example, we can ask whether energy conservation would have held, if the forces had been different. Since the answer is yes, the necessities in explanations by constraint are nomologically more 'stable' than the necessities at the lower levels. Now our question must be: where in Lange's hierarchy do the necessities figure with which constructive theories like KT?

First of all, let us emphasize once more that KT explains *relations*, namely the relations described IGL. For that reason, it is already dissimilar from ordinary laws that explain the (causal) interdependence of certain variables. In that sense it is similar to Lange's explanations by constraint, whose objects are also relations (namely laws). Second, in contrast to Lange's explanations by constraint, we can say in the case of KT that the necessities in the explanations are brought about by causation. That is, whereas Lange insists that the reason why energy conservation holds has nothing to do with the ways in which the fundamental interactions are brought about, in KT, clearly, not only the macrovariables pressure and temperature of gases are brought about causally by the molecular mechanism postulated by KT, but also the relations between those variables (in the form of IGL), are brought about causally by KT. Third, nevertheless, we can say with some justification that KT 'constrains' the empirical laws in that it tells that certain relations between the macrovariables are ruled out. In virtue of that, KT explains by necessities. So, once more, where on Lange's hierarchy are those necessities to be located?

On Lange's account, had there been different force laws than the ones we have, those force laws – whatever their form – would still have had to conserve energy. The same is of course true for energy conservation and the (classical) laws figuring in KT, with which KT represents IGL as a necessity. But what about the relation of the laws in KT and IGL? Just as the force laws could not have taken a different form than they do (and conserve energy), given the truth of energy conservation, IGL *could not have* taken a different form than it does take in the actual world, given the truth of KT. In addition to the constraint set by energy conservation on the force laws, however, KT furthermore provides a *mechanism for why* IGL must take the form that it does take. In that sense KT provides a deeper explanation than energy conservation, even if the necessity of energy conservation is 'more stable' (in Lange's sense) than the necessity of KT.

6 Conclusion

In this paper, I argued that Einstein's constructive theories explain empirical regularities by representing them as necessities. I called this feature of constructive theories 'structural necessitation', which seems to be located between the necessities with which Lange's constraints explain on the one hand and phenomenological laws such as IGL on the other hand. This (in part) accounts for the fact that a constructive theory like KT is usually thought to be more explanatory than IGL, contrary to what Woodward has claimed. Although the necessities of constraints seem to be stronger than the necessities of KT, KT – in contrast to energy conservation – does go beyond the phenomena and offers us a mechanism of how the phenomena are *necessarily* brought about. In that sense, it may indeed be considered to give us ‘deeper’ understanding than explanations by constraint. The lessons for discussions about the explanatory status of the special theory of relativity, which has motivated recent discussions of principle vs. constructive theories, will have to be spelt out elsewhere.

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