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The many laws of the periodic table

Vanessa A. Seifert

University of Athens, Greece

Abstract

There are many- not just one- periodic laws in chemistry. These laws correspond to non-accidental regularity relations about physical and chemical properties of (sets of) chemical elements. I support this by showing how these regularity relations can be understood from the perspective of a philosophical analysis of laws. Specifically, I show that these relations instantiate standard features associated with laws; they can be spelled out in terms of two standard accounts of laws; and, they can coherently figure in debates about the reality of laws as plausible candidates of ceteris paribus laws.

1. Introduction

Several examples have been investigated as paradigmatic candidates of laws, including Newton's law of gravity, the law of supply and demand, and the laws of thermodynamics. With respect to chemistry, a philosophically informed analysis of laws is almost non-existent.[1] This is surprising because chemistry, like physics, economics and thermodynamics, pursues a rigorous analysis of a well-specified domain of phenomena; enjoys enormous empirical success; and, has produced great practical and theoretical advances. So, it is sensible to wonder whether and to what extent this is explainable by the fact that chemistry discovers laws of nature. Furthermore, mention of a 'periodic law' was and remains very common in scientific discourse. It is found in discussions about early classifications of elements and has even preceded the acceptance of Mendeleev's periodic table (Pulkkinen

[1] Exceptions are Harré (2012) who discusses chemical transformations, and Woody (2014) who endorses (without support) a pragmatist stance on the periodic table.

2020, 176). Nowadays, one need not go further than elementary chemistry textbooks to see that reference to a 'periodic law' remains common.

Of course, an investigation of the periodic table in the context of laws presupposes that non-accidental regularities in nature exist. This is far from incontestable. Philosophers argue extensively about whether there are laws and- if so- about how to spell them out (e.g. Cartwright 1983; Mumford 2004). Even though I briefly discuss the diverging views on laws of nature, I do not defend a specific position about them. I only assume that there exist mind-independent, non-accidental regularities in nature which could in principle be spelled out in terms of some account of laws. The aim is not to argue that there are laws of nature, nor to defend a particular account of them. It is to show that the regularities represented by the periodic table are at least as good candidates of non-accidental regularities as other paradigmatic examples considered in philosophy.

Section 2 presents how chemists use the periodic table to form statements about the properties of chemical elements. Section 3 argues that the periodic table is not a representation of a single regularity relation but of multiple regularities between properties of various sets of chemical elements. That is, it is a candidate representation of many laws of nature. Section 4 critically examines a challenge that could undermine this claim.

2. The periodic table and its regularities

The modern periodic table is a visual representation of all known chemical elements. The elements are positioned in the table in terms of increasing atomic number. Starting with hydrogen at the top left, they are positioned consecutively from left to right and top to bottom. Based on this ordering, chemists form statements about physical and chemical properties of matter.

Specifically, the elements found in the same vertical line are said to form 'groups' and those found in the same horizontal line form 'periods'. Groups and periods are useful because certain chemical and physical properties of matter are explicated in virtue of the corresponding element's membership to a group or period.[2] For example, the high reactivity of hydrogen is explicated by the fact that hydrogen belongs to group 1.

The periodic table also classifies elements into sets called 'families'. Chemists invoke membership to a family to form statements about some physical or chemical property of matter. These properties include boiling and melting points, reactivity, electrical conductivity, density, phase, malleability, radioactivity, even softness. For example, matter consisting of elements from the family of alkali metals is said to be highly reactive and to have low melting and boiling points. Finally, the table is said to reveal 'periodic trends'. The way elements are positioned relative to each other reveals trends in how certain chemical and physical properties change relative to changes in the position in the table. For example, the further left and down an element is found, the smaller its atomic radius; the further up and right, the larger its electron affinity and ionisation energy.

These are in a nutshell the sort of regularity statements scientists formulate by analysing the table. Most of them are not visually depicted in the table. Standard versions of the table usually only depict the elements in their particular ordering and include labels (in the form of Arabic and Latin numbers) for identifying groups and periods.[3] Families- when depicted- are identified by different colours. Atomic numbers (and masses) may also be stated next to each element, but properties such as boiling point, electronegativity, reactivity, etc. are not depicted. This implies that these statements cannot be inferred solely by analysing what information is visually found in the table: background knowledge about elements and their properties is also required.[4] Given this, the sense in which I take the table to *represent* these relations is consonant with how scientists themselves often explicate the role of the table in

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[2] There are exceptions as some elements may not instantiate the physical or chemical property that is expected of them as members of a group or period (Scerri 2007: 11).

[3] Alternative tables have been proposed with different elemental orderings (e.g. Scerri 2020a). These are disregarded.

[4] This knowledge is produced through the empirical analysis of matter and the study of physics and chemistry.

identifying these relations. As the American Chemical Society puts it, what the table does is allow scientists "to quickly refer to information about an element" and "to discern trends in element properties".[5]

3. The laws in the periodic table

My claim is two-fold. First, the periodic table represents non-accidental regularities. Secondly, it is not a single regularity which is represented by the table but many. Specifically, the table identifies 118 elements, 18 groups, 7 periods and 8 families. It represents regularity relations about- among other things- their chemical reactivity, boiling point, (non)metallic character, electron affinity, super conductivity and ionisation energy. So, the table represents regularities regarding chemical and physical properties about (sets of) elements; all of them are candidate laws of nature.

The following subsections present three arguments to support this claim.

3.1 Satisfying features of lawhood

No matter what philosophers think of laws, law-like statements play a certain functional role in science in a way that accidental regularities do not. They are statements involving general concepts and not proper names; they are used to make inferences about particular matters of fact and are confirmable by matters of fact; and, they can take the form of counterfactual statements. Moreover, they unify diverse matters of fact, and they have predictive and explanatory power. These features are generally found in statements of candidate laws regardless of whether (and how) philosophers admit their existence.

These features are exhibited by the law-like statements expressed in the table. Whether and which of these features are in fact necessary and/or sufficient for establishing that a regularity is a law, is of course debatable. I leave this open and invoke those features that standardly

[5] https://www.acs.org/education/whatischemistry/periodictable.html#:~:text=Scientists%20use%20the%20periodic%20table,ionization%20energy%2C%20and%20atomic%20radius.

figure in the literature (e.g. Chisholm 1955; Dretske 1977a; Hempel and Oppenheim 1948; Lewis 1973; van Fraassen 1989).

The first requirement for a regularity statement to correspond to a law is that it is factually - not logically- true, and that it does not involve proper names but general concepts. This holds for the law-like statements of the table. Take ‘Halogens are highly reactive’. None of the terms employed corresponds to proper names. Moreover, none of these statements is logically true (or false). Their truth is discovered through empirical testing and observation. In fact, new relationships between previously disregarded or unknown properties of (sets of) elements continue to be discovered (Scerri 2007, 11).

Secondly, statements of laws can be used to make empirically successful inferences about instances of matter (Loewer 1996, 111; van Fraassen 1989, 29). This applies to the statements of the periodic table. For example, that ‘Gold is unreactive’ allows to infer that one’s golden necklace is unreactive. Laws also support counterfactual reasoning in the sense that they make counterfactual statements true (or false) (e.g. Goodman 1947). This too is applicable to the regularity statements of the periodic table. In fact, Chisholm who made one of the first attempts to connect counterfactual reasoning to lawhood, invokes as an example a regularity relation from the periodic table (1955, 97-98). He states that unlike statements of accidental generalisations, statements such as ‘All gold is malleable’ allow one to infer that ‘If that metal were gold, it would be malleable’. Since Chisholm, a lot has been said about counterfactual reasoning and its relation to laws and their modal force (e.g. Lange 2009). While this deserves further analysis, the above suffices to accept that the condition is satisfied for the case in question.

Furthermore, laws unify the behaviour of prima facie disparate things in the world. Indeed, this applies to the statements of the periodic table. Statements about oxygen unify how we understand the behaviour of matter whether it is found in the sky of Athens or on Mars. This feature of laws is connected to the ability of laws to systematise empirical facts. Information about the chemical properties of any particular in the world (for instance, of any gold substance found in jewellery, mines, etc.) is systematically organised by the relevant law about gold. Both these features come down to the fact that laws are universal or statistical claims: they hold at every time and place in the universe, and for all relevant instances of matter (Hempel and Oppenheim 1948, 153).[6] Indeed, the statements of the periodic table hold for all instances of chemical elements found anywhere and anytime in the universe (under specific conditions). One can empirically support this by pointing out the utility of the periodic table in fields such as astrochemistry and geology. In astrochemistry the regularities identified by the table help understand chemical constitution and transformation in other planets. In geology, they are employed to understand how life evolved on earth millions of years ago (e.g. Dobrijevic et. al 2010).

Furthermore, it is expected that lawful statements allow predictions of how instances of matter behaved in the past, present and future (Dretske 1977b, 252). This condition holds for the lawlike statements of the periodic table. In fact, the periodic table is often considered a paradigmatic example of a successful tool for predicting scientific facts. This is based on an analysis of Mendeleev's periodic table which was arguably accepted over alternative tables due to its success in predicting the existence of previously unknown elements (e.g. Lipton 1991). Beyond Mendeleev's version of the table, the statements expressed by the modern table are also ubiquitously used by scientists to predict and retrodict chemical, physical, and biological facts. These facts have contributed to discoveries and theoretical developments in fields such as biology, geology, climate science and astrochemistry. For example, Williams (1997) retrodicted how early life on earth evolved by analysing the stability of transition metals and the reactivity of oxygen, both of which are expressed by the corresponding regularity statements in the periodic table. His analysis of the table, combined with research in geology and biology, lead to novel predictions about how chemical transformations lead to the emergence of life.

Lastly, laws are taken to explain phenomena (e.g. Hempel and Oppenheim 1948). How to spell out explanation is an issue in its own right, but it is generally agreed that laws (in some sense) explain. Assuming a naive understanding of explanation here, one can see how statements in the periodic table offer explanations. For example, that the structure of DNA is spiral is partly explained by the electronic configuration of the elements that make it up. Prima facie, this is a good (though insufficient) indication of the explanatory power of the

[6] I do not examine whether periodic laws are universal or statistical claims.

regularity relations of the table. Given that the explanatory power of the table is contested, I return to this issue in section 4.

All in all, satisfying the above features is a good step towards establishing that the statements expressed in the table correspond to candidate laws. But it is far from sufficient. In the next subsection, I show how standard accounts of laws can be coherently applied to the case in question, further reinforcing that the regularities expressed by the table are as good candidate laws as other paradigmatic examples.

3.2 What kind of laws could the laws in the periodic table be?

Two accounts of laws are considered standard in the literature: the regularity and necessitarian view of laws. Both accounts can coherently apply to the regularities represented in the table, thus reinforcing that these regularities are legitimate candidates of laws. Of course, each view faces challenges and alternative accounts have been proposed. Nevertheless, none of this undermines the paper's claim which is that the regularities represented in the table can be construed as lawful as any other paradigmatic example of laws.

The version of the regularity view I focus on is the Best Systems Account (BSA) advocated independently by Mill (1856), Ramsey (1978) and Lewis (1973; 1986). According to this, "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). Laws of nature are those regularities "that are expressed by the axioms and theorems of an ideal deductive system of our knowledge of the world" (Psillos 2014, 17). The best deductive system consists of axioms and theorems and entails all facts about the world. Being part of the best deductive system is what differentiates lawful regularities from accidental ones, as the latter would not be included in the best deductive system.

One can apply this account to the regularities represented in the table. The principle of distinguishing elements in terms of atomic number can be taken as one of the axioms of the system. The regularity relations which come out from ordering the elements in terms of that principle can then be construed as some of its theorems. Classifying elements into groups, periods and families could also be viewed as axioms of the system. In this context, the regularities regarding the properties and relations between those sets are theorems that come out of that ordering. Note that one would also have to admit as axioms principles from quantum mechanics in order for the theorems to be deduced by the system.[7] But this is not a problem to admitting the axioms and theorems of the periodic table as laws.

From this perspective, the reason for admitting the principles and regularity relations as part of the best deductive system is that they contribute to the system's simplicity and strength. They contribute to its strength because they accurately describe and predict matters of fact regarding the physical and chemical behaviour of matter. They contribute to its simplicity because they offer a concise and unified description of different and diverse matters of fact in terms of well-specified relations between a specific number of elements, groups, periods and families.

Admittedly, one could resist this view by claiming that we allow too many axioms and theorems into the system, thus compromising its simplicity. Indeed, the regularity relations concern different sets of 118 elements and their properties. However, we should not overlook the vast amount of matters of facts that they cover, including facts about reactions after the Big Bang, chemical transformations in the atmospheres of distant planets, and all chemical matters that concern our everyday life (in the past, present and future). Relative to this enormous number of particular matters of fact, the system strikes a fair balance of simplicity and strength.

The necessitarian approach can also coherently apply to the case in question. This view takes laws to be necessitation relations between properties (which are often construed as universals) (e.g. Armstrong 1983; Dretske 1977a; Tooley 1977). While there are disagreements about the precise nature of necessity, it is agreed that things in the world behave as they do because they *must* behave so. For the sake of argument, I consider here

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[7] A possible objection arises if the axioms from quantum mechanics entail (i.e. deduce) all facts that are entailed by the regularities of the periodic table, thus rendering the latter redundant.

Armstrong's version of the necessitarian view which defines laws as contingent necessitation relations between universals (1983, 85).

From this perspective, that 'Gold is unreactive' can be construed as expressing a necessitation relation between being-gold and being-unreactive. Put crudely, this could be interpreted as suggesting that there is something in the nature of gold which necessitates that it exhibits the property of unreactivity. Similarly, the statement 'Lanthanum reacts with halogens' can be construed as expressing a necessitation relation between being-lanthanum and being-an-element-in-the-group-of-halogens. There is something in the nature of lanthanum and of the elements of the group of halogens that necessitates a certain relation (of reactivity) between them.

A possible objection concerns the admittance of groups, periods, and families as universals. One could argue that these classifications do not have the requisite metaphysical import to be admitted as such. This is because there are elements that do not seem to obey the regularity relations that are posited about them in virtue of being members of such classes. For example, flevorium belongs to group 14 and period 7 and is thus expected to behave like a noble gas. However, recent experiments suggest that flerovium's volatility and unreactivity is closer to that of radon of group 18 (Despotopoulos et al. 2016). So, perhaps we should reject these classifications as universals and dismiss the relevant regularities in which they figure as lawful. This is a problem that generally concerns superheavy elements, namely elements with atomic number greater than 103. Empirical evidence suggests that such elements do not always exhibit the properties that are expected of them in virtue of the classes to which they belong. Given this, a possible way to resist this objection is by pointing out that such examples pose a problem to chemistry which in turn is in the process of resolving it (e.g. Despotopoulos et al. 2016). As such, we should remain neutral until this empirical issue has been settled by science. Such a response is also consonant with Armstrong's own view who, as an empiricist, took that science will inform us about which universals exist.

All in all, there is a lot to unpack here, including how to understand simplicity and strength in the context of the BSA, and whether we should admit as universals not only elements (and their properties) but also their classifications. I do not offer answers to these -and possibly other- objections. This analysis should be viewed as an exercise in thought that illustrates how we can coherently conceive the regularities of the table as laws. This further reinforces that these regularities are at least as good candidates of laws as other paradigmatic cases in the sciences.

3.3 What if there are no laws?

Of course, not everyone agrees that there are laws. There are diverse views, ranging from a strong metaphysical commitment to laws to an antirealist stance. For a realist, there are regularities in nature that exist mind-independently, and which are governed by laws of nature. For an antirealist, there are no laws of nature. The latter view can be spelled out in different ways, not all of which are based on the rejection of mind-independent regularities. For example, Cartwright (1983) is an antirealist about laws in the sense that the lawlike regularities are grounded on the causal powers of things in the world. Similarly, Mumford (2004) claims that there are no laws but only properties which govern the behaviour of things. In the present context, there is value in considering a view which admits the existence of mind-independent regularities but does not invoke laws to understand them. [8] This is Cartwright's view which is based on the problem of ceteris paribus laws.

According to Cartwright (1980; 1983), there are no laws of nature because most generalisations in science hold ceteris paribus. This is a problem because if laws are taken as descriptions of actual phenomena, then for the majority of natural phenomena these descriptions are false. Given that the majority of scientific descriptions hold ceteris paribus, Cartwright concludes that we cannot commit to the view that science discovers laws of nature. Instead, we should take law-like statements as serving an explanatory function: they guide scientists in identifying those factors that play a causal role in the occurrence (and thus explanation) of some phenomenon.

Regardless of whether this criticism holds, it can be applied to the law-like statements of the table in the same way it is applied to other paradigmatic candidates of laws. Take the statement 'Lanthanum reacts with halogens'. This is a ceteris paribus statement because it posits a regularity relation that holds under a specific range of temperature and pressure. Moreover, a degree of purity for the reactants is required which is very rarely observed (or

[8] This is a selective analysis of one of the problems raised in the literature.

even experimentally achievable). In general, the regularity relations between the physical or chemical properties of elements are instantiated only within well-specified thermodynamic and environmental conditions. This applies to all law-like statements expressed in the periodic table: they are true only under particular conditions. This renders them plausible candidates of non-exceptionless laws.

If one prescribes to this (as it seems sensible to do), then there are ways to maintain that there exist mind-independent regularities which are represented by the periodic table. For example, one could claim that these regularities are grounded on something other than laws, such as the causal powers of the elements. Following the spirit of Cartwright's account, one could argue that the ceteris paribus statements connecting properties of (sets of) elements identify the causal factors that are relevant to explaining the chemical and physical behaviour of matter. Alternatively, one could claim that laws of nature need not be exceptionlness. One way to do this is by understanding them as idealisation laws. Friend, for example, offers a Humean account of laws that permits the admittance of idealisations laws as meta-laws in a best deductive system (2023, 162-167).

Following the same spirit as in the previous section, I am neutral as to which of these routes best spells out the nature of the law-like regularities of the table. The fact that the statements of the table can figure in discussions about the reality of laws should not be viewed as undermining the claim that they represent legitimate candidates of laws. Rather, it demonstrates that (i) one need not commit to a realist stance towards laws to admit that the regularities represented in the table are non-accidental; and (ii) at the very least, the regularities of the table are as good candidates as other paradigmatic candidates of laws that similarly figure in discussions about the reality of laws.

4. A challenge to the periodic table representing laws

A putative problem with the lawful status of the periodic table is connected to its explanatory power. Scerri (2020b) claims that the periodic table lacks genuine explanatory power because quantum mechanics and reference to the electronic configuration of elements do all the explaining of the relevant phenomena. Therefore, the table is explanatorily redundant. This worry is an instance of a more general problem raised against special science laws, and is usually based on the adoption of a reductionist stance towards the special sciences (e.g. Fodor

1989; Kim 2010). On this view, if special science regularities are somehow ‘grounded’ or reduced to more fundamental physical regularities, then we should not grant them lawful status.

Applied to the periodic table, the claim is that there are no lawful regularities in the table because physical laws (expressed in quantum physics via the solution of the Schrödinger equation) are - at least in principle- sufficient in explaining the relevant phenomena. On this view, if we were able to accurately describe how the physical entities that make up chemical elements interact with each other, then we could explain the relevant chemical and physical phenomena. So, admitting regularities about chemical elements as candidate laws is undermined because physical laws do all the explanatory work. Put differently, the regularities represented in the table are derivative and should not be granted lawful status.

There is more than one way to overcome this challenge. First, one could contest that quantum physics manages to explain sufficiently the phenomena which are explainable by the regularities of the table. This is based on developing an antireductionist stance about chemistry and its relation to quantum physics (in the form of some account of emergence or pluralism; e.g. Hendry 2010; Lombardi and Labarca 2005; Scerri 1997).

Alternatively, one could overcome this challenge without denying that a more fundamental theory or law explains the regularities discovered by a special science. A possible reply of this sort is that we need to distinguish between what a law explains and how a law is explained. Take for instance a paradigmatic candidate law: $PV = nRT$ (the ideal gas law). The law itself may not explain why this mathematical relation holds between pressure, volume, and temperature. One could even claim as a reductionist that statistical mechanics explains why this relation holds between these properties. Nevertheless, one can maintain that this law-like statement has explanatory power as it explains how particular instances of matter behave when we increase- say- their temperature. A similar response can be formulated about the regularities expressed in the table. Take ‘Actinium reacts rapidly with oxygen’. The electronic configuration of actinium and oxygen may explain why they react as they do. Nevertheless, this does not diminish the statement’s explanatory power with respect to observed instances of chemical transformations.

Once again there is a lot to unpack here. Nevertheless, I take the present aim to be fulfilled. I showed that it is possible to overcome worries about the table's explanatory power and thus maintain its lawfulness, both from a reductionist and an antireductionist perspective.

5. Conclusion

The relationships identified by scientists through the study of the periodic table are candidate laws of nature; i.e. non-accidental regularity relations connecting chemical and physical properties of (sets of) elements. I support this by showing how these regularity relations can be understood from the perspective of a philosophical analysis of laws. I show that they instantiate standard features associated with laws; they can be spelled out in terms of two standard accounts of laws; and, they can coherently figure in debates about the reality of laws as plausible candidates of ceteris paribus laws.

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