ARTICLE IN PRESS

Studies in History and Philosophy of Science xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Studies in History and Philosophy of Science

journal homepage: www.elsevier.com/locate/shpsa

The periodic table and the turn to practice

Eric R. Scerri

Department of Chemistry & Biochemistry, UCLA, Los Angeles, CA, 90095, USA

HIGHLIGHTS

- Andrea Woody's claims regarding the explanatory role of the periodic table, per se, are discussed.
- Different representations of the periodic table used by Mendeleev and Lothar Meyer are examined.
- The relative virtues of prediction and accommodation in the context of the periodic table are discussed.
- Do chemical explanations based on quantum mechanics carry more weight than those that appeal directly to the periodic table?

ABSTRACT

The philosopher of chemistry Andrea Woody has recently published a wide-ranging article concerning the turn to practice in the philosophy of science. Her primary example consists of the use of different forms of representations by Lothar Meyer and Mendeleev when they presented their views on chemical periodicity. Woody believes that this distinction can cast light on various issues including why Mendeleev was able to make predictions while Meyer was not. Secondly, she claims that it can clarify the much-debated question concerning the relative values of prediction and accommodation of data in the way that the periodic system was accepted. Thirdly, Woody believes that such differences in the representation of periodicity can be used to argue for the explanatory nature of the periodic table in contrast with the more traditional view that the periodic table is not explanatory.

This discussion examines each of these claims and argues that they need to be qualified and in some cases rejected.

When citing this paper, please use the full journal title *Studies in History and Philosophy of Science*.

1. Introduction

The following is a discussion of a recent article by philosopher of chemistry Andrea Woody (Woody, 2014), that represents a significant contribution to the philosophical study of the periodic system and that can serve to reinvigorate research on this topic.

However, I believe that there are some problems with Woody's account including her focus on what she takes to be two contrasting kinds of representation of the periodic law, as exemplified in the work of two of the discoverers of periodicity. According to Woody, Mendeleev used a tabular representation while Meyer used a graphical one. Woody proceeds to claim that this difference can cast new light on the much-debated question of why Mendeleev, rather than Meyer, succeeded in making predictions about yet undiscovered elements. In addition, Woody claims that this contrast in representational styles can illuminate another intensely debated issue in the context of the periodic table, that of the relative value of prediction and accommodation of data in the acceptance of new scientific developments. Even more ambitiously perhaps, Woody's ultimate goal is to challenge the traditional view of scientific explanation, once again using the periodic law as an example.

In fact, Meyer was equally fond of, and reliant upon, the tabular format and indeed he published such periodic tables in 1864, a full five years before Mendeleev ever ventured to do so. These tables also contained a number of gaps as can be seen in Figs. 1 and 6. If tables and gaps are what enabled Mendeleev to make predictions it is difficult to see why Meyer made no such significant predictions. Moreover, the Meyer article of 1870 in which he introduced his now famous atomic volume curve also contains a tabular periodic table (Meyer, 1870). I suggest that the use of continuous curves was a secondary aspect of Meyer's approach, rather than his modus operandi as Woody would have us believe.

One should also ask whether the two formats are as inherently different as claimed by Woody. As I will argue, it becomes difficult to maintain this contrast on close inspection.

E-mail address: scerri@chem.ucla.edu.

https://doi.org/10.1016/j.shpsa.2019.06.001
Received 10 September 2018; Received in revised form 17 March 2019; Accepted 6 June 2019
0039-3681/

Please cite this article as: Eric R. Scerri, Studies in History and Philosophy of Science, https://doi.org/10.1016/j.shpsa.2019.06.001

	4 werthig	3 werthig	2 werthig	1 werthig	1 werthig	2 werthig
	––	––	––	––	Li = 7.03	(Be = 9.3?)
Differenz =	––	––	––	––	16.02	(14.7)
	C = 12.0	N = 14.04	O = 16.00	Fl = 19.0	Na = 23.05	Mg = 24.0
Differenz =	16.5	16.96	16.07	16.46	16.08	16.0
	Si = 28.5	P = 31.0	S = 32.07	Cl = 35.46	K = 39.13	Ca = 40.0
Differenz =	$\frac{89.1}{2}$ = 44.55	44.0	46.7	44.51	46.3	47.6
	––	As = 75.0	Se = 78.8	Br = 79.97	Rb = 85.4	Sr = 87.6
Differenz =	$\frac{89.1}{2}$ = 44.55	45.6	49.5	46.8	47.6	49.5
	Sn = 117.6	Sb = 120.6	Te = 128.3	I = 126.8	Cs = 133.0	Ba = 137.1
Differenz =	89.4 = 2 x 44.7	87.4 = 2 x 43.7	––	––	(71 = 2 x 35.5)	––
	Pb = 207.0	Bi = 208.0	––	––	(Tl = 204?)	––

	4-werthig	6-werthig	4-werthig	4-werthig	4-werthig	2-werthig	
	Ti = 48	Mo = 92	Mn = 55	Ni = 58.7	Co = 58.7	Zn = 65	Cu = 63.5
			Fe = 56				
Differenz	42	45	49.2	45.6	47.3	46.9	44.4
			48.3				
	Zr = 90	Vd = 137	Ru 104.3	Rh = 104.3	Pd = 106.0	Cd = 111.9	Ag = 107.94
Differenz	47.6	47	92.8 = 2 x 46.4	92.8 = 2 x 46.4	93.0 = 2 x 46.5	88.3 = 2 x 44.2	88.8 = 2 x 44.4
	Ta = 137.6	W = 184	Pt = 197.1	Ir = 197.1	Os = 199.0	Hg = 200.2	Au = 196.7

Fig. 1. Lothar Meyer's two tabular form periodic tables of 1864.

S (32)

As (75) Se ? Br (80)

Te (127.5)

$$(32 + 75 + 80 + 127.5)/4 = 79$$

Fig. 2. Mendeleev's use of two triads to calculate the properties of an 'unknown' element.

2. Why did only Mendeleev make predictions and what is the relative virtue of prediction versus accommodation?

A number of authors believe that the traditional view is correct and that the greatest credit concerning the discovery of the periodic table should be accorded to successful predictions. They believe that Mendeleev should receive the greatest credit since he made the successful prediction of several elements, among which the best-know were gallium, germanium and scandium (Lipton, 1991; Maher, 1988; Howson, 1984). This view is not necessarily held by the whole scientific community however. It has been argued that Mendeleev's accommodations of known elements may have counted just as much, if not more, to his overall success (Brush, 1989; Scerri, Worrall, 2001).

However, Woody considers that the periodic table is not a good arena for discussing this question because she believes that the periodic law is insufficiently well characterized. Woody is well aware of the need to explain why only Mendeleev made any serious predictions and considers this to be due to the particular choice of representation that Mendeleev opted for.

3. The periodic law and its relevance to the prediction-accommodation debate

Woody wonders whether the periodic law, that has featured in the prediction – accommodation debate, can serve its intended function. Her doubt stems from a belief that the "content of the periodic law remained indeterminate in early years, while still making predictions." She also believes that the periodic table should not be used in this debate because the periodic law cannot be made to fit the standard philosophical mold of scientific laws. It is not at all clear to the present author why the status of the periodic law, as such, should disqualify the periodic table from featuring in the prediction - accommodation debate.

Woody mentions several features that she considers weaken the status of the periodic law. They include the fact that few efforts have been made to give it a mathematical form. However, I believe this objection to be irrelevant since the periodic law is now largely explained by quantum mechanics, which provides the necessary mathematical form, even if this form of reduction may not be complete

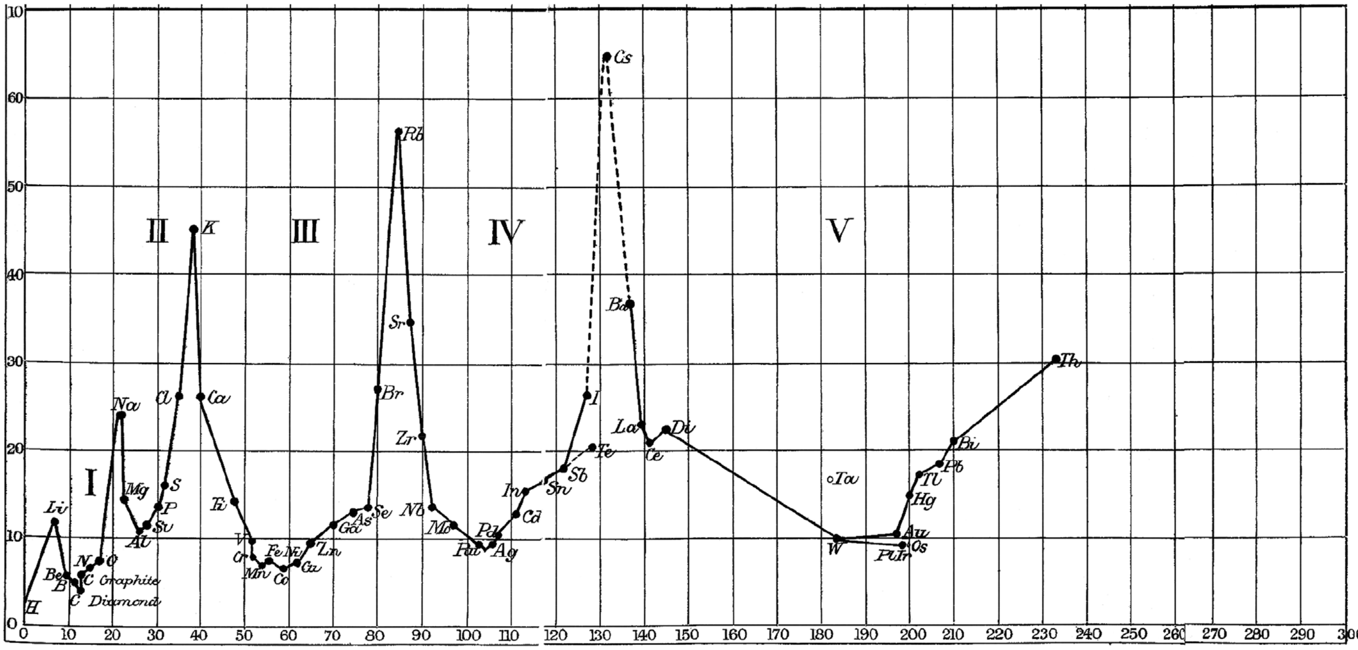

Fig. 3. A version of Meyer's graph of atomic volume, of the kind labeled as Fig. 4.1 by Woody.

преимущественно найдти общую систему элементовъ. Вотъ этотъ опытъ:

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4
			Fe=56	Ru=104,4	Ir=198.
			Ni=Co=59	Pl=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=27,4	?=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?		

Fig. 4. A version of Mendeleev's vertical tabular form, labeled as Fig. 4.2 by Woody.

(Scerri, 2016). Secondly, as one moves away from physics, chemical laws are inherently less mathematically precise, a fact that should not therefore cause too much concern. A more fruitful strategy for Woody to adopt might be to look at how Mendeleev actually made his predictions, something that is lacking in Woody's analysis in spite of her goal of putting scientific practice to the fore.

Mendeleev's approach was essentially one of interpolation between the known properties of surrounding elements on the periodic table in order to deduce the properties of any unknown element. He illustrated this notion by explaining how to calculate the atomic weight of selenium, an element that was known at the time of his writing. One can estimate the atomic weight of the central element, selenium in this case, by adding the weights of all four surrounding elements and dividing by four (Fig. 2). Mendeleev calculated a value of 79, that is close to the then known experimental atomic weight of 78 for selenium, and thus helped to establish the value of this approach (Mendeleev, 1891).

4. Woody on alternative representations of the periodic law

The way in which Woody examines scientific practice in the context of the periodic table is to consider "explicit choices made regarding representation of the periodic law." She then sets out four aims and/or questions that she wishes to consider.

1. Why was the periodic table entrenched in the first place?
2. In what respects is it an inferential tool?
3. Why should we consider it explanatory?
4. To re-engage with the prediction-accommodation debate.

There have indeed been many representations of the periodic table, as Woody states, and it is therefore relevant to ask why Mendeleev's version became entrenched. My first response is that all representations of the periodic system, within reason, are essentially the same and that representation is something of a secondary issue. What matters are the connections between the chemical elements that are established by any representation of the periodic table. Broadly speaking, all six of the original representations achieve similar connections (Scerri, 2007; Van Spronsen, 1969).

Each one of these co-discoverers could in principle have made predictions about unknown elements had they believed deeply enough in the underlying pattern in their periodic system. I believe it was Mendeleev's motivation, rather than his choice of representation, that led to his predictive success.

Mendeleev's triumph was due to the institutional norms of the period. Whereas Mendeleev worked within the relatively new and adventurous Russian chemical milieu, Meyer was operating in a highly established and conservative German context that discouraged speculation. In addition, Mendeleev is known to have modeled himself on Newton and consequently would have been pre-disposed to making predictions in the typical fashion of a physicist (Gordin, 2004).

On the other hand, Meyer trained as a medical doctor, a field that is not known for its predictive prowess. Moreover, Mendeleev worked within the newly formed chemical society that was in the process of launching a journal, which tolerated more speculative forms of research such as the making of predictions. I do not therefore share Woody's view that Mendeleev's periodic table triumphed because of his choice of representation.

MENDELÉEFF'S TABLE I.—1871.

Series.	GROUP I. R_2O.	GROUP II. RO.	GROUP III. R_2O_3.	GROUP IV. RH_4. RO_2.	GROUP V. RH_3. R_2O_5.	GROUP VI. RH_2. RO_3.	GROUP VII. RH. R_2O_7.	GROUP VIII. RO_4.
1	H=1							
2	Li=7	Be=9.4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27.3	Si=28	P=31	S=32	Cl=35.5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Ce=59 Ni=59, Cu=63
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	? Y=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104 Pd=106, Ag=108
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	I=127	
8	Cs=133	Ba=137	? Di=138	? Ce=140	....	....	....	....
9	....	....	....	....	....	....	....	....
10	....	....	? Er=178	? La=180	Ta=182	W=184	....	Os=195, In=197 Pt=198, Au=199
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	....	....	
12	....	....	....	Th=231	....	U=240	....	....

Fig. 5. A version of Mendeleev's 1871 horizontal tabular form, labeled as Fig. 4.3 by Woody.

MEYER'S TABLE OF 1868.

1	2	3	4	5	6	7	8
Cr=52.6	Mn=55.1 49.2 Ru=104.3 92.8=2.46.4 Pt=197.1	Al=27.3 $\frac{28.7}{2}$=14.8 Fe=56.0 48.9 Rh=103.4 92.8=2.46.4 Ir=197.1	Al.=27.3 Co=58.7 47.8 Pd=106.0 93=2.465 Os=199.	Ni=58.7	Cu=63.5 44.4 Ag=107.9 88.8=2.44.4 Au=196.7	Zn=65.0 46.9 Cd=111.9 88.3=2.44.5 Hg=200.2	C=12.00 16.5 Si=28.5 $\frac{89.1}{2}$=44.5 $\frac{89.1}{2}$=44.5 Sn=117.6 89.4=2.41.7 Pb=207.0
9	**10**	**11**	**12**	**13**	**14**	**15**	
N=14.4 16.96 P=31.0 44.0 As=75.0 45.6 Sb=120.6 87.4=2.43.7 Bi=208.0	O=16.00 16.07 S=32.07 46.7 Se=78.8 49.5 Te=128.3	F=19.0 16.46 Cl=35.46 44.5 Br=79.9 46.8 I=126.8	Li=7.03 16.02 Na=23.05 16.08 K=39.13 46.3 Rb=85.4 47.6 Cs=133.0 71=2.35.5 Te=204.0	Be=9.3 14.7 Mg=24.0 16.0 Ca=40.0 47.6 Sr=87.6 49.5 Ba=137.1	Ti=48 42.0 Zr=90.0 47.6 Ta=137.6	Mo.=92.0 45.0 Vd=137.0 47.0 W=184.0	

Fig. 6. Lothar Meyer's tabular form of 1868.

4.1. *Woody's comparison of Mendeleev's and Lothar Meyer's presentations*

The main thrust of Woody's article is her comparison between Meyer's atomic volume curve and Mendeleev's periodic table that she describes as being two very different representations of periodicity.

While one can readily agree with this apparent difference, one can still doubt whether it serves to characterize the difference between Meyer's and Mendeleev's approaches. One immediate concern, that Woody does not address, is that Meyer also published several tabular forms, and well before Mendeleev did.

Perhaps a better way to express the difference would be to say that both Mendeleev and Meyer published tables, while Meyer also published an influential graph featuring atomic volume vs. atomic weight. Said differently, it is perfectly legitimate to compare Meyer's graph with Mendeleev's periodic table but it will not answer the question of why Mendeleev made predictions while Meyer did not. Even though Meyer *did* publish several tabular representations he failed to make any substantial predictions. This would seem to imply that his failure to make predictions lies beyond his choice of representation.

In this context it is useful to examine his tabular representations more closely. In 1864 Meyer published two short tables, in which he became the first to use valency (werthig) as a means of classifying elements together (Fig. 1). The larger of the two tables contains 28 elements in which Meyer left several empty spaces, four of which can reasonably be interpreted as indicating possible new elements. In the case of the first column he actually predicted the existence of such a new element including its atomic weight, by arguing in terms of differences between the atomic weights of successive elements in a vertical column. This approach is essentially identical to that of Mendeleev, as well as several earlier pioneers of the periodic system (Scerri, 2007; Van Spronsen, 1969). Such an approach does not rely on the use of an atomic volume curve, which in any case Meyer did not publish until 1870. When he did publish the atomic volume curve the article also contained an updated tabular representation with all the elements combined together.

These facts taken together would seem to indicate that, rather than representing Lothar Meyer's modus operandi, his inclusion of an atomic volume curve was designed for a more specific purpose. Meyer's aim was to examine the large variation that exists among elements within the same period. As Meyer wrote:

> However, if we wish to portray the nature of the elements as they depend on the size of their atomic weights, we must investigate the alteration of each property stepwise from element to element. The goal of what follows here is to establish a starting point for such an endeavor. One of the properties that changes rather regularly with atomic weight is the filling of space by elements – the atomic volume. (Meyer, 1870, p. 359, p. 359)

Meyer then proceeded to present his now famous atomic volume curve and used it to predict the value for elements whose values were unknown at the time. For example he used it to correct the then known atomic weight of the element indium, as a result of which he successfully placed this element in his periodic table. It is worth noting that Mendeleev misplaced indium in his first periodic table of 1869. Meanwhile, in the article of 1870 in which Meyer introduces his atomic volume curve he writes:

> The equivalent of indium is In = 37.8 according to the recent determinations of Cl. Winkler, which are nearly the same as those of Reich and Richter. Since the density of the metal has been found to be = 7.42, that means that the equivalent volume is = 5.1. This cannot be the atomic volume, since that would lie far outside the curve. If one assumes that In = 75.6 is divalent, it would lie between As and Se, where malleable electropositive elements fit so poorly, like the associated atomic volume 10.2 in the path of the curve. But if one were to set In = 3 × 37.8 = 113.4, like Al apparently trivalent, actually tetravalent, it falls between Cd and Sn with the atomic volume = 15.3, which fits rather well into the curve. (Meyer, 1870, p. 363, p. 363)

The main thrust of Meyer's proposal still concerned a tabular representation as it had done in his earlier publications of 1864. Meanwhile, Woody suggests that the graphical format would not allow the prediction of unknown elements as compared with tabular representations. She writes,

> Moreover, because the representation holds an explicit metric, locating a missing element would require determining a quantitative pattern for increasing atomic weights (the spacing, in effect, of x-coordinates for the data). Clearly, the graphical format does not indicate the presence of missing elements in any straightforward sense. It does not reveal 'holes'. (Woody, p. 134)

I believe that this may only be an apparent difference between the two forms of representation. Firstly, the atomic weight gap between successive elements is highly irregular in the tabular format, which means that it is not clear how many elements might be missing between any given two known elements. As a result, the prediction of new elements is not as categorical in the case of the tabular format as compared with the graphical form as Woody is proposing.

Secondly, making predictions from Meyer's curve would not have been as difficult a task as Woody implies. As I argued above, Meyer certainly used his atomic volume curve in order to correct the atomic weights of elements like indium. Moreover, in Fig. 3 it is not difficult to see that an element probably exists between calcium and titanium, given the relatively large distance between the points shown for these elements along the x-axis. This element turns out to be scandium, one of Mendeleev's famous three successfully predicted elements.

An even larger gap is seen between the elements symbolized by Di and W, thus suggesting the existence of one or more unknown elements. Although Meyer's curve does not literally imply empty spaces, the net effect is also to imply the existence of missing elements provided one might be inclined to making predictions about new elements. In any case, Meyer did leave a number of empty spaces in the various tables that he published in his earlier articles as Alan Rocke has recently argued (Rocke, 2019 unpublished manuscript).

More generally, if making predictions is somehow dependent on arriving at a tabular form of representation, it is difficult to understand why other co-discoverers, including Odling or Newlands, failed to make predictions, since they too arrived at a tabular format and, like Meyer, well before Mendeleev did (Scerri, 2007; Van Spronsen, 1969).

Woody writes that establishing the length of the period is sufficient for gaps to appear in Mendeleev's table if one assumes, as Mendeleev did, the constancy of period lengths. She continues by saying that the table makes the absence of unknown elements

> … starkly visible, and this is all that is required for the prediction of missing elements. (Woody, 2014, p. 134, p. 134)

Once again, if this is indeed all that is required for making predictions, then Newlands and Odling should have also made predictions, something that they did not do. Moreover, as shown clearly in Fig. 4, Mendeleev's period lengths are not equal, but are all different at 2, 7, 12, 19, 15 and 15 elements. And yet Mendeleev predicted the existence of four elements with atomic weights of 45, 68, 70, 180 even with this first published periodic table of 1869. In addition, if the mere presence of gaps implies the prediction of new elements one must wonder why Mendeleev did not predict eka-antimony, ruthenium, rhodium, palladium, silver, barium, dydium, osmium, iridium and platinum, all of which represent gaps in his system (Fig. 5).

The periodic law *equally* underlies both Mendeleev's periodic table and Meyer's atomic volume curve. As a result, the two approaches that Woody wishes to contrast are not fundamentally different, but only appear to be so if one restricts oneself to just examining the two forms of *representation*.

I turn to Woody's third question, namely why we should consider the periodic table as explanatory. Woody also wishes to compare Mendeleev and Meyer's representations from the point of view of the community of chemists. In doing so she claims that chemists should have preferred a graph form (Meyer) because of its emphasis on quantitative data and the fact that chemists wanted to be more like physicists. This makes it difficult to understand why, to this day, chemists have not preferred Meyer's representation. Whereas periodic tables are ubiquitous in chemistry and science in general, the appearance of curves such as those for atomic volume is far less common.

Continuing her characterization of the tabular representation, Woody adds that Mendeleev did not predict the existence of noble gases because of,

> … how representational format conditions the pathways of our thoughts and conceptualizations. (Woody, 2014, p. 137, p. 137)

However, Meyer did not fare any better when it came to predicting, or accepting, the noble gases because of his own representational approach. On the basis of his own representation Meyer would also have found it difficult to predict the existence of the noble gases, even if he had been disposed to making predictions.

Returning to her claim that the periodic table is explanatory, Woody canvasses support from a chemistry textbook from 1975 and quotes the author as saying:

> With the help of the periodic law, it is possible to organize and to systematize the chemistry of the elements into a manageable subject. Learning descriptive chemistry then becomes a process of discovery and assessment of facts, prediction and verification of chemical behavior, and evaluation of correlations and explanations. *All this leads to an understanding of why elements have the properties they do*. (Mahan, 1975, p. 569 (my italics))

It should be noted that this quotation is now 44-years old and drawn from one general chemistry textbook which may not be entirely representative of whether the chemical community regards the periodic table per se to possess explanatory power. An alternative interpretation might be that Mahan's final sentence is just a *façon de parler*. Although one may well concede that the periodic table unifies and systematizes, this would not necessarily imply an explanation. I am more inclined to believe that the periodic table, *as representation*, plays only a weak explanatory role if indeed it plays any such role.

Woody maintains that it is the periodic table, rather than the periodic law, that explains chemical behavior and that as a consequence we should not appeal to the periodic law in trying to clarify the question of prediction and accommodation. But why require that prediction should only be carried out through a scientific law?

5. So where do explanations come from?

On the question of explanations in chemistry, my disagreement with Woody lies with the degree to which the periodic table serves an explanatory role. My claim is that more meaningful and powerful explanations for chemical behavior come from atomic structure, electronic configurations and ultimately from quantum mechanics. My reason for wanting to relegate the explanatory role of presentations such as the periodic table is that any such explanations provide neither a mechanism nor a cause for the chemical behavior in question (Glennan, 2018).

On the other hand, Woody claims that the periodic law is not explanatory, because it suppresses quantitative data and is mathematically imprecise. I would reply that the periodic law must suppress chemical data since it deals with the relationship of the elements in general, just as any formula in science deals in generality.

Woody thinks that the periodic table itself, as a 2-D representation, facilitates and guides reasoning because

> … the representational format of the periodic table makes these patterns evident, and partly as a consequence, enables types of reasoning that facilitate dominant forms of inquiry. (Woody, 2014, p. 141, p. 141)

Woody seems to be well aware of the difficulties that such a view might encounter when she concedes that:

> Although many will agree that the periodic table organizes, and even classifies, there is no similarly robust intuition that it explains. Yet the insight implicit in Mahan's statement is that an understanding of the chemical elements and their properties consists, in large part, in the recognition of patterns among these elements and a capacity to use these patterns to guide chemical inquiry (Woody, 2014, p.141).

> Although I am perfectly willing to go along with Mahan's talk of facilitation and guidance I would still maintain that facilitation and guidance do not constitute explanation in any meaningful manner. Woody also asks, Is it *possible* that all the productivity and explaining power is more accurately located in the theory of electronic structure? (Woody, 2014, p.141, p.141)

As I see the matter, professional chemists do indeed believe that the theory of electronic structure provides more comprehensive explanations of chemical behavior, and far more so than the periodic table does qua representation.[1] In all fairness to Woody, her claim appears to be that the periodic table plays *some* role in chemical explanations, which is something that I would be inclined to agree with. However, at times she also claims that it plays an 'essential role'. I believe that the latter claim is more problematic as I will explain below.

But Woody presses her point, Even if we assume every trend and pattern identified by the periodic table could be captured through electronic structure, unless we also presuppose a reductionist account of explanation, it does not follow that this electronic theory necessarily gets explanatory credit with respect to particular chemical properties (Woody, 2014, p. 141, p.141).

Here too I beg to differ. Unlike the qualitative explanation that a representation might offer, an appeal to electronic structure instead would offer a causal mechanism that refers to the manner in which electrons behave (Ross, in press). On the other hand, an explanation that only appeals to the periodic table, as representation, might amount to saying that a certain element behaves in a certain way because it lies in a particular group. Since the periodic table is a human-made device there is no similar reference to any ontological chemical entities in this alternative mode of explanation.

Moreover, Woody cites Scerri in support of this anti-reductionist claim because he has previously pointed out that a 4-quantum number account of electronic structure cannot be reduced fully to quantum mechanics (Scerri, 1997). However, this feature does not deprive the 4-quantum number approach of approximate explanatory value. In addition, it is worth noting that Scerri's more recent writings on electronic structure indicate that he now concedes a good deal more ground to the reductionist view. Scerri now writes that that his earlier questioning of the reductive power of quantum mechanics, in the context of the periodic table, may have been somewhat naïve. He now believes that he may have underestimated the way in which quantum mechanics explains such features as the anomalous configurations that occur among the atoms of approximately twenty elements (Scerri, 2016).

While Woody repeatedly claims that we should recognize the periodic table as explanatory, this may only be true for particular sectors of the chemical community, such as students or qualitative inorganic chemists. I do not believe it to be true in general. It depends on whether one may be referring to the practice recommended by a textbook author or a chemistry instructor. This may differ from the kind of explanation that a theoretical chemist might appeal to.

Admittedly some professional chemists, such a Roald Hoffman, have correctly argued for the importance of qualitative explanations for certain chemical trends and the fact that a fully reductive approach can fail to capture some forms of chemical behavior that a chemist might be interested in (Hoffman, 1997). Although I am not arguing for a purely reductionist approach to chemical explanation I believe that Woody may be attaching a little too much importance to the explanatory value of the periodic table purely as a representation.

Woody also makes a valid philosophical point, while citing Hempel, to the effect that a true universal empirical generalization explains an instance of that generalization, while explaining the generalization itself requires a separate argument.

One may also be willing to grant that the periodic table guides us to navigate effectively, but navigation is not necessarily tantamount to explanation. The periodic table is a wonderfully good tool for seeing relationships between elements but that does not help to explain specific chemical facts in anything but a cursory manner. The table provides relative comparisons, not accurate numerical predictions. For the latter, we need a means of computing all manner of quantitative data about particular elements. Quantum mechanics appears far better suited to this task than the periodic table. To the extent that the periodic table, as a representation alone, can provide any explanation I believe it must be regarded as a weak form of qualitative explanation that might only satisfy certain segments of the chemical community.

In any case, a reductive quantum mechanical explanation of chemical behavior makes no reference whatsoever to the periodic table.[2]

[1] A cursory inspection of any chemistry textbook shows that the explanatory work is carried out by appeal to electronic structure and quantum mechanics and not just the periodic table itself (Atkins & de Paula, 2012).

[2] Attempts to understand the periodic table did contribute to the development of quantum mechanics such as in the case of Bohr's old quantum theory and

This fact further emphasizes that whatever role the periodic table may play it does not constitute an essential role as Woody wishes to claim.

6. Woody's conclusions on the turn to practice in the context of the periodic table

In her concluding section Andrea Woody provides a list of features that she considers as the characteristics of the return to practice in recent philosophy of science. These features are presented as a checklist, which Woody uses to persuade the reader that her own account of the periodic table meets each point.

The first point is the move from conceptions, in the old-fashioned approach, to the use of representation. Woody writes:

> … I have argued that we need recourse to the particular representational format of the periodic table to properly assess both the role of prediction in the law's acceptance and the law's explanatory status. (Woody, 2014, p. 145, p. 145)

But as I have replied in the present paper, neither of these claims are entirely convincing, at least to this author. I do not think that the predictive role of the periodic table is diminished by the fact that the periodic *law*, which underlies it, cannot be cast in a strictly mathematical form. Secondly, I have disputed the notion that Mendeleev was more successful in making predictions as a result of his opting for a tabular representation rather than a graphical one. Thirdly, I propose that the periodic table possesses only a qualitative explanatory power by virtue of its being a representation and prefer to locate the major explanatory role in the underlying theoretical account, namely quantum mechanics. To be fair to Woody, she does not deny the role of quantum mechanics in chemical explanations. To reiterate my earlier point, my disagreement over the question of explanation is a matter of degree rather than a rejection of the view that the periodic table per se offers some explanatory power.

Woody's second point consists of the move from a priori to empirical. As she sees it, her argument that the periodic table should be considered explanatory is

> … grounded by appeal to a prominent practitioner's public assessment and subsequently to contemporary disciplinary practice in chemistry. (Woody, 2014, p. 145)

It should be noted however that this practitioner is a relatively unknown textbook author, writing a statement about the role of the periodic table in 1975. The statement cannot therefore be taken as representative of the manner in which the periodic table is regarded in the wider chemical community vis à vis whether it provides a satisfactory form of explanation. Nor is it clear how this assessment could be considered as a move towards the empirical. Such a claim would perhaps require an empirical study to sample the views expressed in the intervening 44 years, by more contemporary textbook authors, on whether indeed the periodic table per se is explanatory. Of course I concede that the periodic table serves to unify and systematize chemistry but this does not imply that it provides anything but a token explanation. After all, any system of classification can provide unification and systemization but not necessarily a satisfactory explanation of the entities that are being systematized.

The third item on Andrea Woody's return to practice checklist is, "ideal agent to human practitioners":

> Analysis of the graphical and tabular formats makes crucial reference to the general perceptual capacities of practitioners, the kinds of background knowledge available to them, and the sorts of reasoning commonly employed within the relevant communities. (Woody, 2014, p. 145, p. 145)

Again, one needs to ask what the relevant communities might be. Does the community in question consist of practicing inorganic or theoretical chemists? The community that Woody is referring to seems to be one of textbook authors or chemistry students, and perhaps some professional chemists who might be satisfied with pointing to the position of an element in the periodic table as providing a form of explanation.

The fourth criterion that accompanies the turn to practice, as Woody portrays it, is the move from "knowing subject to social epistemology":

In explaining both the original entrenchment of the periodic table and its role in contemporary practice, I have appealed to the aims of the relevant chemical communities (Woody, 2014, p. 145, p. 145).

However, as I argue above, I do not believe that Woody has in fact explained the original entrenchment of the periodic table or its role in contemporary practice. Whereas she believes the entrenchment of Mendeleev's table occurred because of its tabular rather than graphical form, all six discoverers of the periodic table appealed to a tabular form. Yet it was only Mendeleev's table that has become entrenched.

Finally, although I am in favor of the turn to practice in the philosophy of science, I wish to emphasize that my disagreements with Woody's article have only been directed at the way that she has chosen to discuss this issue in the context of the periodic table. In the case of the claimed intrinsic explanatory power that the periodic table may provide, my disagreement consists of the degree to which this may be true rather than being an across-the-board rejection of Woody's stimulating proposal.

Acknowledgement

I thank Alan Rocke for discussion and for providing an English translation of Lothar Mayer's article of 1870.

References

Atkins, P., & de Paula, J. (2012). *Elements of physical chemistry* (6th ed.). New York: W.H. Freeman.
Brush, S. J. (1989). Prediction and theory evaluation. *Science, 246*, 1124–1129.
Glennan, S. (2017). *The new mechanical philosophy.* New York: Oxford University Press.
Gordin, M. (2004). *A well-ordered thing: Dmitrii Mendeleev and the shadow of the periodic table.* New York: Basic Books.
Hoffman, R. (1997). *The same but not the same.* New York: Columbia University Press.
Howson, C. (1984). Bayesianism and support by novel facts. *The British Journal for the Philosophy of Science, 35*, 254–261.
Mahan, B. H. (1975). *University chemistry.* Reading, MA: Addison-Wesley Publishing Company.
Meyer, J. L. (1870). Die natur der Chemischen elemente als function ihrer atomgewichte. *Annalen der Chemie, Supplementband, 7*, 354–364.
Rocke, A. (2019). *As yet unpublished manuscript presented at conference on the history of chemistry, maastricht.* july 29th – 2nd August, 2019.
Ross, L. N. (2018). Causal explanation and the periodic table. *Synthese.* https://doi.org/10.1007/s11229-018-01982-0.
Scerri, E. R. (1997). Has the periodic table been successfully axiomatized? *Erkenntnis, 47*, 229–243.
Scerri, E. R. (2007). *The periodic table, its Story and its significance.* New York: Oxford University Press.
Scerri, E. R. (2016). The changing views of a philosopher of chemistry on the question of reduction. In E. R. Scerri, & G. Fisher (Eds.). *Essays in the Philosophy of chemistry* (pp. 125–143). New York: Oxford University Press.
Scerri, E. R., & Worrall, J. (2001). Prediction and the periodic table. *Stud. Hist. Phil. Sci. 32*, 407–452.
Van Spronsen, J. (1969). *The periodic System of chemical elements: A History of the first hundred years.* Amsterdam: Elsevier.
Woody, A. I. (2014). Chemistry's periodic law: Rethinking representation and explanation after the turn to practice. In L. Soler, S. Zwart, M. Lynch, & V. Israel-Jost (Eds.). *Books, science After the practice Turn in the philosophy, history, and social Studies of science.* London: Routledge Taylor & Francis Group.

(*footnote continued*)
Pauli's Exclusion Principle. However once quantum mechanics became established its predictions and explanatory power no longer appealed explicitly to the periodic table.