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The value of laws in chemistry

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Abstract
In philosophy, the empirical success of a science is often explained by the fact that it has managed to discover some law(s) of nature. This line of thought has not been thoroughly explored with respect to chemistry. The aim of this paper is to fill this gap by showing how we could think about laws in chemistry. Specifically, it briefly presents how laws of nature are understood in philosophy of science. It then discusses two case studies from chemistry—the periodic table and chemical reactions—and explains how general ideas about lawhood can be applied to these cases. Lastly, it presents research questions and philosophical problems that arise by considering chemistry from the perspective of laws. This analysis illustrates that there is value in thinking about laws in chemistry.

Keywords Laws of nature · Periodic table · Chemical reactions · Causation

Introduction

> Apparently without reservation, for over three hundred years scientists have called the intelligible, measurable, predictable regularities they find in nature "laws". (Ruby 1986: 341)

Law is a familiar concept. One can find it in diverse fields of human enquiry including the legislature, religion, and science. When it comes to science, there is no discipline as far as I know, that does not purport to have its own laws: from physics, chemistry, biology and mathematics to economics, psychology and sociology. Students are taught to pay special attention to laws; it is expected that in order to acquire a sufficient understanding of a science, one needs to learn its basic laws. For example, even an elementary study of physics requires getting acquainted with Newton's laws, and of biology with Darwin's principles of natural selection.

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In chemistry too, one can find regular mention of laws. The most characteristic example is the periodic law according to which "physical and chemical properties of elements are a periodic function of their proton number".[12] This term was already used in the nineteenth century when chemists started to propose classifications of chemical elements (e.g. Pulkkinen 2020).[3] For example, Dmitri Mendeleev titled his seminal paper 'The Periodic Law', and John Newlands claimed that he was the first to discover a law of periodicity with regard to chemical elements (Newlands 1884; see also Pulkkinen 2020). Among other laws that one learns when studying chemistry (at any level) are Boyle's law, the ideal gas law, the law of multiple proportions, the law of correlation (or catalysis law), and Henry's law.[4] Admittedly, not all laws belong in the purview of chemistry. Many of them- while vital to understanding chemical phenomena- come from physics or thermodynamics. Nevertheless, it remains the case that talk of laws is far from unusual in chemical practice and education.[5]

This ubiquity comes in sharp contrast with how laws are studied in the philosophy of chemistry. With the exception of Rom Harré and Andrea Woody (to whom I return in the next section), there is very little talk of laws despite the fact that the latter have been extensively examined in the general philosophical corpus.[6] The aim of this paper is to offer motivation for such analyses by presenting how two paradigmatically chemical case studies can coherently be thought of as candidate laws of nature. The intention of this paper is not to advocate the existence of a particular chemical law.[7] Instead, its aim is to show that interesting research questions arise by thinking of this metaphysical issue from the perspective of chemistry.

Section 1 presents how the idea of laws of nature has been investigated in philosophy, by offering a brief overview of the main accounts and concepts that have been developed thus far. Section 2 explains why we should think about laws with respect to chemistry by presenting two case studies to which the idea of laws can be applied: the periodic table and chemical reactions. It presents new research questions and interesting philosophical problems that can be investigated in the context of these case studies. Section 3 concludes.

The idea of laws in philosophy

The idea of laws, that is, of mind-independent regularities in nature, has occupied scientists and philosophers for a long time. Historians of science track this idea back to Kepler and Descartes, while others argue that it can be found in the works of Ovid, Seneca and Shakespeare (Zilsel 1942; Ruby 1986: 342).[8] Some of the most significant advancements in

[1] This definition is from the following reference: periodic law. *Oxford Reference*. Retrieved.

[2] Jan. 2024, from https://www.oxfordreference.com/view/10.1093/oi/ authority.20110803100317683.

[3] Early versions of the periodic law (such as Mendeleev's) understood periodicity in terms of atomic weight, not atomic number (as is today).

[4] The *Goldbook* of the International Union for Pure and Applied Chemistry mentions the term 'law' around 50 times (IUPAC 2014).

[5] Rom Harré lists some examples of purported laws used in chemistry such as Dalton's Law of Partial Pressures and Beer's Law (2012: 339- 341).

[6] Those that have investigated laws in chemistry are discussed in Sect. 2. While their work has contributed significantly to this topic, I show that there is still a lot more to be investigated with respect to laws in chemistry, especially from a metaphysically-informed perspective.

[7] I defend such a thesis with respect to the regularities of the periodic table in Seifert (accepted/preprint).

[8] The term 'law' is also used in fields outside the sciences (such as the legislature and in religion) with different connotations than those standardly associated within the sciences (see Ott 2022 for a brief overview). Such understandings and analyses of law-hood are disregarded here.

science have been associated with the discovery or postulation of laws, including Newton's laws, the laws of thermodynamics, the laws of refraction, and many others. The term holds special weight. Put crudely, a statement in science that is referred to as a law is regarded in some way more important or fundamental than other parts of that science.

Philosophers have tried to understand what it is that makes laws so special. Among other things, it has been argued that laws are what separate science from pseudoscience. Ruse (1982) for example argues that the absence of genuine laws is what makes creation science a pseudoscience. Moreover, laws are often offered as the explanation of science's enormous success- both practical and theoretical. In general, a plethora of views have been formulated that attempt to explain not only laws' role in science but also their nature and metaphysical significance. In fact, one can find numerous accounts that purport to explain what a law of nature is, and if there exist any laws at all.[9]

Before presenting some of these accounts, let me first mention the main features that are standardly (though not uncontroversially) associated with laws of nature (see Carroll 2020 for an overview and Seifert accepted/preprint; Seifert 2024). Laws are taken to be represented by statements that are factually true and contain general concepts (Dretske 1977b; Mill 1856).

Such statements can be used to make empirically successful inductive inferences about particular matters of fact, and to make accurate predictions and retrodictions (Dretske 1977b: 252; Goodman 1983; Loewer 1996: 111; van Fraassen 1989). Moreover, laws are taken to unify the behaviour of seemingly disparate things in nature. They offer a systematisation of empirical facts and are universal or statistical claims (e.g. Hempel and Oppenheim 1948). This means that they hold at any time and place in the universe and for all relevant instances of matter (under specific conditions). Lastly, laws render counterfactual claims true or false, and they explain phenomena (e.g. Chisholm 1955; Goodman 1947; Hempel and Oppenheim 1948).

As an example consider the conservation of mass law which states that no mass is created or destroyed during a chemical reaction.[10] This statement does not involve any proper name. It does not for instance concern a particular chemical reaction that was studied by Lavoisier one September morning in his laboratory in Paris. Instead, it is a statement involving general concepts. Also, this statement is not logically true; it has been empirically studied and its truth is corroborated by invoking well-established empirical evidence. The statement is invoked to make inferences about any and all chemical reactions one studies either in theory or in a laboratory. In fact, one can predict from this statement that if the total mass of reagents of a particular reaction A is B then the total mass of its products will also be B. Moreover, it unifies all reactions taking place in the world: it is true for reactions that happened millions of years ago on earth, as well as for reactions that take place in distant planets in the present and future. The latter feature is also what constitutes this statement a universal claim about reactions. Furthermore, counterfactual statements of the form 'If the total mass of reagents is B, then the total mass of products is B' are rendered true by

[9] The use of the term 'genuine' is redundant: either there are laws or there are not. Nevertheless, I use the term to stress that laws are examined here is a strictly metaphysical sense, referring to mind-independent regularities in nature. Note that the latter also implies that my analysis of laws of nature is restricted to metaphysical issues around laws.

[10] I do not claim that the conservation of mass is a genuine law. While this seems like a plausible claim, the present analysis does not suffice to establish it and I only invoke this example to illustrate some of the most standard features associated with laws.

this law. Lastly, the law explains any and all instances that one finds in which the total mass of a (closed) system that undergoes a chemical reaction, remains stable.[11]

While these features shed some light into the nature of laws, philosophers disagree whether this is all there is to them. On the one hand, some argue that law-like statements are statements which satisfy these features and nothing more. In this context, it is assumed that nothing is responsible for the (lawful) regularities found in nature.[12] On the other hand, others argue that there is something more to being a law. This view is motivated by the assumption that something must govern, constrain or produce the regularities that are observed in nature (Hildebrand 2023: 29).[13] What this is precisely is a matter of contention, and different accounts have been offered to spell it out.

Disagreement about whether the aforementioned features are all there is to being a law lead initially to two opposing camps which are broadly referred to as the regularity and necessitarian view of laws.[14] Each view has been spelled out in more than one ways. One of the most discussed versions of the regularity view is the so-called Best Systems Account (BSA) which was spelled out and defended independently by John Stuart Mill (1856), Frank Ramsey (1978) and David Lewis (1973b; 1986).[15] The BSA takes that "all there is in the world is a vast mosaic of local matters of particular fact, just one little thing and then another" (Lewis 1986: ix). These matters of fact can be described by different sets of statements. On this account, there is one set which forms a deductive system comprised of axioms and theorems, and which manages to describe those matters of fact in a way that is—at the same time- most informative and simple. This is called the ideal deductive system, and only this system's axioms and theorems are qualified to be called 'laws of nature'. The deductive system is ideal in the sense that (and because) it strikes the best balance between simplicity and strength (see also Psillos 2014: 17). That is, the number and content of these axioms and theorems are such that the system overall could not be simpler without losing in strength, and could not be stronger without losing in simplicity (see also Hildebrand 2023: 9–10).

There is a lot to unpack here that I cannot fully cover in the present context (see also Seifert accepted/preprint and Seifert 2024). Among other things, several problems have been raised against this account as well as the more general view within which the BSA is subsumed. For example, one major issue regarding the BSA is whether it is possible (and if so how) to spell out simplicity and strength in an objective (i.e. mind-independent) manner, and what it means to achieve the best balance between these two virtues (e.g. Woodward 2014). Another problem which vexes the regularity view is that it does not purportedly succeed in distinguishing lawful regularities from merely accidental ones. This is because, among other things, it does not manage to explain why laws render counterfactual statements true or false. Given that on the regularity view, laws of nature focus only on local

[11] These features require a much more nuanced analysis as it is not evident- for example- what constitutes a successful explanation, prediction or unification. For the present purposes such discussions are disregarded, though I return to some relevant issues in the next section.

[12] This is often called the Humean view about laws and involves the claim that these regularities could have been different (Hildebrand 2023: 29). I do not use this term for the reason given in footnote 15.

[13] In contrast to the Humean view, this view is called anti-Humean and takes that observed regularities could not have been different. They are as they are by necessity. This necessity is not logical (as for example it is necessary that two plus two equals four) but rather metaphysical.

[14] These are also referred to as the Humean and anti-Humean views respectively.

[15] This is why it is also referred to as the Mill-Ramsey-Lewis view. Another regularity view is the Naive Regularity Theory that is considered to face significant problems (Hildebrand 2023: 7–9).

matters of particular fact, it is consistent with actualised regularities being a 'cosmic accident' (Lowe 2002: 380).

On the other side is the necessitarian view. Here also we find different versions of it. Among its main representatives are David Armstrong (1983), Fred Dretske (1977a), and Michael Tooley (1977). The common thing between them is their belief that there is something more to the regularities in nature than what one observes: namely, they are in some sense necessary. Necessitarians oppose the view that laws just track regular occurrences of patterns of events (Ney 2014: 291). Instead, things behave as they do because they *must* behave so. As Dretske puts it: "laws tell us what (in some sense) must happen, not merely what has and will happen (given certain initial conditions)" (1977a: 263).

One of the most prevalent versions of the necessitarian view has been independently offered by Dretske, Tooley, and Armstrong (thus called the DTA view) who spell it out in terms of a nomic relation between universals. Universals are types of entities that "may be instantiated at multiple locations at once by distinct entities" (Ney 2014: 291). For example, red can be regarded a universal because it is the type of entity that is instantiated by multiple red things. In this context, laws are second-order necessitation relations between universals. Armstrong puts it as follows:

> Suppose it to be a law that *F*s are *G*s. *F*-ness and *G*-ness are taken to be universals. A certain relation, a relation of non-logical or contingent necessitation, holds between *F*-ness and *G*-ness. This state of affairs may be symbolized as '*N*(*F*,*G*)'. (Armstrong 1983: 85)[16]

Similarly to the regularity view, there are purported challenges for the necessitarian view of laws. For example, van Fraassen points out two problems: the identification and the inference problem (1989: 96). These two (related) problems concern the nature and force of the purported necessitation relation; namely what exactly is this relation (the identification problem) and does this relation between Fs and Gs entail that Fs are Gs (the inference problem). Van Fraassen claims that the necessitarians do not offer clear answers to these questions. Another purported problem with the necessitarian view is its apparent unempiricalness. Following a Humean spirit, it is pointed out that necessary connections are not observable.[17] One cannot invoke an experiment or observation in nature as evidence for the existence of a necessary connection between properties or events. All one observes is regular occurrences of events.[18] Therefore, we shouldn't posit the existence of laws as per the necessitarian view.

Apart from the BSA and the DTA account of laws, there are other accounts that have been proposed either within the regularity or necessitarian context, or outside both camps.[19] For example, within the necessitarian context, some believe that laws are primitives: they cannot be further analysed and are part of the fundamental ontology (Hilderbrand 2023: 32; see for example Carroll 1994; Maudlin 2007). More recently, Ioannidis

[16] The next section spells out how this view- as well as the regularity view- can be applied to chemical case studies.

[17] For this reason the regularity view is often characterised as Humean. However, recently philosophers argue that this is misleading because Hume himself was purportedly a necessitarian with respect to how he understood laws of nature (e.g. Strawson 2015).

[18] Attempts have been made to overcome this objection by, among other things, coming up with experiments which could in principle show the existence of a necessitation relation (e.g. Wright 1974).

[19] There are also philosophers who in light of such challenges deny the existence of laws altogether. I briefly present such views later.

et al. (2021) proposed a dualist account of laws where laws are not sufficient yet are necessary to capture how the regularities in nature are governed and determined. According to them, “both laws and powers (suitably conceived) are equally fundamental and irreducible to each other, and both are needed in order to give a satisfactory account of the nomological structure of the world” (2021: 1).

There are also reductive and anti-realist views of laws. An anti-realist view is held by Nancy Cartwright (1983) who believes that statements of laws describe causal powers. Another example is the form of dispositionalism that is advocated by Stephen Mumford (2004), who believes (very roughly) that there are no laws because the nomic and causal role is played by the properties of things in the world. A dispositionalist need not hold such a view though. Alexander Bird for example is a dispositional essentialist who believes in the metaphysical necessity of laws.[20] As he famously puts it “laws flow from the essences of properties” (2007: 5).

All in all, there are many views which spell out differently how laws relate to the regularities observed in nature. Each view understands differently how observed regularities in nature relate to laws and what it is to be a law. The next section sketches how this metaphysical analysis of laws can inform discussions in the philosophy of chemistry.

Why think of laws in chemistry: case studies, research questions, and challenges

Hildebrand makes a distinction between two sorts of questions about laws which can help us appreciate the value of thinking about them with respect to chemistry (2023: 1). Scientists, he claims, ask what laws there are. For instance, what is the law that governs the behaviour of mass bodies, of gases, or of social groups? Philosophers on the other hand, ask what laws themselves are. For instance, what are the necessary and sufficient conditions for any regularity to be considered lawful?

Philosophers’s question is in large part prompted by the observation that even though plenty regularities can be found in nature, only a few of them are given lawful status. For example, that there is no solid gold sphere whose diameter is larger than a mile is considered somewhat different from the fact that there is no solid uranium sphere of similar diameter (van Fraassen 1989: 27). The first expresses an accidental regularity: something that is (probably) true but could nevertheless be otherwise. The second expresses a lawful regularity: it is a physically impossibility that uranium forms spheres of such diameter. So philosophers ask: what are the features that distinguish lawful regularities from accidental ones?

The accounts presented in the previous section all purport to offer an answer to this and to specify the nature of lawful regularities.[21] This, however, does not imply that they are also not relevant to the question scientists raise about what laws there are. In fact, examining laws from the perspective of chemistry shows that the two questions are intertwined. In order to answer whether chemistry has any laws of nature (and which ones those are), one has to have some idea of what laws are. This is because different views on the nature of laws may lead to diverse positions about whether or not to admit lawlike statements that are made in chemistry, as representing (genuine) laws.

[20] Such views are broadly referred to as power-based accounts of laws.

[21] Whether they succeed to do so is another matter.

Another reason why thinking of laws in chemistry is something we should pursue more actively (especially in the philosophy of chemistry) it due to its relevance to the issue of reduction. As is known, since its emergence as a field of study the philosophy of chemistry has extensively investigated if and how chemistry is reduced to physics (especially, to quantum mechanics) (e.g. Hendry 2010; Scerri 1994; Scerri and Fisher 2016). The question of chemistry's reducibility has even been connected to ideological and normative considerations pertaining to the survival of chemistry and to the support of philosophy of chemistry as a worthwhile field of study (e.g. Chang 2015; Lombardi 2005; Scerri and Fisher 2016). While I am not particularly fond of how such normative considerations influence our talk of chemistry's reduction, I must admit that the issue of laws can offer novel insights and perspectives through which to consider not just chemistry's relation to physics, but also the value of chemistry's philosophical analysis.

This is because a major topic in metaphysics is whether one should admit only statements from fundamental physics as candidate representations of laws, or whether the special sciences also track genuine laws (e.g. Cohen and Callender 2009; Schrenk 2006). This question has prompted various responses in the literature that extend beyond the question of reductionism and which can inform how we understand the place of chemistry among the natural sciences, regardless of whether or not it is reduced to physics (in any sort of way).

To further reinforce the value of thinking about laws in chemistry, the remainder of this section sketches some of the research questions, problems and claims one can develop when considering laws from the perspective of two chemical case studies: the periodic table and chemical reactions.[22]

The periodic table

The periodic table is a visual representation of all known chemical elements.[23] The elements are placed in order of increasing atomic number and chemists employ it so as to make statements about various physical and chemical properties of matter. Such statements include for instance that 'Metals are poor conductors of heat', 'Plutonium is radioactive' or 'When a metal reacts with oxygen it forms a metal oxide'. The information chemists have managed to enclose in this representation via its classification of elements (into groups, periods, metals, non-metals, and so forth) and via the purported relations among different sets of elements, is vast and extremely valuable to chemical practice. This information is employed for the prediction of chemical facts that are in turn used in fields such as climate modelling, biology, drug design, etc., as well as for the explanation of chemical, physical and biological phenomena that occur not only on earth but on distant planets as well. All in all, the table plays an extremely important role in science, technology and engineering, and has exhibited enormous empirical success since its development by Dmitri Mendeleev almost two centuries ago.[24]

[22] This is an extremely selective analysis that is not developed with the aim to support a specific metaphysical view about chemical laws. Instead, the reader should treat it as a sketch of how subsequent work can be further pursued with respect to laws in chemistry.

[23] This section about the periodic table is largely based on Seifert accepted/preprint.

[24] The table of course has changed from its original form that was proposed by Mendeleev. The most important change is that elements are now classified in terms of increasing atomic number and not atomic weights (as was initially). The history of how the table was developed is fascinating and by no means can

All this is fairly known about the periodic table. And while the table has received considerable attention in philosophy as a very successful classificatory scheme and an important part of the history of chemistry, there is a different way to investigate it which can produce interesting new research questions (e.g. Scerri and Worrall 2001; Weisberg 2007). Specifically, one can consider the table as a representation of a law- and not just one law, but many. For example, one could claim that the periodic table is a representation of multiple lawful regularities in nature (see Seifert accepted/preprint for an analysis of this argument). Put differently, the statements chemists make by employing the periodic table (such as that 'Metals are poor conductors of heat') are candidate statements of laws of nature. That is, they correspond to lawful regularities that are observed and empirically corroborated in the same way as other paradigmatic candidates of laws in science.

There are—at least- two good reasons to consider these statements as candidate statements of laws. First, they prima facie satisfy all features that are expected of lawful statements (see previous section). That is, they are statements that involve general concepts and not proper names; their truth is not decided on the basis of logic; they render counterfactual statements true; they unify diverse matters of fact; they explain and predict a vast range of phenomena; and, they are used to make inductive inferences about particular matters of fact. Secondly, standard accounts of laws (such as the BSA and the DTA) can be applied to these statements coherently. For example, one can understand these regularities in terms of the regularity view and claim that statements such as 'Metals are poor conductors of heat' are theorems in the ideal deductive system because they contribute to the system's simplicity and strength. Or, alternatively, one could claim that these statements describe necessitation relations between universals. For the case of metals for example, one could say that being-metal and being-poor-conductors-of-heat are two universals that are related via a second order nomic relation (Seifert 2024: 55- 60).

In fact, examining the regularities expressed by the periodic table in the context of the two main accounts on laws can inform existing questions and problems regarding the latter. For example, a major issue (if not problem) in the context of the BSA is how to evaluate simplicity and strength. As mentioned above, these values have been criticised because- among other things- there are different ways to spell them out and this may be suggestive of their ambiguous- if not subjective- nature. From the perspective of the periodic table, it is possible to cast new light onto these values in a way that can contribute positively to the further development of the BSA.

Similarly with the necessitarian view. One interesting issue is that of uninstantiated laws and how it is dealt by standard necessitarian accounts, such as Armstrong's account in terms of universals (see above). According to Armstrong, "(s)tatements of uninstantiated law tell us that a certain law would govern the antecedent universal, if, contrary to fact, that universal existed, that is, was somewhere instantiated" (1983: 117). In the case of the periodic table, one could argue that there are uninstantiated universals in the form of superheavy elements which have not yet been discovered but are (or at least seem) possible. Do the regularities purported by the periodic table about these elements count as examples of uninstantiated laws and, if so, does this undermine Armstrong's denial of such laws?[25]

Footnote 24 (continued)

I do justice to it here. So I direct the reader to some references: Brock 2012; Pulkkinen 2020; Scerri 2011; 2019.

[25] This is a very complex issue as it is still quite controversial whether (i) superheavy elements are physically possible; and (ii) even if they are, if they obey the regularities that are purported by the periodic table

Admittedly, there is a lot to unpack here and I do not purport to have sufficiently supported any of these views of laws with respect to the regularities depicted by the periodic table. I do not wish to convince the reader that the statements chemists make via the use of the periodic table are definitely laws of some form (see Seifert accepted/preprint). Instead, I wish to show that one can coherently entertain this idea and that interesting research questions arise by doing so. To be fair, this is not the first time someone has expressed the need to investigate this issue in more detail. Andrea Woody brings out the idea of lawful regularities with respect to the periodic table and emphasises the need to thoroughly examine the table from the perspective of laws. As she states:

> (Chemistry's periodic law) has served as stock example in contemporary discussions of the relative evidential weight of accommodation versus prediction even while its status as a law has seldom been scrutinised. (Woody 2014: 3)

Chemical reactions

Another case study worth considering from the context of laws are chemical reactions (see also Seifert 2024). In light of the above analysis, this should not come as a surprise. Many of the statements that are embedded in the periodic table are statements of regularities concerning reactions between chemical elements. Nonetheless, there is value in studying chemical reactions in their own right, as chemical transformations do not only take place between elements but between various kinds of chemical entities (including substances).

So far, philosophical and historical work on chemical reactions focuses mainly on (i) chemical education; (ii) the history of chemistry; (iii) conceptual analysis; (iv) the relation of chemistry with biology; and (v) the metaphysics of chemistry (e.g. de Berg 2021; Korobov 2005; Villani 2017; Harré 2008). However, none of this work offers a detailed and complete account of what chemical reactions are, nor applies the extensive body of knowledge that has been produced on laws of nature (see previous section).[26] In fact, there is little overlap of the philosophical study of chemical reactions with the literature on metaphysics and philosophy of science.

Moreover, understanding the nature of chemical reactions requires investigating them in their own right as causal and thus potentially lawful relations. Chemical reactions hold an ineliminable role in conveying the causes that determine the course of a chemical transformation, and this role cannot be substituted by identifying and studying only the entities and properties of the reacting substances. Thinking of reactions as causal relations in turn prompts questions about reactions representing laws of nature, as causal relations are traditionally understood as corresponding to regularities in the behaviour of things in the world (Heathcote and Armstrong 1991: 63).

Specifically, there are two key questions that need to be answered with respect to chemical reactions. First, do they correspond to genuine causal relations, and if so, what is their nature? Secondly, what are the relata that figure in this putative causal relation? Regarding the first question, that reactions correspond to causal relations is not uncontroversial, especially if we consider the following. Unlike paradigmatic cases of causal relations, chemical

Footnote 25 (continued)

(e.g. Despotopoulos et al. 2016). However, given that these are open scientific questions, the philosophical implication about uninstantiated laws is still worth considering.

[26] A notable exception is Rom Harré to which I return later.

reaction statements do not describe events where chemical entities irreversibly transform into other entities, just like- say- a rock would irreversibly cause the shattering of a window (Seifert 2024: 62- 65). Instead, they describe dynamic processes which- once reaching equilibrium- result in a state where the system continuously and at a constant rate transforms into the products and reverses back into the reactants. From the perspective of a metaphysical analysis of causes and laws, this suggests that reactions exhibit causal loops and as such they either should not be considered as genuine causal relations, or they pose a challenge for both regularity theorists and necessitarians who require the temporal priority of causes (e.g. Mumford and Anjum 2011).

Beyond this issue, there are also other routes one can pursue so as to make sense of reactions as causal relations. For example, one could understand them as causal mechanisms. The literature on causal mechanisms is extensive and I cannot do justice to all versions of this view. To illustrate how reactions can be conceived in this context, consider how Stuart Glennan defines mechanisms:

> A mechanism for a phenomenon consists of entities (or parts) whose activities and interactions are organized in such a way that they produce the phenomenon. (2017: 13)

Prima facie, there is empirical evidence to support that this is a suitable way of thinking of reactions. This becomes apparent if we take into account how the term 'mechanism' is used in practice in order to explain the course of chemical reactions. Reaction mechanisms are detailed descriptions of the process reactants undergo during a chemical transformation. They specify the properties of intermediary entities and transition states formed during a reaction. This seems in line with how mechanisms are construed in causal terms and may offer empirical support for such a view of reactions. Note that this is not a new approach to reactions. The role of reaction mechanisms in the explanation of chemical reactions has prompted philosophers to advocate a mechanistic view of chemical explanation (e.g. Goodwin 2012; Weininger 2014). Investigating this from a metaphysical perspective can offer further support for a mechanistic view of reactions.

Regarding the second question, namely what are the relata of this putative causal relation, here too there are different views one can explore and interesting features of chemical reactions to take into account. For example, one issue is how to accommodate the role of catalysis. Catalysts are chemical substances that- when present in a chemical transformation- increase the rate of the reaction without modifying its overall standard Gibbs energy change. Their presence can be said to partly cause a reaction because their absence often explains why a reaction does not take place. Nonetheless, they do not substantively participate in the reaction because they do not transform into products. This explains why chemists include them as both a reactant and a product in a chemical reaction statement (Seifert 2024: 64).

The role of catalysts raises the question of whether they should be construed as genuine causes of a reaction or as part of the environment which accommodates a reaction's realisation. This is not a new question to the metaphysics of causation and philosophers have argued about whether we can objectively distinguish between causes and background conditions. This problem vexes even the most mundane examples of causal relations, such as the lighting of a match. Does the presence of oxygen count as one of the causes for the lighting of a match or is it just a background condition? Lewis for example took this issue to be pragmatic: we choose, he claims, depending on our pragmatic needs and purposes, which factors to regard as causes and which as background conditions (1973a; see also Gallow 2022: 1.2.3).

To my knowledge, not many philosophers have investigated chemical reactions as candidate causal relations and laws of nature. A notable exception is Rom Harré (2008; 2012) who has discussed chemical reactions as candidate laws and causal relations in a way that is very close to the spirit of the present paper. In fact, some of the points I make here have also been made by Harré, including how regularities described in chemistry satisfy some of the key features of laws. To support this with respect to chemical reactions, Harré considers three accounts of causation: the Humean approach, Mackie's INUS conditions and agent causation. Without going into detail, he concludes that "the concept of the causal agencies of various classes of powerful particulars plays an indispensable role in the examination of the idea that chemical equations might have the status of laws of chemistry" (Harré 2012: 348).

Before concluding, note that for the regularities depicted both by the periodic table and by chemical reaction statements, one of the most pressing questions is how to maintain their lawful status. This is a particularly challenging issue that is not unique to chemical examples but rather concerns any case study from the special sciences. There are several reasons why this challenge emerges, and these do not solely concern issues around the reducibility of the special sciences to physics.[27] Instead, in the literature about laws, one finds that the primary concern with special science laws is that they are too restricted, whereas laws are thought to be exceptionlness. As Hildebrand puts it:

> Laws in the special sciences have a different character than laws in fundamental physics. in particular, the former admit of exceptions, apply in fewer circumstances, and generally seem less stable. (2023: 50)

In response to the above, one option is to reject that the chemical cases correspond to genuine laws. This would amount to holding an antirealist position, but note that there are at least two ways one can be an antirealist about them. One can either reject altogether that- say- chemical reactions correspond to mind-independent regularities in nature, or one could maintain that such regularities exist but reject laws as a suitable way to characterise them. A position of the second sort is advocated by Nancy Cartwright (1983) who is an antirealist about laws and proposes capacities as a suitable way of spelling out the nature of law-like regularities. Another, fairly antirealist view about chemical laws, is to be a reductionist and take the regularities depicted in chemistry to be reduced to (exceptionlness and stable) regularities of their physical constituents. In this context, one admits their lawful status only to the extent that she admits the existence of the underlying physical laws (in a similar way one would maintain that a reduced entity exists to the extent that its reducing entity exists).

This view also shows how one could maintain the reality of chemical laws: namely by supporting some form of antireductionism. Antireductionist views about chemistry have been discussed extensively so I direct the reader to those references to see how such arguments can be spelled out and empirically supported (e.g. Hendry 2010; Lombardi and Labarca 2005; Scerri 1994). A different and fairly novel approach (at least in the philosophy of chemistry) is to construe chemical laws in terms of patterns. A view like this has been advocated by Ladyman and Ross (2007), Psillos (2014) and Kimpton-Nye (2022). Investigating this view from the perspective of chemistry could offer novel insight into chemistry but also the metaphysics of laws.

[27] Though one could argue that all these problems ultimately stem from the purported reduction to fundamental physics.

Another problem that challenges the lawful status of chemical laws concerns the nature of properties that figure in lawful regularities. Some philosophers (of both the Humean and non-Humean camp) believe that for a regularity to be lawful, the relevant properties need to be natural (e.g. Armstrong 1989; Sider 2013).[28] This is called the naturalness constraint and, for the case of the BSA, it is formulated as follows:

> The best systematization must be expressed in a language whose predicates refer to perfectly natural properties. (Hilderbrand 2023: 14)

This issue may pose a problem especially for those regularities that are depicted in the periodic table and which concern not regular relations between specific chemical elements, but rather relations between sets of elements. These sets may be for example groups, periods or other sets that chemists posit. In this context, one could argue that the property of -say- being a metal is not a natural property and thus the regularity relations in which this property figures are not genuinely lawful. While I do not sketch possible responses to this problem, note that this issue is closely connected to that of natural kinds and whether chemical entities can be admitted as such (including entities such as metals or other groups, periods and families; see Seifert 2024: chapter 1).

Conclusion

A lot has been said about laws in science but not so much in chemistry. The aim of this paper is to motivate a discussion of laws from this perspective. Investigating chemical case studies, such as the periodic table and chemical reactions, from the perspective of laws can rejuvenate existing discussions about the place of chemistry relative to the other sciences in a way that hasn't been thoroughly pursued before.

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[28] What 'natural' means exactly is a matter of contention.

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