Preprint
Forthcoming in *Synthese*

Causal Explanation and the Periodic Table

Lauren N. Ross

The periodic table represents and organizes all known chemical elements on the basis of their properties. While the importance of this table in chemistry is uncontroversial, the role that it plays in scientific reasoning remains heavily disputed. Many philosophers deny the explanatory role of the table and insist that it is "merely" classificatory (Shapere, 1977, 534-5) (Scerri, 1997a, 239). In particular, it has been claimed that the table does not figure in causal explanation because it "does not reveal causal structure" (Woody, 2014, 143). This paper provides an analysis of what it means to say that a scientific figure reveals causal structure and it argues that the modern periodic table does just this. It also clarifies why these "merely" classificatory claims have seemed so compelling–this is because these claims often focus on the earliest periodic tables, which lack the causal structure present in modern versions.

1 Introduction. To the extent that there is a trademark figure for the field of chemistry it is surely the periodic table. Considered by many to capture the "essence" of this scientific domain, the periodic table represents and organizes all known chemical elements on the basis of their properties (Scerri, 2007, xiii). While the importance of this table in chemistry is uncontroversial, the role that it plays in scientific reasoning remains heavily disputed. Many suggest that this table serves as a helpful tool for classifying chemical substances, while denying that it figures in scientific explanation (Shapere, 1977, 534-5). The periodic table is said to resemble classifications such as Linnaean taxonomy and the Dewey decimal system, which organize phenomena on the basis of various features without explaining them (Scerri, 1997a, 239). More specifically, it has been claimed that the periodic table does not figure in causal explanation because it "does not reveal causal structure" (Woody, 2014, 143).[1] Typically, causal explanations involve explaining some outcome by appealing to its causes. If the periodic table lacks causal information or causal structure, this would indicate its inability to participate in such explanations.

These claims about the explanatory nature of the periodic table have been related to various topics in philosophy of science. One related set of topics involves the concept of scientific theories, their role in explanation, and their connection to non-explanatory projects such as prediction and classification. Some of these analyses have adopted a theory-centered view of explanation, where explanations involve derivations from or reductions to particular theories. In this work, the periodic

*I would like to thank Jim Woodward, Eric Scerri, Julia Bursten, and two anonymous reviewers for helpful feedback on this paper.

†To contact the author, please write to: Lauren N. Ross, Department of Logic and Philosophy of Science, University of California, Irvine, 3151 Social Science Plaza A, University of California, Irvine 92697-5100; email: rossl@uci.edu.

[1] Even those philosophers who ascribe some explanatory status to the periodic table deny its role in causal explanation (Kitcher, 1989, 428-9) (Woody, 2014, 143).

table is often used as a paradigmatic example of a non-explanatory project as it cannot be reduced to or derived from any underlying theory (Shapere, 1977; Scerri, 1997a; Scerri and Worrall, 2001; Woody, 2014). In this sense, the periodic table is said to be "devoid of theoretical status" as it does "not seek to explain the facts but merely to classify them" (Scerri, 1997a, 239). These and other analyses go to great lengths to clarify how the table lacks explanatory power, despite being useful for classification and prediction (Shapere, 1977; Scerri, 1997a; Scerri and Worrall, 2001). In recent work, more diverse accounts of explanation have been acknowledged, beyond these theory-centered formulations.[2] However, despite this work, it has still been suggested that the periodic table "seems a rather poor candidate for explanatory status" under any of these various accounts (Woody, 2014, 143).

This paper examines the status of the periodic table with respect to causal explanation. It engages with claims that the table lacks "causal structure" (Woody, 2014, 143) and explanatory power (Scerri, 1997a, 239). When these claims are examined in the context of chemists' discussions and use of the periodic table, they raise a number of puzzles. First, chemists claim that the table allows them to explain particular properties of the elements and their periodic nature (Chang, 2007, 326) (Myers, 2003, 66) (Weller et al., 2014, 273). Second, they often invoke information in the table in ways that suggest it has causal implications. The table contains information about chemical and physical properties of the elements, which chemists state are "explained," "rationalized," and "determine[d]" by atomic structure (Weller et al., 2014, 271), (Myers, 2003, 44, 66, 85). The relationship between atomic structure and chemical properties is said to be "best conceived as one of cause and effect, with atomic structure determining chemical properties" (Strong, 1959, 344). Relatedly, standard chemistry textbooks maintain that a goal of the field is to "explain periodic variations in atomic radii, electronegativities, charges, and covalent bond types in terms of our theory of the electronic structure of the atom itself" (Wulfsberg, 1991, 371). These considerations lead to a number of questions. First, if the table is "merely" classificatory, why do scientists seem to invoke it in explanations of these phenomena? Second, if the table lacks causal structure, why is it cited in explanations that appear to be causal? Furthermore, what exactly does it mean to say that a figure has or "reveals" causal structure as opposed to capturing some non-causal classification? The central nature of this table in the field of chemistry and the strong tension between philosophical and scientific claims about its explanatory status motivate these questions and the search for satisfying answers.

This paper argues that the modern periodic table does reveal causal structure in the sense of containing causal information that figures in explanations in chemistry. I provide an analysis of what it means for a figure to reveal causal structure where this distinguishes the project of causal explanation from mere classification, prediction, and description. The rest of this paper is organized as follows. Section 2 reviews background leading up to the development of the modern periodic table. In section 3, the interventionist account of causation is introduced and used to specify a set of criteria for causal structure. These criteria are used to examine the table in sections 3 and 4 where information relevant to the explanandum and explanans are examined. Section 5 clarifies differences between the modern periodic table and systems that are "merely" classificatory, such as Linnaean taxonomy and the Dewey Decimal system. Section 6 concludes.

[2]A non-exhaustive list of different accounts of scientific explanation include: causal (Woodward, 2003), non-causal (Batterman, 2010; Saatsi and Pexton, 2018), mechanistic (Bechtel and Richardson, 2010), unificatory (Kitcher, 1989), and deductive-nomological accounts (Hempel, 1965).

2 The periodic table: Some background. The modern periodic table originated with developments in the mid-19th century. Soon after the acceptance of a standardized set of atomic weights published by Cannizzaro from 1858-1860, it was discovered that many chemical and physical properties of the elements are a periodic function of their atomic weight (Moeller, 1980 p. 23) (Scerri, 2007, 66). Properties such as atomic volume were shown to increase in repeated intervals among elements serially ordered by atomic weight, as shown in Meyer's graph in figure 1 (Meyer, 1870). In this figure, the repeating peaks correspond to elements that share the property of large atomic volume (Li, Na, K, Rb, Cs), while the valleys correspond to elements with low atomic volume (B, Al, Co, Rh). Attempts to clearly capture this pattern led to a number of representational formats, including some of the earliest periodic tables. Mendeleev produced some of the most well-known examples of these tables in which he ordered elements of increasing atomic weight in columns from top-to-bottom and left-to right, such that their chemical similarity or "family resemblance" was captured along a horizontal dimension, by rows (in later tables, including the modern one, these similarities are captured vertically) (Mendeleev, 1869) (Scerri, 2007, 125).[3] This can be seen in figure 2 where, for example, the 14th row from the top identifies elements (Li, Na, K, Rb, Cs, Tl) with the shared properties of large atomic volume and a valence (or combining power) of 1. The consistent periodic relationship between an element's properties and atomic weight led Mendeleev to use this "periodic law" to make a number of predictions about the behavior of undiscovered elements of particular atomic weights (Moeller et al., 1980, 158). Some of these predictions would be confirmed in later work and they are represented by various question marks in his table.[4]

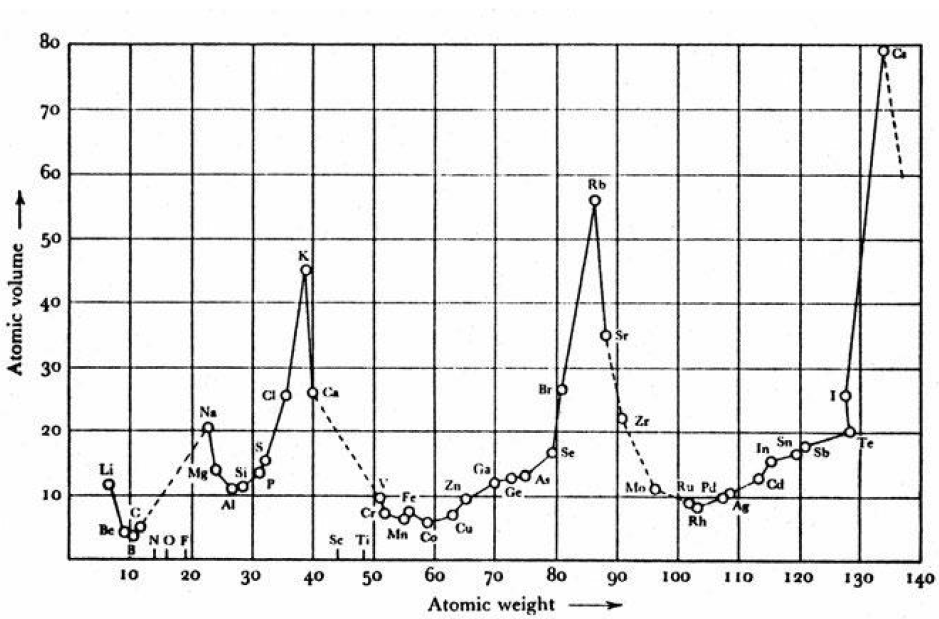

Figure 1: Periodicity in graphical format (Meyer, 1870).

[3]Meyer and others produced similar tables, with horizontal similarities. Mendeleev had other non-tabular representations of chemical periodicity.
[4]For example, the question marks "?=68" and "?=70" represents such predictions.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,1.
			Fe=56	Ru=104,4	Ir=198.
			Ni=Co=59	Pd=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be= 9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,3	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Figure 2: Periodicity in tabular format (Mendeleev, 1869).

While many chemical and physical properties were shown to follow a periodic pattern, ordering the elements on the basis of atomic weight sometimes produced inconsistencies in this pattern. For example, although Tellurim (Te) should be ordered after Iodine (I) due to its higher atomic weight, reversing their order placed both in horizontal rows among similar elements. Mendeleev's careful studies of chemical properties (and his conviction that they should approximate periodicity) led him to attribute these inconsistencies to incorrectly measured atomic weights (Scerri, 2007, 125-126) (Scerri and Worrall, 2001, 435).[5] While the atomic weights of some elements would be adjusted in the future, many of these imperfections were largely resolved after the implementation of a new ordering principle in the early twentieth century–namely, atomic number. The discovery of x-rays and research on radioactivity led to the identification of positive charge in the nucleus. This positive charge would be associated with the number of protons in an element, reflected by atomic number. Ordering elements on the basis of atomic (or proton) number produced a more consistent periodic pattern than ordering on the basis of atomic weight. While the exact reason for this would be pursued in further work, it was at least clear that proton number reliably increased by a single unit through element ordering, while atomic weight was much more variable. Atomic weight did not increase by a standard amount through serially ordered elements and it could vary across different samples of the same element. These features would later be explained by variations in neutron number, which are uncharged particles in the nucleus of an atom. While both protons and neutrons contribute to atomic weight, neutrons do not reliably track increases in proton number and they can vary across different samples of the same element (as in the case of isotopes). This clarified how an ordering on the basis of atomic weight and atomic number could differ and why imperfections found in the former were resolved with the latter. If an element with fewer protons than another had far more neutrons, it could have a lower atomic number but a higher atomic weight. This made sense of the Tellurium and Iodine case. Although Tellurium had a lower number of protons (52)

[5]He claimed that the correct weight of Tellurium was less than Iodine, which restored the periodic pattern (Mendeleev, 1871). Mendeleev's reversal of these elements can be seen in figure 2.

(and thus, a lower atomic number) than Iodine (53), naturally occurring samples of Tellurium had far more neutrons than Iodine and, thus, weighed more (Scerri, 2011, 82). Ordering on the basis of atomic number placed Tellurium before Iodine, which captured a more consistent periodic pattern.

Throughout this early work, the main phenomena of interest were various chemical and physical properties and the periodic nature of these properties across elements. Of course, identifying this periodicity required the right kind of ordering principle. While both atomic weight and atomic number worked well enough to reveal much of this pattern, they were quite limited in explaining aspects of this pattern that interested scientists, such as why it was present at all and why it had particular features. As Mendeleev would state, the periodic law and reoccurring properties of the elements remained "unexpected phenomena without explanation" (Mendeleev, 1871, 42). Chemists were "capable of discovering the law, but not of knowing its true cause" (Mendeleev, 1899, 221). Nothing about these ordering principles explained why elements in a particular row all shared the same set of properties or why other properties varied periodically across serially ordered elements. In some sense, many early periodic tables represented *that* elements follow this periodic pattern, without involving any underlying explanation for *why* they do.

Conceptions of the proper ordering principle would undergo one more change before influencing our modern periodic table. This change involved the incorporation of electronic structure into an ordering based on atomic number. We now know that atomic (or proton) number also reflects the number of electrons in an element–in neutrally charged atoms changes in proton number track changes in electron number. In modern chemistry, scientists frequently appeal to atomic structure in explaining the chemical and physical properties of the elements and their periodic character. As Moeller states, "Mendeleev's ordering of the elements is completely explained by modern atomic theory" (Moeller et al., 1980, 159). While these explanations typically cite subatomic particles, including protons and electrons, they typically place significant emphasis on electronic structure. As Scerri states, "it is still generally believed that the electron holds the key to explaining the existence of the periodic table and the form it takes" (Scerri, 2007, 183). Furthermore, these explanations often appear causal in nature. Chemists claim that electronic structure "determines," "dictates," and "is responsible for" the behavior of the elements and, relatedly, that these behaviors "depend on" and are a "consequence of" this structure (Housecroft and Sharpe, 2010, 20). This interpretation is consistent with other statements in the literature. For example, it is claimed that "the concept of electronic configuration as a *causally explanatory* feature has become very much the domain of chemistry or to be more precise it is the dominant paradigm in modern chemistry" (Scerri, 1997a, 236, emphasis added).

If electronic and atomic structure play a role in explaining the periodic behavior of the elements, how should we understand these explanations? What role does the periodic table play in this explanatory process and is best understood as causal in nature?

3 Interventionism and causal structure. Before considering the role of electronic and atomic structure in explanations in chemistry, it will help to briefly clarify the basic account of causal explanation I rely on, the relevant explanatory targets in this example, and how information about these targets is represented in the modern periodic table. Once these are specified, I will provide an account of what it means to say that atomic and electronic factors explain various properties of the elements. In particular, I will show that the periodic table contains causal information that figures in these explanations. A main goal of this section is to begin sketching what criteria need to be met in order to maintain that a figure contains causal structure. By scientific figure, I refer to visual representations (typically included in scientific publications) that are associated with and used to describe scientific concepts. After outlining a set of criteria that distinguish figures with causal structure from those that lack it, I apply these criteria to the periodic table and then consider their more general application.

My analysis relies on an interventionist account of causation, which maintains that causes are factors that "make a difference" to their effects (Woodward, 2003). On this account, causal relationships take place between variables that represent properties capable of taking on differing values. Consider the following minimal interventionist criterion (I): to say that X is a cause of Y means that, in some background circumstances B, changes in X produce changes in Y. In other words, if one were to intervene on X and change its values, this would lead to changes in the values of Y.[6] For example, suppose we have a light switch X and a light bulb Y that can each take on the values (0, 1), representing the 'off' and 'on' states of the switch and bulb, respectively. When we say that the switch causes the light to turn 'on' or 'off,' we mean that manipulating the switch provides control over these states of the bulb. This "change relating" conception of causation relates changes in a cause variable to changes in an effect variable. These changes have to do with the hypothetical control a cause exerts over an effect and, relatedly, the way in which an effect depends on its causes.[7]

Two features of this account should be highlighted. First, in order to capture changes in causes and effects, the variables representing them need to take on at least two different values (and they will often take on a larger range of values). Second, it needs to be clear how values of the cause variable systematically relate to values of the effect variable in a way that meets the minimal interventionist criterion (I). In identifying causal relationships it is not enough to simply specify two properties that have a purported causal connection or even two properties that can each take on some range of different values. It needs to be clear how changing values of the cause variable produces changes in values of the effect variable or, similarly, how changes in values of the effect variable depend on changes in values of the cause variable. To be clear, this formulation crucially depends on the notion of intervention without suggesting that counterfactual dependence alone is sufficient for causation. These considerations suggest three criteria that a scientific figure should meet if it contains causal structure or causal information. At the very least, such figures should specify (i) some cause variable C that can take on different values, (ii) an effect variable E that can take on different values, and (iii) how values of C systematically relate to values of E in the interventionist sense (I) captured above.[8]

What does this account of causation have to do with explanation? Causal explanations are often characterized as the explanation of some effect by appealing to its causes. On the interventionist account an explanandum is represented by some range of values in an effect variable. The corresponding explanans involves some cause variable (or variables) and how its different values systematically relate–in an interventionist sense–to the range of values in the effect. Intervening on and changing values of the cause produces systematic changes in the value of the effect, or al-

[6]The relevant notion of an intervention here is an "ideal intervention," which guarantees that X is manipulated without also manipulating factors that cause or are associated with Y. For more on this see (Woodward, 2003).

[7]The control is "hypothetical" because we often talk about factors causing particular outcomes, even though we lack the ability to actually intervene on the causes. What we mean is that if such causes were manipulated, they would produces changes in the effect (Woodward, 2003).

[8]A further requirement that is assumed in this analysis is that these variables and relationships represent true claims about actual properties in the world (Woodward, 2016; Woodward, 2014a).

ternatively, varying states of the effect depends on varying states of the cause. In the philosophical literature there is a long tradition of distinguishing explanation from other scientific activities such as classification, description, and prediction. The interventionist account follows this tradition and distinguishes causal explanation from these activities on the basis of their identification of relationships with interventionist causal control in the sense captured in (I). Of course, scientists are interested in all sorts of phenomena and relationships, including some that fail to meet this interventionist standard. For example, they may be interested in classifying or describing organisms on the basis of "surface level" phenotypic features without concerning themselves with the causes of such features. Moreover, these features might help in predicting the presence of some future phenotypic outcome, without it being the case that they cause the outcome itself (perhaps there is a mere correlation). This is all to say that legitimate classificatory, descriptive, and predictive projects can be guided by considerations that do not involve causal information. However, where the hallmark of causal explanation involves supplying "difference making" information–i.e. information relevant to manipulation and control–these projects will *not* be viewed as providing causal explanations.[9]

4 The modern periodic table. Consider the modern periodic table, shown in figure 3, which represents various chemical and physical properties of the elements and their periodic nature. Each box in this table represents an element, where the letters and numbers indicate the element's abbreviated symbol and atomic number, respectively. Elements are organized in horizontal rows called "periods" and vertical columns called "groups." Ordering on the basis of atomic number starts at the top left of the table with Hydrogen (which has an atomic number of 1) and continues from left-to-right and top-to-bottom throughout the table. Elements are "defined" by their atomic number–no two elements have the same atomic number and substances with the same atomic number are the same element (Nath and Cholakov, 2009, 94).

4.1 Explanandum. Elements in the table are organized in a way that captures various patterns in their properties. Two types of these patterns are group trends and periodic trends. Group trends refer to clusters of chemical behaviors that are shared among elements in the same group or column of the table. These columns of elements are referred to as "chemical families" due to the fact that they contain "chemical homologues" or elements that exhibit similar chemical behaviors (Seaborg, 1959, 472). For example, group 17 is the halogen family, which contains highly reactive, non-metals (poor conductors of heat and electricity) that frequently combine with other elements to form compounds. Another example is the noble gas family, or group 18, which is comprised of odorless, colorless, nonflammable gases with low reactivity in standard conditions. Where many of Mendeleev's earlier tables (e.g., figure 2) captured these chemical similarities or "family resemblance" relations along the horizontal dimension, the modern table captures these similarities vertically.[10] Group trends exhibit periodicity in the sense that they identify clusters

[9]Here I refer to "difference making" information that is relevant to manipulation and control as a kind of hallmark of causal explanation. This should not be confused with the claim that all explanations (e.g. non-causal explanations) require such information. In fact, a significant amount of recent work has examined non-causal explanations that involve counterfactual or "difference-making" information, where such information need not be relevant to manipulation or control (Saatsi and Pexton, 2018; Reutlinger, 2016).

[10]In order to see the similarities between Mendeleev's table in figure 2 and the modern periodic table, Mendeleev's table should be rotated by 90 degrees and reflected across the vertical axis (Gordin, 2004, 28).

Periods \ Groups	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Figure 3: The modern periodic table.

of chemical properties that periodically reoccur throughout serially ordered elements. The modern table is organized so that these reoccurrences line up in a vertical manner.

A second set of patterns found in the table are periodic trends. Where group trends capture changes in clusters of properties, periodic trends capture changes in single properties. Examples of standard periodic trends include atomic radius, electron affinity, ionization energy, and metallic character. The modern table is organized in a way that captures trends in these single properties throughout all elements in the table. These trends are explicitly shown in figure 4. In order to see this clearly, consider atomic radius–the arrows in figure 4 indicate directions of increasing atomic radius throughout all elements in the table. This property increases from top-to-bottom and right-to-left throughout the table. In other words, atomic radius increases as one moves down groups and leftward in periods. Other periodic trends can be read off this figure in a similar fashion.

Group and periodic trends represent one layer of information in the modern periodic table. Inorganic chemists refer to this information as "descriptive chemistry" because it describes the brute, observable "hard facts" about properties of the elements (Williams, 1979, viii) (Weller et al., 2014, 271). The table organizes these facts in a way that captures trends in these properties and it renders them more comprehensible than a rote study of individual elements. Instead of memorizing the unique features of over 100 individual elements, a qualitative understanding of these features is provided by spatial trends in the table and the relative location of any element (Scerri, 2011, 28). This involves "discussing the chemistry of an element in terms of its position in the periodic table" (Williams, 1979, 277). Impressively, the table serves this role for all known or naturally occurring elements, which leads chemists to speak of its "unifying" nature and the fact that it is

Some of Mendeleev's later tables captured group trends in a vertical manner, similar to the modern table.

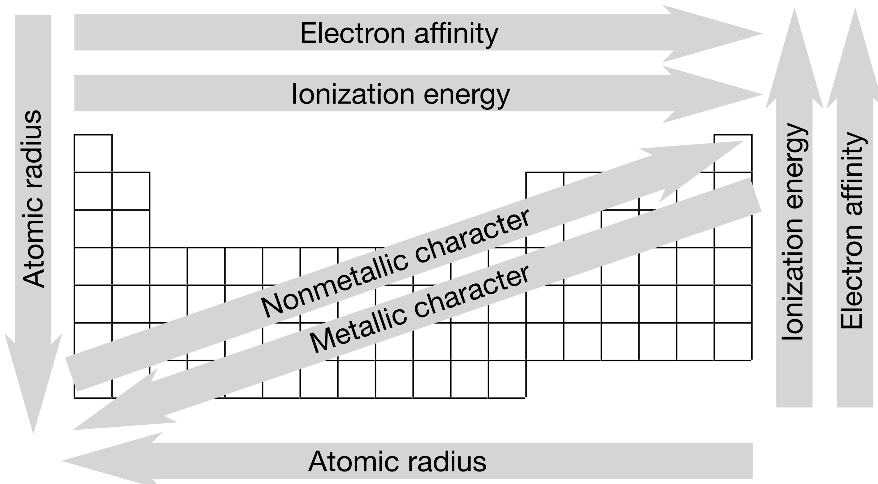

Figure 4: Periodic trends.

a "single chart" that "embodies the whole of the discipline" (Scerri, 2012, 329). This descriptive information serves other purposes as well. The "close neighbor" relations of nearby elements in the table facilitates comparisons and suggests elements that could replace others in chemical reactions (Woody, 2014, 139) (Scerri, 2011, 10-11). These features of the modern periodic table have led to its use as a key pedagogical tool in teaching descriptive chemistry (Moeller et al., 1980, xxv). In fact, Mendeleev's earliest periodic tables were motivated by an interest in pedagogical utility and in making the periodic pattern intelligible.[11] As efforts to organize these descriptive "facts" led to some of the earliest periodic tables, it is claimed that "descriptive chemistry forms the historical basis of the periodic table" (Houten, 2009, 11).

However, chemists are not just interested in describing and organizing these facts about properties of the elements–they also want to explain them. Inorganic chemists distinguish "descriptive chemistry," which *describes* facts about properties of the elements, from "theoretical chemistry," which employs theories and principles to *explain* these facts. The theories and principles that they view as providing these explanations concern the atomic and electronic structure of the elements. Chemistry textbooks often mention this distinction and its relevance to explanation:

> This part of the book describes the physical and chemical properties of the elements as they are set out in the periodic table. This 'descriptive chemistry' of the elements reveals a rich tapestry of patterns and trends, many of which can be rationalized and explained by application of the [atomic] concepts developed in Part 1" (Weller et al., 2014, 271).
>
> The principles of chemistry are the explanations of the chemical facts; this is where you meet the hypothesis, the laws, and the theories. Descriptive chemistry, as you might expect, is the description of the elements and compounds, their physical states, and how they behave" (Moeller et al., 1980, 7).

[11]Mendeleev states that tables of elements have a "pedagogic importance as a means of learning easily various facts, systematically arranged and united one to another" (Gordin, 2004, 28-9)(Mendeleev, 1871).

> [I]norganic chemistry is not just the study of properties and reactions; it includes explanations. To explain "why" it is necessary to look at the principles of chemistry, such as atomic structure, bonding, intermolecular forces, thermodynamics, and acid-base behavior" (Rayner-Canham, 1996, xii).

> So far in this book we have explored ways in which the chemical reactions and physical properties of the elements and their compounds are related to some more fundamental properties of the atoms of the elements: their radii, electronegativities, charges, covalent-bond types and energies, and periodic table positions. But in chemistry we also seek to explain periodic variations in atomic radii, electronegativities, charges, and covalent bond types in terms of our theory of the electronic structure of the atom itself. This is the job of the field of *theoretical chemistry* (Wulfsberg, 1991, 371).

These quotes and the previous analysis help reveal a number of things. First, chemists are interested in explaining properties of the elements and they distinguish this project from merely describing these properties.[12] Second, some of the properties they seek to explain are group and periodic trends, which are the main explanatory targets of the modern periodic table. Group and periodic trends represent an *explanandum* or *effect* overlay in the table. They capture a layer of information in the table that represents changes in the chemical and physical properties of the elements that scientists are interested in explaining. The interventionist framework provides a natural way to understand such explananda. For a particular group or periodic trend, the property in question can be represented by a variable P that is capable of taking on a range of values. For example if P_p is atomic radius, the different values of this property are qualitatively depicted by the arrows in figure 4, which capture consistent, step-wise changes in this property across all elements in the table. The table captures how P_p changes when one starts at any element in the table and moves to any other. This basic point is true for group behaviors as well. Group behaviors are best thought of as variables P_g that take on discrete, binary values (as opposed to the continuous values taken on by P_p) that are present in some groups (1) and absent (0) in others. Changes in these values are represented by the location of elements within vertical columns of the table. The values of P_g change when moving across columns (or horizontally) in the table because elements in the same column have the same behaviors and, thus, the same value.[13] The values of both P_p and P_g vary periodically when one follows elements ordered by atomic number. A third point is that this explanandum overlay clarifies how the periodic table meets one of the three criteria for causal structure. It meets the second criterion because it contains information about an effect variable and the different values it can take. This does not deny that chemists can be interested in this layer solely for its descriptive information. The point is that when chemists want to explain these

[12] Notice that these scientists connect the notion of "theory" to "explanation" in a way that might appear similar to earlier theory-centered accounts of explanation (Shapere, 1977; Scerri, 1997a). While these earlier views take explanation as involving reductions or derivations, I suggest something different. In many cases, the use of "theoretical" by chemists can be understood as referring to important causal relationships that explain how various properties of elements change as a result of changes in atomic structure. In this sense, genuine understanding and explanation is provided by atomic theory, which specifies a causal relationship between some explanandum (atomic structure) and explanans (chemical behavior) of interest.

[13] For example, if P_g represents the cluster of chemical behaviors displayed by group 17, elements in this column have value of 1 for this variable (representing the presence of these behaviors), while elements in other others have a value of 0 for this variable (as they lack these behaviors).

descriptive properties, they serve as an explanatory target. The effect variable is a given property specified by the group or period trends. The different values that it takes are specified by changes in the property as one moves throughout the table. Fourth, these quotes do not just reveal what chemists want to explain, but also what they view as doing the explanatory work. They clearly view electronic and atomic structure as explanatorily relevant to various properties of the elements.[14] I argue that some of these explanations have a causal interpretation and that information about these causal relationships is captured in the modern periodic table. In order to see this, I turn to an examination of electronic and atomic properties of the elements, their representation in the periodic table, and how they figure in these explanations.

4.2 Explanans. As mentioned earlier, electronic structure is importantly related to atomic number. In particular, atomic number does not just reflect the number of protons in an atom of an element, but also its number of electrons.[15] For elements of increasing atomic number, the additional protons are located in the nucleus (or center) of the atom, while electrons are added to shells–and orbitals within these shells–that surround the nucleus. Different shells contain different orbital types as shown in figure 5. In this figure, shells (n) are represented horizontally and orbital types (l) vertically. The first shell contains one s orbital, the second contains one s and one p orbital, the third contains one s, p, and d orbital, and so on. Distinct orbitals within these shells hold different maximum amounts of elections. Orbital types s, p, d, and f can hold a maximum of 2, 6, 10, and 14 electrons, respectively. The order in which these shells and orbitals are filled with electrons is specified by the Madelung rule, which is represented by the winding arrow in figure 5 (Allen and Knight, 2002) (Housecroft and Sharpe, 2010).[16] This arrow shows that in following elements of increasing atomic number, electrons are added first to the s orbital of the first shell (1s), then the s orbital of the second shell (2s), the p orbital of the second shell (2p), and so on.[17] While this filling principle holds generally, it should not be viewed as a "strict rule" because there are some exceptions to it (Myers, 2003, 67) (Scerri, 1997b, 552). Nevertheless, in most cases, this principle allows one to use the atomic number of an element to determine its electronic configuration or the relative location of its electrons in particular orbitals and shells.

When scientists explain group and periodic trends, they place significant emphasis on electron configuration and, in particular, on an atom's "valence electrons," which are those electrons in its outermost orbitals. The outermost position of these electrons influences chemical reactivity, the stability of an atom, and properties like atomic radius.[18] Chemists explicitly appeal to valence electrons in their discussions of the periodic table and chemical explanations:

[14]This is related to the claim that microstructural features of the elements explain some of their macroscopic properties (Bursten, 2014).

[15]This is the case with neutrally charged atoms, which are assumed in standard characterizations of the periodic table (Myers, 2003, 41), (Hofmann, 2002, 6).

[16]The Madelung rule is also referred to as the $(n + l)$ rule, the Janet rule, and the Klechkowsky rule. This rule is related Bohr's Aufbau (or "building up") principle, which states that atoms are built up by adding protons and electrons, where electrons occupy orbitals of lowest energy.

[17]Notice that electrons are not added in a manner that tracks increasing shell number. For example, electrons are added to the s orbital of the fourth shell (4s) before the d orbital of the third shell (3d).

[18]These features have to do with the fact that the valence electrons are more available for bonding, the degree to which they fill up the outermost shell influences stability, and their orbital location alters how close protons can pull them centrally (Rayner-Canham and Overton, 2010, 30-31) (Myers, 2003, 66).

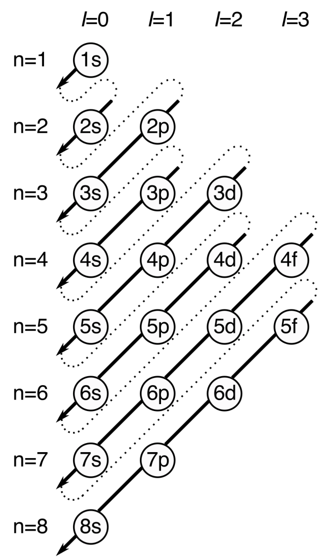

Figure 5: Madelung rule and filling of orbitals.

> "the electron configurations of the elements provide the basis for explaining many aspects of chemistry. Particularly important are the electrons in the outermost orbital of an element. These electrons, known as the valence electrons, are responsible for the chemical properties elements display, bonding, the periodic table, and many chemical principles" (Myers, 2003, 43-44).

The best way to understand these claims–and a main feature of these explanations–is that electronic and atomic structure are causally responsible for various chemical and physical properties of the elements, in an interventionist manner. These atomic features "make a difference" to these properties in the sense that changes in these features produce changes in these properties. Before I explore this in more detail, it will help to connect this discussion of electronic structure to the periodic table and the explicitly *periodic* nature of elemental properties displayed in the table. Even if electronic structure were causally relevant to chemical behavior, how could this explain the distinctively periodic nature of this behavior? One might wonder "how a simple arrangement could provide such regularities" (Niaz, 2009, 69) or how a simple ordering would produce such an elaborate and consistent periodic pattern.

The answer chemists provide has to do with the fact that as elements are ordered by increasing atomic number, there is a periodic pattern in their valence electron configuration. This results from a pattern in the Madelung rule or in the types of orbitals that electrons successively fill. As seen in figure 5, this filling cycles through s, p, d, and f orbitals such that serially ordered elements have a repeating pattern in the types of orbitals occupied by their outermost electrons. This is represented by different "blocks" of the periodic table, shown in figure 6, that reflect the different orbital types occupied by an element's outermost electrons (Allen and Knight, 2002). In following elements of increasing atomic number in the table, the sequence of blocks one moves through mirrors the sequence of orbitals specified by the Madelung rule. Elements in the s block have valence electrons in s orbitals, elements in the p block have their valence electrons in p orbitals, and so on. Each orbital is "progressively filled across a period" where each position (or vertical column) in the block indicates how many electrons occupy the respective orbital (Myers, 2003, 66). For example, elements in the first position of the p block (group 13) have a single valence electron in a p orbital, while elements in the second position (group 14) have two valence electrons in this orbital. This creates an alignment in the table where groups (or vertical columns) contain elements with similar valence electron configurations and where periods capture repeating sequences of these configurations. The fact that groups in the table contain elements with the same valence electron configuration is cited as the reason for their shared behavior (Myers, 2003, 66) (Scerri, 2011, 27-28). Relatedly, periodic changes in these configurations are cited as the reason for periodic changes in other properties of the elements (Myers, 2003, 66). As chemists state, "periodicity is a consequence of the variation in ground state electronic configurations" and "[e]lectron configurations of elements help to explain the recurrence of physical and chemical properties" (Housecroft and Sharpe, 2012, 20) (Chang, 2007, 326). Thus, serially ordered elements exhibit periodic changes in their properties, because these properties are caused by atomic features which themselves vary periodically with this ordering. This involves explaining repeating changes in an effect by appealing to repeating changes in its causes.

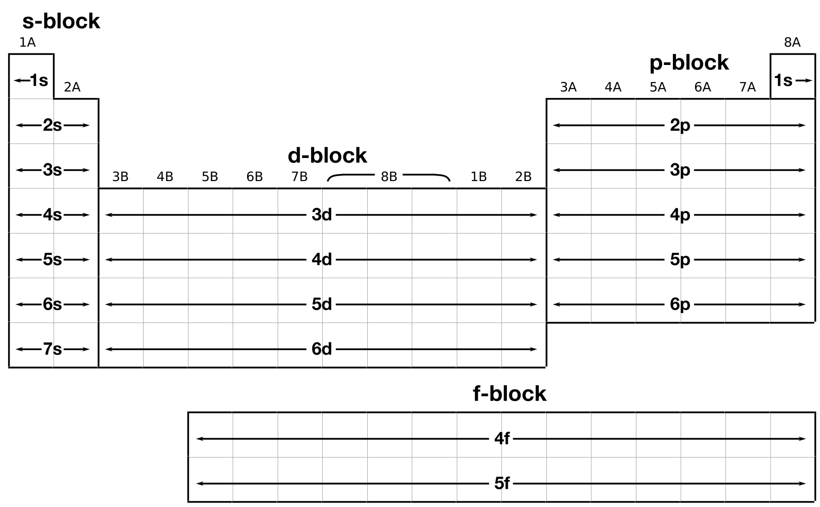

Figure 6: Blocks of the periodic table.

This reveals another layer of information in the table–information about the electronic configuration and proton number of the elements. This information represents an *explanans* or *cause* overlay in the table because it contains information that chemists appeal to in explaining what causes the chemical and physical properties of the elements. The table captures how these atomic features change across the elements and how these changes follow a periodic pattern. We now have two layers of information in the table that both reveal periodic changes in the elements–one at the level of chemical and physical properties and another at the level of atomic structure. These layers are superimposed in the table in a way that reveals how they are systematically related. The way that these layers are superimposed reveals how changes in atomic features correspond to changes in elemental properties. It might be suggested that the chemical properties of the elements are largely a result of electron number, but not proton number, which is also present in the table. However, as indicated in figure 6, atomic number is correlated with electronic configuration in an important way. Information about atomic/proton number provides information about the electron number. In this manner, atomic number can be understood as a correlate or indicator of what is doing much of the explanatory work.[19]

In order to explore this further, recall that chemists cite atomic and electronic features to explain the chemical and physical properties of the elements. What exactly does it mean to say that these atomic features explain these properties? Some of these explanations have a causal interpretation and are well understood within an interventionist framework. In these cases, chemists are stating that these atomic features are causally responsible for these chemical and physical properties in the sense that if one were to intervene on and manipulate these features, this would produce changes in these properties. Relatedly, chemists suggest that variations in these properties depend on variations in these features. This is suggested by Krebs in the following passage:

> "What makes chemistry so interesting is that each specific chemical element is related to its own kind of atom. Elements with specific characteristics have unique atoms. Each type of atom is unique to that element. *If you change the basic structure of an atom, you change the structure and properties of the element related to that atom*" (Krebs, 2006, xxiv; emphasis added).

This change-relating relationship is captured by the two overlays of information in the modern periodic table. These overlays contain information about properties that stand in a causal relationship. Variations in atomic structure are represented by different locations in the explanans or cause overlay of the table, while variations in elemental properties are represented by different locations in the explanandum or effect overlay of the table. As one moves through the table (to elements in different "locations"), various properties change. These include atomic and chemical properties, which can be considered two different layers of information in the table. The systematic connection between these two properties is captured by the superimposition of each overlay over the other– manipulating atomic structure involves spatial movement along the cause overlay, which produces subsequent movement in the effect overlay. Movement in the effect overlay reveals how elemental properties change as a result of this manipulation. This involves reading causal information in the table "forward" from cause to effect. In other words, reading out what elemental changes are produced from atomic alterations. Alternatively, the table can be read "backward" from changes in elemental properties to atomic structure. The forward reading captures the causal control of atomic features over elemental properties, while the backward reading captures the dependency of elemental properties on atomic features. These characteristics of the table help clarify how it meets the criteria for causal structure. Where the explanandum or effect overlay meets the second criteria, the explanans or cause overlay meets the first criteria. The cause overlay meets the first criteria because it captures changes in a cause variable of interest. Furthermore, the superimposition of these overlays indicates how the table meets the third criteria for causal structure. This superimposition, or layering feature, specifies the systematic relationship between particular values of a cause variable and particular values of an effect variable. The layering of this information

[19]This is not to say that proton number plays no role in these causal explanations. As discussed in the rest of this section, the table assumes that changes in chemical properties follow from changes in both proton and electron structure, and clearly both are involved in producing such chemical differences. Moving along the explanans overlay of the table assumes that changes in proton number and electron configuration go hand-in-hand and the table clearly provides information about both.

in the table is no accident–it serves to show how particular values of atomic structure relate to particular values of elemental properties.

Further reasons support the view that the periodic table contains causal information. This view is supported by our general understanding of nuclear transmutation, experiments used in the discovery and synthesis of "man-made" elements, and current theories of interstellar nucleosynthesis. Each of these relies on the interventionist causal control that atomic features have over elemental properties. Consider nuclear transmutation, which involves the conversion of one element into another.[20] This process was dismissed by eighteenth and nineteenth century chemists until Soddy and Rutherford witnessed transmutation during a radioactive decay process (Rutherford and Soddy, 1903). Rutherford followed up this observation with transmutation experiments in which he converted nitrogen into oxygen through alpha particle bombardment (Rutherford, 1919). This work revealed that atomic alternations could in fact cause changes in the chemical and physical properties of a substance and result in the conversion of one element into another. These conversions became the focus of later experiments designed to synthesize previously unidentified elements.[21] These experiments changed one element into another by intervening on atomic structure. These atomic interventions involved bombarding target atoms with high speed particles or small atoms that altered the proton and electron constitution of the original atoms. The periodic table was often consulted in these experiments–it helped in identifying suitable target elements, suitable projectiles, the final products their interaction would form, and the chemical and physical properties such final products were likely to have. Finally, chemists' understanding of the causal relationship between atomic features and elemental properties underlies current theories of naturally occurring nucleosynthesis. It is theorized that the first synthesis of elements in our universe took place during the early part of the Big Bang and then later on within the high heat and high pressure of the stars. The energy in these environments led to atomic alternations that produced the variety of elements present in our universe today (Clayton, 1983). These examples involve chemical concepts and theories that characterize atomic features as having interventionist causal control over elemental properties.

4.3 Criteria for causal structure. This analysis indicates that the periodic table meets the criteria for causal structure introduced in section 3. It has shown how this table specifies (i) some cause variable C (i.e. atomic properties), (ii) some effect variable E (i.e. chemical behaviors and properties), and (iii) how the values of C systematically relate to the values of E in an interventionist sense. How can we understand the application of these criteria to other scientific figures? Furthermore, what exactly is meant by "scientific figure" and what are the purposes of applying such criteria? First, by "scientific figure" I refer to visual representations typically included in scientific publications, which are associated with and used to describe scientific concepts. My use of "scientific figure" is similar to the use of "scientific diagrams" in the literature (Abrahamsen and Bechtel, 2014; Griesemer, 1991; Bechtel et al., 2014). In particular, I agree with Abrahamsen and Bechtel (2014) that "[t]he term *diagram* does not have clear boundaries" and that "[i]ts etymology suggests a very inclusive meaning–any visuospatial representation–which would cover virtually all

[20]Interest in transmutation dates back to the alchemists of ancient Greece who sought to turn base metals into gold and silver and who postulated that a special material called "the philosopher's stone" was a required catalyst for such a process (Hofmann, 2002, 1) (Krebs, 2006, 4).

[21]These experiments included elements in the lanthanide and actinide series, which are too heavy to occur naturally in large quantities.

of the figures in a scientific paper including photographs, flow charts of a procedure, and line drawings of an experimental apparatus" (Abrahamsen and Bechtel, 2014, 117-118, emphasis original). General examples of scientific figures include graphs, tables, venn diagrams, bar charts, equations, and pictures. More specific examples include the periodic table in chemistry, reaction mechanism diagrams in biochemistry, Punnet squares in biology, pathway diagrams in ecology, directed acyclic graphs in economics, and Feynman diagrams in physics. Of course, these general and concrete examples are not exhaustive–as indicated, "scientific figure" can refer to any visual representation that is used to capture a scientific concept or phenomenon of interest.

Second, the criteria for causal structure proposed in this analysis serve the purpose of distinguishing figures that capture causal information from those that do not. This is useful for identifying figures that can participate in causal explanation and for ensuring that figures intended to represent causal information successful do so. For example, Punnet squares in biology are intended to capture the causal influence of genotype on phenotype, and assessment of such figures with the above criteria reveals that they successfully do this. In these figures, (i) genotype is the cause variable (represented outside the square), (ii) phenotype is the effect variable (represented inside of it), and their locations in the diagram capture how (iii) values of the genotype systemically relate, in an interventionist sense, to values of the phenotype. In other words, these squares convey information about how changes in genotype produce changes in phenotype. Applying the same criteria to a visual representation of Linnaean taxonomy, an illustration of fruit fly anatomy, or a network diagram of correlations between gene variants and disease traits reveals that such figures lack causal structure. These figures fail to meet these criteria, as they fail to reveal causes and the interventionist control that they have over their effects. Where diagrams such as Punnet squares contain information that can figure in causal explanation, the latter examples lack such information and explanatory status–they do not capture "handles" that can be intervened upon to produce changes in the world. Finally, one notable advantage of these criteria is that they function across wide variations in representational format. For example, these criteria work for the periodic table, despite the fact that this table represents causal information in a fairly unique way, relative to other scientific figures. This is evident when considering the third criterion, which the periodic table meets by means of superimposing information about cause and effect variables. Of course, a scientific figure can convey causal structure without representing the systematic relationships between cause and effect by means of superimposition or in the layered manner found in the periodic table. Figures such as Punnet squares, reaction mechanism diagrams, directed acyclic graphs, and pathway diagrams all contain causal information without presenting in such a layered way. In other words, distinct diagrams can meet these criteria by employing varying representations of cause and effect variables. Different representational formats are common in science–they can serve different purposes, highlight important features of a causal relationship, or be more perspicuous in some contexts than in others. Thus, these criteria provide a way of determining whether a diagram conveys causal information, while accommodating the variety of representational formats in which this can be done.

5 Explanation, classification, and causal structure. This paper has argued that the modern periodic table has causal structure in the sense of containing causal information that figures in explanations in chemistry. While these explanations are explicitly causal, I am not claiming that this is the only sense in which the periodic table is explanatory. Woody has suggested other ways to understand the explanatory nature of the table and she mentions the possibility of interpreting it with Kitcher's unificationist account (Woody, 2014, 150)(Kitcher, 1989). This unificationist interpretation may seem compelling given that atomic number appears to unify elements in a way that captures the periodic nature of their properties. Such an interpretation will have to address at least two potential challenges. First, while it is true that atomic number (or even atomic weight) unifies the elements in this way, it is not clear that chemists view this as explanatory. As discussed in section 2, chemists indicate that they view this "unification" as showing *that* the elements exhibit periodicity without explaining *why* they do. This is consistent with the distinction they draw between "descriptive" and "theoretical" chemistry, which distinguishes descriptions of properties of the elements from explanations of these properties. More would need to be said about how this (or some other) form of unification is explanatory as opposed to being merely descriptive or informative. Second, unificationist accounts of explanation continue to receive significant scrutiny in the philosophical literature and are thought to suffer from various problems that many view as unresolved (Woodward, 2014b). Providing a convincing argument that the periodic table figures in unificationist explanation will likely require addressing these concerns. This paper leaves open the question of whether the periodic table figures in unificationist or other forms of explanation. The main focus of this analysis is to show that the table figures in causal explanation, without suggesting that this is the only way to understand its explanatory value.

Additionally, I am not claiming that the table explains everything about elemental properties that one might be interested in or that it contains maximal atomic detail for such explanations. Surely there are explananda that the table does not address and it clearly omits detail that may provide a "deeper" or more "complete" understanding of those phenomena it does. A main goal of this paper is to show how the table contains at least some causal structure and that it figures in at least some explanations without suggesting that these are the only explanations of periodicity or that they are as detailed as other explanations that invoke more atomic theory. These points relate to common criticisms of the explanatory nature of the periodic table. It has been argued that the table is non-explanatory because the information it contains fails to completely explain elemental properties and their periodicity. One example of this is the claim that electronic configurations do not fully account for the "closure of the periods" or the number of elements that span each horizontal row (and end or "close" at a noble gas configuration) (Scerri, 1997b, 551-2) (Scerri, 2007, 234). As Scerri states, this explanatory target "does not appear to have a strictly quantum-mechanical explanation" as it "has never been derived from the principles of quantum mechanics" (Scerri, 1997b, 551-552). A related criticism is that the order of shell filling (represented in figure 5) is merely supported by empirical and experimental considerations, but that it has not been explained itself in the sense of being derived from any underlying theory (namely, quantum mechanics) (Scerri, 1997b, 551-2) (Scerri, 2007, 234) (Woody, 2014, 142). As these claims indicate that derivation from first principles is a necessary feature of explanation, the lack of such a derivation–and the reliance on "mere" empirical data–is said to pose serious objections to viewing the table as genuinely explanatory (Scerri, 1997b, 551).

A first point to make is that such criticisms place an unrealistically high bar on what counts as explanatory in the sense of assuming that explanations should be "rigorous" or "complete" with respect to the number of phenomena that are addressed.[22] Where chemists appeal to the order

[22]This point is motivated by (Woody, 2014, 142) and early papers by (Scerri, 1997a, 239), which emphasize the non-causal and non-explanatory character of the table, respectively. In recent work, Scerri argues that electronic explanations of the table are "approximate" or partial. Scerri's claims are resistant to my first point in this section and I view them as largely consistent with the main thesis of this paper, although we

of electron filling to explain patterns in elemental properties, these criticisms may suggest that a genuine explanation goes deeper–it should also explain *why* electrons fill in this order. One clear worry with this approach is that it can lead to an infinite regress in the phenomena to be explained. It seems to suggest that for something to be explanatory, it should explain everything (or many things) about a topic or in a domain. It either explains everything in full detail or nothing at all. This is an inappropriate standard to expect explanations to meet. It means that nothing will ever qualify as explanatory because their will always be some why-questions that a given body of information does not answer or some why-questions that require a seemingly endless amount of explanatory detail. This can make explanation seem impossible, which conflicts with the common view that successful explanations are provided in science. Furthermore, it does not make sense of the fact that chemists claim that periodicity has some kind of explanation.

Second, these criticisms assume that if chemists' explanations do not fit a deductive, reductive, or traditional "theory-centered" framework, then they do not qualify as genuinely explanatory. One problem with this assumption is that it is not clear that these frameworks well-accommodate explanation in this domain. In fact, chemists' insistence that they are providing explanations despite their unintelligibility within a theory-centered framework should raise worries about how well this framework reflects the explanations they have in mind. One advantage of the interventionist account is that it captures some of these explanations without being impeded by the aforementioned criticisms related to lack of derivation from underlying theory. Even if period length cannot be deduced from theory, this does not change the fact that alterations in proton and electron number produce changes in elemental properties and that this relationship is useful for purposes related to explanation and control. The lack of a deductive explanation of electron filling does not prevent experiments on transmutation, efforts to synthesize elements, or the intelligibility of modern accounts of cosmic nucleosynthesis. These change-relating relationships exist between atomic features and elemental properties even if some of these features cannot be derived from the first principles of quantum mechanics. Furthermore, chemists do not appear to downgrade empirical evidence or view this evidence as inferior to theoretical derivations as suggested by these criticisms. The fact that such information is "merely" empirical or experimental is no issue. It is simply how information about these relationships is discovered and it is not inferior to information derived from theoretical principles.

Another criticism of the explanatory role of the modern periodic table has to do with classification. This criticism is associated with the worry that the table merely classifies elements on the basis of their properties without explaining them. For example, as Scerri states:

> The periodic systems, both naive and sophisticated, are systems of classification which are devoid of theoretical status in much the same way as the Linnean [sic] system of biological classification or the Dewey decimal system of library classification. None of these systems can be regarded as theories since they do not seek to explain the facts but merely to classify them (Scerri, 1997a, 239).

Consider the Linnaean and Dewey Decimal systems–both involve classifying entities on the basis of some property or set of properties. In the former, organisms are classified and distinguished from one another on the basis of whether they exhibit particular properties (Ereshefsky, 2001). For example, within this taxonomy different species of plants are differentiated on the basis of

provide different interpretations of how these explanations work.

distinct characteristics of their fructification systems (sex organs) (Ereshefsky, 2001). Similarly, the Dewey Decimal system classifies books on the basis of differences in their subject matter. In this system library books are categorized into main classes such as literature, religion, history and geography, and pure science, and then more specific sub-groups within these classes (Seyler, 1987, 186-7). Both of these systems involve classifying, sorting, and distinguishing items on the basis of various properties. However, notice that these classifications do not rely on or provide causal information. They do not contain difference-making information in the sense of specifying how changes in one property produce changes in another. They tell one how to sort and identify entities on the basis of identifying various properties, but not what factors can be manipulated to change these properties or what manipulating these properties will produce. In these cases, classification requires the successful identification of relevant properties, but it does not require knowing what the causes or effects of these properties are. For example, you can know that a plant has various features without knowing what causal relationships these features figure in. This information can be used to classify the plant (and distinguish it from other plants) without explaining why the plant has these features. Of course, these classifications may generate interest in understanding and discovering these causal relationships, but the classifications themselves are not contingent on this information.[23]

This is all to say that classification is possible without causal information and that the Linnaean and Dewey Decimal systems classify in this manner.[24] Thus, in the context of causal explanation, it makes sense to view these systems as "mere" classifications that do not explain. However, it is incorrect to equate them with the modern periodic table in this sense. The modern periodic table differs from these systems in that it involves classifying elements on the basis of various properties, while also containing information about what causes–and, thus, what explains–these properties. Unlike these classification systems, the modern periodic table contains difference-making information, as it specifies how changes in atomic features cause changes in elemental properties. Because of this, the modern periodic table provides information about how to control and change things in the world, which is not the case with the Linnaean and Dewey Decimal systems. These systems clarify how to identify and sort things in the world, but not what properties can be manipulated to change things in the world. This is central to what it means to say that the modern periodic table has causal structure.

This suggests that the modern periodic table is not "merely" classificatory in the way that the Linnaean and Dewey Decimal systems are. However, these concerns about the table being "merely" classificatory are not entirely misguided. In order to see this, recall how chemists divide up information in the modern table on the basis of whether it is representative of "descriptive" or "theoretical" chemistry. Descriptive information captures the observable "facts" about chemical and physical properties of elements, while theoretical information involves the relationship between these properties and the atomic level features that they depend on. It is this atomic level information that gives the periodic table its explanatory character–these atomic level features explain why the elements have particular properties that they have.[25] However, notice that information about

[23]Of course, some classifications do involve causal information. This makes the "merely" classificatory claim somewhat puzzling, because classification and explanation are not mutually exclusive. I take it that worries about cases of "mere" classification are situations where a system can can classify, but not explain.

[24]For further support of this first point, see (Ereshefsky and Reydon, 2014).

[25]For an analysis of the explanatory role of the periodic table that attends to modeling practices and theory construction, see (Weisberg, 2007).

atomic structure was completely absent in the earliest periodic tables, as little to nothing was known about this structure at the time. Instead, these tables relied solely on chemical and physical properties of the elements–properties that are still found in the modern periodic table and that are associated with descriptive chemistry. This descriptive information is viewed as the starting point or the "original basis" of the earliest periodic tables (Houten, 2009, 13). As Hofman states, "[a]ll that looking at natural substances and experimenting with the ways in which they interacted with one another did, in the course of time, throw up a vast amount of empirical information which eventually demanded explanation" (Hofmann, 2002, 1). This descriptive information is similar to the information used in classifications such as Linnaean taxonomy and the Dewey Decimal system because it involves properties of some phenomena of interest without an understanding of the causal relationships they may figure in.

While this descriptive information helped to classify and organize the elements, it did not explain their properties or why they exhibited periodicity. The absence of such an explanation is reflected by the lack of causal structure in the earliest periodic tables. In these tables, elemental properties were indexed to atomic weight, which was one of the earliest ordering principles. Why not view atomic weight as an explanation of elemental properties and their periodicity? If atomic weight was causally or explanatorily relevant to the periodic nature of elemental properties, it should be possible (at least hypothetically) to produce this periodic pattern by manipulating atomic weight alone. However, we know this relationship not to be true. This is because there are ways to change the atomic weight of an element (e.g. by altering neutron number) that fail to produce this periodic pattern. Atoms of the same atomic weight can have different behaviors and atoms of different atomic weight can have similar ones. What causes these periodic changes are alterations in the particular atomic properties of proton and electron structure. When atomic weight was replaced with atomic number, the table began to include causal information. The reason for this is that atomic number contains information about proton and electron structure, which does "make a difference" to the periodic nature of elemental properties. What this shows is that the periodic table originated as a classification device that contained descriptive information about elemental properties. The table only became explanatory as information about what explains these properties–namely, atomic level features–was discovered and incorporated into its later versions. It can make sense to hesitate in viewing the table as anything more than a classification device because it originated as such a device and only figured in explanation once it was modified to include information about atomic structure.

6 Conclusion. This analysis raises an interesting puzzle. If it is true that the earliest periodic tables lacked causal structure and, thus, lacked an explanatory role, how were they able to predict particular chemical and physical properties of undiscovered elements? This is because, while atomic weight does not cause these properties of the elements, it is reliably correlated with factors that do. Atomic weight is reliably correlated with an element's proton number and electron configuration. In this manner, atomic weight can be used as a fairly accurate tool for ordering elements by incremental changes in their atomic structure without being a direct measure of this structure itself. A similar rationale guides the identification and search for biomarkers in medicine–the goal in this situation is to identify factors that are reliable indicators of disease, even if they do not cause disease themselves (Joffe et al., 2012, 12). These factors can be useful for predicting the occurrence of disease traits despite the fact that they do not figure in explanations of them. In fact, these predictive factors can be exploited to discover causal structure–this is seen in the case of the periodic table, in which the identification of a stable pattern ultimately took on a causal interpretation. The periodic table shows how a system that originates as a tool for classification, description, and prediction, can develop into one that explains. Such an interpretation is supported by the historical record. While Mendeleev repeatedly referred to the periodic table as a classification device that represented an accurate and reliable periodic law, he explicitly denied that the table offered any explanation of this law (Mendeleev, 1871; Mendeleev, 1899). According to Mendeleev, the periodic law and reoccurring similarities of elemental properties remained "unexpected phenomena without explanation," in which chemists were "capable of discovering the law, but not of knowing its true cause" (Mendeleev, 1871, 42) (Mendeleev, 1899, 221). Relatedly, he states that "[w]e currently do not have an explanation for the periodic law...[and] its fundamental rationale is unclear. Nevertheless, one may hope that, with time, one will discover this rationale" (Mendeleev, 1899, 225).[26] Advances in understanding atomic properties and electronic structure began to provide this rationale and information that chemists viewed as explanatorily relevant to periodic changes in the chemical properties of the elements. Chemists would still refer to the periodic table as a classification system, but they would now suggest that this system was rationalized and (at least partially) explained. They would connect this explanation to new understanding of the *causes* of periodicity. Bohr would refer to electronic structure as "offering a complete explanation of the remarkable relationships between the physical and chemical properties of the elements" and others have explicitly referred to these phenomena as related by causal connection (Bohr, 1938, 434).[27] This is consistent with modern views that continue to understand the table as "rationalized and explained" by these atomic and electronic features (Weller et al., 2014, 271). This suggests that the earliest versions of the table served more of a classificatory, descriptive, and predictive role, as they lack the causal structure that has been incorporated into modern versions. This is likely to be a common developmental trajectory for causal discovery in science. While particular patterns and regularities can hint at causal structure, successfully identifying this structure often requires significant work.

[26] Mendeleev did sometimes suggest that such a rationale would come from an understanding of atomic structure, but he and his contemporaries merely hypothesized about how exactly this would work.

[27] For example, it has been claimed that with respect to atomic structure and chemical properties "the relation is best conceived as one of cause and effect, with atomic structure determining chemical properties" (Strong, 1959, 344).

References

Abrahamsen, A. and Bechtel, W. (2014). Diagrams as Tools for Scientific Reasoning. *Review of Philosophy and Psychology*, 6(1):117–131.

Allen, L. C. and Knight, E. T. (2002). The Löwdin challenge: Origin of the n + l ,n (Madelung) rule for filling the orbital configurations of the periodic table. *International Journal of Quantum Chemistry*, 90(1):80–88.

Batterman, R. W. (2010). On the Explanatory Role of Mathematics in Empirical Science. *The British Journal for the Philosophy of Science*, 61(1):1–25.

Bechtel, W., Burnston, D., Sheredos, B., and Abrahamsen, A. (2014). Representing time in scientific diagrams. *Proceedings of the Annual Meeting of the Cognitive Science Society*, 36(36):164–169.

Bechtel, W. and Richardson, R. C. (2010). *Discovering complexity*. The MIT Press, Cambridge, MA.

Bohr, N. (1938). Biology and atomic physics. *Il Nuovo Cimento*, 15(7):429–438.

Bursten, J. R. (2014). Microstructure without Essentialism: A New Perspective on Chemical Classification. *Philosophy of Science*, 81:633–653.

Chang, R. (2007). *Chemistry*. McGraw-Hill, New York, NY, 10th edition.

Clayton, D. D. (1983). *Principles of stellar evolution and nucleosynthesis*. The University of Chicago Press, Chicago, IL.

Ereshefsky, M. (2001). *The poverty of the Linnaean hierarchy: A philosophical study of biological taxonomy*. Cambridge Studies in Philosophy and Biology, New York, NY.

Ereshefsky, M. and Reydon, T. A. C. (2014). Scientific kinds. *Philosophical Studies*, 172:969–986.

Gordin, M. D. (2004). *A well-ordered thing: Dmitrii Mendeleev and the shadow of the periodic table*. Basic Books, New York, NY.

Griesemer, J. R. (1991). Must scientific diagrams be eliminable? The case of path analysis. *Biology & Philosophy*, 6(2):155–180.

Hempel, C. (1965). *Aspects of scientific explanation*. The Free Press, New York, NY.

Hofmann, S. (2002). *On beyond uranium*. Taylor and Francis, New York, NY.

Housecroft, C. E. and Sharpe, A. G. (2010). *Inorganic chemistry*. Pearson Education Limited, Essex, 3rd edition.

Housecroft, C. E. and Sharpe, A. G. (2012). *Inorganic chemistry*. Pearson Education Limited, Essex, 4th edition.

Houten, J. V. (2009). "Jeopardy" in the inorganic classroom - Teaching descriptive chemistry using a television game show format. In *Chemistry Education in the ICT Age*, pages 11–17. Springer, Dordrecht.

Joffe, M., Gambhir, M., Chadeau-Hyam, M., and Vineis, P. (2012). Causal diagrams in systems epidemiology. *Emerging Themes in Epidemiology*, 9(1).

Kitcher, P. (1989). Explanatory unification and the causal structure of the world. In *Scientific Explanation*, pages 507–531. University of Minnesota Press, Minneapolis.

Krebs, R. E. (2006). *The history and use of our earth's chemical elements*. Greenwood Press, Westport, CT, 2nd edition.

Mendeleev, D. I. (1869). On the relationship of the properties of the elements to their atomic weights. In Jensen, W., editor, *Mendeleev on the periodic law*, pages 405–406. Zeitschrift für Chemie, Mineola, NY.

Mendeleev, D. I. (1871). On the periodic regularity of the chemical elements. *Annalen der Chemie und Pharmacie*, 8(Suppl):133–352.

Mendeleev, D. I. (1899). How I discovered the periodic system of elements. In Jensen, W. B., editor, *Mendeleev on the periodic law*. Revue Générale de Chimie Pure et Appliquée.

Meyer, J. L. (1870). Die natur der chemischen elemente als function ihrer atomgewichte. *Annalen der Chemie*, 7:354–364.

Moeller, T., Bailar, J. C., Kleinberg, J., Guss, C. O., Castellion, M. E., and Metz, C. (1980). *Chemistry with inorganic qualitative analysis*. Academic Press, New York, NY, 3rd edition.

Myers, R. (2003). *The basics of chemistry*. Greenwood Press, Westport, CT.

Nath, B. and Cholakov, G. S. (2009). *Pollution control technologies*, volume 1. EOLSS Publishers, Oxford.

Niaz, M. (2009). *Critical appraisal of physical science as a human enterprise*. Springer, Dordrecht.

Rayner-Canham, G. (1996). *Descriptive inorganic chemistry*. W.H. Freeman and Company, New York, NY, 1st edition.

Rayner-Canham, G. and Overton, T. (2010). *Descriptive inorganic chemistry*. W.H. Freeman and Company, New York, NY, 5th edition.

Reutlinger, A. (2016). Is there a monist theory of causal and noncausal explanations? The counterfactual theory of scientific explanation. *Philosophy of Science*, 83:733–745.

Rutherford, E. (1919). Collisions of alpha particles with light atoms. An anomalous effect in nitrogen. *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science*, 37(222):581–587.

Rutherford, E. and Soddy, F. (1903). Radioactive change. *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science*, 5(29):576–591.

Saatsi, J. and Pexton, M. (2018). Reassessing Woodward's account of explanation: Regularities, counterfactuals, and noncausal explanations. *Philosophy of Science*, 80:613–624.

Scerri, E. R. (1997a). Has the periodic table been successfully axiomatized? *Erkenntnis*, (47):229–243.

Scerri, E. R. (1997b). The periodic table and the electron: Although electronic configurations are traditionally invoked to explain the periodic system, their explanatory power remains only approximate. *American Scientist*, 85:546–553.

Scerri, E. R. (2007). *The periodic table: Its story and its significance*. Oxford University Press, Oxford.

Scerri, E. R. (2011). *The periodic table: A very short introduction*. Oxford University Press, Oxford.

Scerri, E. R. (2012). The periodic table. In *Philosophy of Chemistry*, pages 329–338. Elsevier, Oxford.

Scerri, E. R. and Worrall, J. (2001). Prediction and the periodic table. *Studies in History and Philosophy of Science Part A*, 32:407–452.

Seaborg, G. T. (1959). Recent work with the transuranium elements. *Proceedings of the National Academy of Sciences*, 45(4):471–482.

Seyler, D. U. (1987). *Read, reason, write*. Random House, New York, 2nd edition.

Shapere, D. (1977). Scientific theories and their domains. In Suppe, F., editor, *The Structure of Scientific Theories*. University of Illinois Press.

Strong, F. C. (1959). The atomic form periodic table. *Journal of Chemical Education*, 36(7):344.

Weisberg, M. (2007). Who is a Modeler? *The British Journal for the Philosophy of Science*, 58(2):207–233.

Weller, M., Overton, T., Rourke, J., and Armstrong, F. (2014). *Inorganic chemistry*. Oxford University Press, Oxford, 6th edition.

Williams, A. F. (1979). *B*. Springer-Verlag, Berlin.

Woodward, J. (2003). *Making things happen*. Oxford University Press, Oxford.

Woodward, J. (2014a). A functional account of causation; Or, a defense of the legitimacy of causal thinking by reference to the only standard that matters: Usefulness (as opposed to metaphysics or agreement with intuitive judgment). *Philosophy of Science*, 81:691–713.

Woodward, J. (2014b). Scientific explanation. http://plato.stanford.edu/entries/scientific-explanation/#PraTheExp. *Standford Encylopedia of Philosophy*.

Woodward, J. (2016). The problem of variable choice. *Synthese*, 193(4):1047–1072.

Woody, A. I. (2014). Chemistry's periodic law: Rethinking representation and explanation after the turn to practice. In Soler, L., Zwart, S., Lynch, M., and Israel-Jost, V., editors, *Science After the Practice Turn in the Philosophy, History, and Social Studies of Science*. Routledge Taylor & Francis Group, New York.

Wulfsberg, G. (1991). *Principles of descriptive inorganic chemistry*. University Science Books, Sausalito, California.