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Missing Elements and Missing Premises: a Combinatorial Argument for the Ontological Reduction of Chemistry

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ABSTRACT

Does chemistry reduce to physics? If this means ‘Can we derive the laws of chemistry from the laws of physics?’, recent discussions suggest that the answer is ‘no’. But supposing that kind of reduction—‘epistemological reduction’—to be impossible, the thesis of *ontological reduction* may still be true: that chemical properties are determined by more fundamental properties. However, even this thesis is threatened by some objections to the physicalist programme in the philosophy of mind, objections that generalize to the chemical case. Two objections are discussed: that physicalism is vacuous, and that nothing grounds the asymmetry of dependence that reductionism requires. Although it might seem rather surprising that the philosophy of chemistry is affected by shock waves from debates in the philosophy of mind, these objections show that there is an argumentative gap between, on the one hand, the theoretical connection linking chemical properties with properties at the sub-atomic level, and, on the other, the philosophical thesis of ontological reduction. The aim of this paper is to identify the missing premises (among them a theory of physical possibility) that would bridge this gap.

1 Introduction: missing elements and the mystery of discreteness

> The law of periodicity first enabled us to perceive undiscovered elements at a distance which formerly was inaccessible to chemical vision; and long ere they were discovered new elements appeared before our eyes possessed of a number of well-defined properties. We now know three cases of elements whose existence and properties were foreseen by the instrumentality of the periodic law.....When in 1871, I described to the Russian Chemical Society the properties, clearly defined by the periodic law, which such elements ought to possess, I never hoped that I should live to mention their discovery to the Chemical Society of Great Britain as a confirmation of the exactitude and the generality of the periodic law.
>
> Dimitri Mendeleev, 'The Periodic Law of the Chemical Elements'

Thus Mendeleev refers, in his Faraday Lecture to the Chemical Society of the Royal Institution, to his dramatic anticipation of the discovery and properties of gallium (Mendeleev's name for it when it was still a prediction had been 'eka-aluminium'; it was discovered in 1875), scandium ('eka-boron'; discovered in 1879), and germanium ('eka-silicon'; 1886). The basis of the predictions was a mixture of theory and conjecture. Having arranged the known elements in a periodic sequence, Mendeleev found that there were gaps: spaces for elements with properties whose values should lie between those of neighbouring elements. Rather than eliminate these gaps, Mendeleev took a crucial step beyond previous attempts to systematize the elements, and asserted, with extraordinary boldness, that these spaces represented unknown elements existing in nature. The story, of course, is well known, but it raises a number of questions.

One question concerns the history of ideas. Why was Mendeleev so confident that the elements he predicted actually existed? This is not a question about his confidence in the periodic law (that, as he formulated it, 'the elements, if arranged according to their atomic weights, exhibit an evident periodicity of properties' (Mendeleev [1889], p. 635)), but rather about an implicit conceptual move. Granted that the gaps in Mendeleev's table represented genuine possibilities, elements that could exist, why assume that the possibilities were realized? Was there, somewhere in his system of thought, a version of the principle of plenitude, that all possibilities are (at some time) realized?[1] William Ramsay showed a similar confidence in nature's abhorrence of a modal vacuum (in the form of unactualised possibilities) when, in his Presidential address to the British Association for the Advancement of Science, he predicted the existence and properties of neon (Ramsay [1897]).

Some of Mendeleev's other missing elements were discovered after his death. One of these was technetium (Mendeleev's 'eka-manganese'), discovered in 1937. This was the first *artificial* element, produced by bombarding molybdenum with deuterons, and it was believed by its discoverers not to occur in nature. (It had in fact previously been identified in columbite ores by means of X-ray spectroscopy, and given the name 'masurium', by Ida Tacke and her colleagues in 1925, but their findings were regarded as doubtful.) Modern versions of the periodic table make room for elements beyond the latest to be manufactured (2000), with atomic number 116, and some of these elements will, it is reasonable to suppose, remain mere possibilities.[2] If nature does, after all, tolerate a modal vacuum, then Mendeleev and Ramsay were fortunate in their choice of predictions.[3]

Another question is related, but purely philosophical: even if some elements in the table are merely possible, there is a genuine difference between the physical possibility of an element between, say, zinc and arsenic (atomic numbers 30 and 33, and the mere logical possibility of an element between potassium and calcium (19 and 20). But how do we define this difference? One way of putting this is that chemistry is *discrete* rather than *continuous*. Given any two physically possible elements, there are at most a merely finite number of intermediate elements between those two in terms of atomic weight.[4] For Mendeleev, discreteness and periodicity went hand in hand:

> Not only are there no intermediate elements between silver, which gives AgCl, and cadmium, which gives $CdCl_2$, but, according to the very essence of the periodic law there can be none; in fact a uniform curve would be inapplicable in such a case, as it would lead us to expect elements possessed of special properties at any point of the curve. The periods of the elements have thus a character very different from those

> which are so simply described by geometers. They correspond to points, to numbers, to sudden changes of the masses, and not to a continuous evolution. In these sudden changes destitute of intermediate steps or positions, in the absence of elements between, say, silver and cadmium, or aluminium and silicon, we must recognize a problem to which no direct application of the analysis of the infinitely small can be made. (Mendeleev [1889], 641)

The periodic law did not explain discreteness; it simply embodied it. The discreteness of chemistry remained a mystery until the emergence of the quantum theory of the atom. That theory is the main source of the view that chemistry reduces to physics. The path to the reduction of chemistry, however, is full of hidden dangers. What I propose to do in this paper is to explore the rather subtle connections between the discreteness of chemistry and the reductionist programme.

Does chemistry reduce to physics? Discussions of this issue in the (mostly relatively recent) literature on the philosophy of chemistry are often concerned with the possibility of deriving chemical laws—for instance the Periodic law—from quantum physics. That a complete derivation is impossible, in practice and perhaps even in principle, is suggested by the following considerations:

(a) The calculations required to derive the properties of elements from the motion of electrons would be enormously complex beyond a certain point in the periodic table, and calculations of their behaviour in reactions would be even more so (Christie and Christie [2000], pp. 45-6).
(b) There are few 'laws of chemistry' that admit of the same rigour of formulation as laws of physics (Ibid., 39-44).
(c) The idea of reduction only makes sense in the context of realism about both chemical and quantum theory, but it is hard to sustain realism about both of these, since quantum theory falsifies some of the assumptions about electronic configuration used to derive chemical properties (Scerri [1991], 317-18), motivating an instrumentalist approach to chemical models of atomic structure and bonding.

The strong form of reduction that these considerations tell against we may call *epistemological reduction*. With the emergence of Bohr's model of the atom (discussed later) in 1913, and its further development by Pauli, the prospects for epistemological reduction looked good. It is ironic that the advance of physics in the 20th century should have made those prospects rather less secure. But there is another, weaker,[5] form of reduction that we may call *ontological reduction*. The thesis of ontological reduction is that properties we would recognize as paradigmatically falling within the domain of chemistry are determined by more fundamental properties. Ontological reduction is not committed to the view that we are already acquainted with these more fundamental properties, nor even that, once acquainted with them, we could successfully derive the chemical properties from the fundamental ones. There is, I think, a strong intuition that ontological reduction is true, whatever the fortunes of epistemological reduction. But what is the source of this intuition? Can ontological reduction be defended independently of epistemological reduction?

Mendeleev supplied some missing elements in nineteenth century chemistry, and gave us the tools to predict many more. I will attempt, more modestly, to supply some missing premises in the argument for the ontological reduction of chemistry. Without those premises, the reductionist thesis is vulnerable to two powerful objections. To these I now turn.

2 The refutation of physicalism

Physicalism, in its most general form, is the assertion that all concrete states and properties are *physical* states and properties. This is an ontological thesis, and its contemporary defenders sharply distinguish it from the stronger thesis that the laws of any more abstract discipline—chemistry, biology, psychology, sociology—are derivable, at least in principle, from the laws of physics (c.f. our distinction above between the epistemological and ontological reduction of chemistry).[6] In the philosophy of mind, physicalism, while remaining orthodoxy for many writers after vigorous defences of it by Davidson, Lewis and others, has been subject to sustained attack on a number of fronts. One source of criticism is specific to mind, and that is physicalism's alleged failure to account for the existence and characteristic features of the mental: consciousness, intentionality, and content. This kind of attack does little to unseat physicalism's standing in other areas. Other difficulties, however, are quite general, and threaten physicalist approaches in any field, and I shall be concerned with two of them.

The first difficulty we shall name *the vacuity problem*. It goes as follows: if physicalism is to have any substantive content, we have to have a clear and contentful characterisation of what it is to be physical. Suppose, then, that we take '*x* is physical' to be equivalent to '*x* is wholly describable in the terms of physics'. We then face a dilemma. If 'physics' means *current* physics (which is both incomplete, and—it is only reasonable to assume—partly false) then it is simply false that everything (even within a given domain) is physical, since current physics does not truly describe everything. But if 'physics' means instead an *ideal* (i.e. true and complete) physics, physicalism becomes a vacuous theory, equivalent to the tautology that everything is truly describable by the science whose defining feature is that it truly describes everything. Defining the physicalist thesis in terms of physics, then, makes it either false or trivial. (Crane and Mellor [1990]; Crane [1991]; see also Robinson [1982].)

One response to the vacuity problem is to provide a characterisation of the ideal physics without explicit reference to completeness. Suppose, then, we characterize it as the science both of the very small (electrons, quarks) and of the very large (galaxies). Other sciences are those that are concerned only with objects of intermediate size. It is reasonable to suppose that developments in physics, including revisions in our view of what the very small constituents of matter are, would survive this characterisation. Triviality is still not avoided, since a complete science will include the science of the very small and the very large, and so count as 'physics' on this definition. And, trivially, all properties are described by the complete science. So even if we do not explicitly define physics in terms of completeness, characterising it in terms that would necessarily be satisfied by the complete science would still render physicalism trivial.

We could try expunging all explicit references to physics, and define the physical in other ways. Still the dilemma remains a threat. Suppose, for instance, we take the appellation ‘physical’ to imply composition out of very small particles. Then physicalism is essentially the thesis of micro-reductionism (Crane and Mellor [1990] p. 86). Setting aside the worry that certain paradigmatically physical entities are not obviously captured in this way (such as space), this approach still presupposes a particular theoretical outlook, in terms of fundamental particles, and any theoretical outlook may, by the pessimistic induction, be replaced. True, if physicalism is the thesis that all properties supervene on the properties exhibited by the smallest entities, then it is not trivial; but then we have no reason to suppose it true.

The second difficulty we shall call *the asymmetry problem*. It goes as follows: suppose that, according to an accepted theory, properties *F* and *G* are identical. What could justify our selecting, e.g., *F* as the more fundamental? Consider, for instance, the relationship between ‘dispositional’ and ‘categorical’ properties. The key that I have in my hand has the capacity to unlock the door of my garden shed. That is one of its dispositional properties. But it also has a distinctive shape. That is one of its categorical properties. Now there is a strong inclination to suppose that it has the capacity to unlock the shed door *by virtue* of its shape. The categorical property, it is sometimes suggested, is more fundamental than the dispositional. Why? One reason, often appealed to in these and other cases, is that a relation of *supervenience* holds, and moreover the relation in this case holds only one way: the dispositional property supervenes on the categorical property, whereas the categorical does not supervene on the dispositional.

But does supervenience really exhibit a direction in these cases? Here is a standard characterisation of the relation: property A supervenes on property B iff two entities could not differ in terms of A without also differing in terms of B (cf Davidson [1970], p. 214). Nothing in this definition implies that supervenience can only hold one way. What is supposed to introduce the asymmetry, in those cases where it apparently does hold only one way, is *variable realization*. The reductionist about the dispositional takes the dispositional to supervene on the categorical, rather than vice versa, because a disposition can be realized in a number of categorical ways. Thus a key can possess the power to unlock by virtue of having any of a number of possible shapes. But a given shape in a key is not similarly associated with different and incompatible capacities to unlock in different instances. As one might put it, a dispositional difference between two keys implies a categorical difference, but a categorical difference does not imply a dispositional difference.

However, the appearance of asymmetry here may be illusory. Granted that objects alike with respect to dispositional properties may differ with respect to their categorical properties, these categorical differences are *irrelevant* ones—irrelevant to the determination of the disposition, that is. Once one has a sufficiently abstract description of the categorical state, such that it includes nothing that is irrelevant to the determination of the disposition, satisfaction of that description will entail satisfaction of the dispositional description *and vice versa*, so there is in fact no variable realization. Consider the key again. What matters, as far as shape is concerned, is that it relates in a certain way to the shape of the lock. If the lock has shape S, then the key will unlock it if and only if it is, as we might dub the shape, *S-complementary*. Only by having that particular categorical property will the key have the capacity to unlock S-locks. There is no variable realization after all. So appeals to supervenience will not after all ground the asymmetry.

Do these objections, to physicalism in the philosophy of mind, and to reductionism about dispositions, threaten the ontological reduction of chemistry? It might seem odd to suggest that a physicalist view of chemistry is even in question: chemistry is, after all, one of the physical sciences. But, although in a wide sense of ‘physical’, chemical properties are obviously physical, the view that chemical properties are determined by more fundamental properties is a substantial and controversial thesis. And that thesis is indeed threatened by both the vacuity and asymmetry problems. That chemical properties supervene on those properties described by the complete science is just as trivial as the thesis that mental properties do. And even supposing a one-to-one correspondence between a given chemical property and one described by physics, that correspondence would not by itself suggest that one is more fundamental than the other. Suppose, for example, valency to supervene on electronic configuration. At first sight, the relation appears to be asymmetric, because a valency of 1, for example, can be realized by a number of distinct configurations, but nothing can differ in terms of valency without also differing in terms of electronic configuration. However, the relevant part of the configuration—the part that determines valency—will not vary among elements of the same valency. The determination therefore goes both ways (Mumford [1994]). So chemical reductionism, the one thing that physicalists supposed they could hold up to the world as a shining example of the success of their programme, is suspect for some of the same reasons that physicalism about the mental is suspect.

None of this warrants the thought that chemistry is ontologically autonomous (this being the equivalent of dualism about the mental), nor the thought that chemical properties are emergent, rather than being determined by properties at a lower level. Those thoughts are also vulnerable to the vacuity problem: if physicalism cannot be given substantive content, neither can its denial.

The conclusion of this section is that the well-entrenched belief that chemical properties are not independent of properties studied by physics, though plausible, does not provide adequate grounds for the substantial thesis of ontological reduction, since the latter clearly implies an asymmetry that is left unexplained by the former. What then could explain the asymmetry? I want to pursue the suggestion that a certain approach to possibility could do so, namely combinatorialism.

3 A combinatorial theory of physical *possibilia*

The central contention of combinatorialism is this: possibilities are just combinations of actually existing simple items (individuals, properties, relations). Let us call this the *principle of recombination*. To illustrate it, suppose the actual world to contain just two individuals, *a* and *b*, and two monadic properties, *F* and *G*, such that (*Fa* & *Gb*). Assuming *F* and *G* to be incompatible properties, and ignoring the possibility of there being nothing at all, then the following is an exhaustive list of the other possibilities:

1. *Fa*

2. *Fb*

3. *Ga*

4. *Gb*

5. *Fa* & *Fb*

6. *Ga* & *Gb*

7. *Ga* & *Fb*

1-4 are ‘contracted worlds’, ones that lack one or more components of the actual world.

The advantage of combinatorialism, of course, is that it offers to make sense of modal talk whilst avoiding quantification over non-existents. (See Armstrong [1989] for an extended exposition and defence.) The only domains of quantification are actual objects and actual properties. However, two objections immediately present themselves. The first is that the principle of recombination does not, and cannot, constitute a full theory of modality; the second that it provides an unduly restricted account of what possibilities there are.

According to the first objection, a theory of modality is one that explains *what it is* for something to be possible or not possible. The principle of recombination does not provide this since there will be restrictions on what combinations are possible that cannot be explained in purely combinatorial terms. For instance, we specified that *F* and *G* are incompatible properties: it is not possible for *a* to be both *F* and *G* (at the same time, at any rate). But this assumption had to be made prior to the generation of the list of possible recombinations. If possibility were simply definable in terms of what appeared on the lists of permutations, and the business of generating that list were purely mechanical, then no *F* and *G* would be incompatible, unless definitionally so. This is clearly wrong, as any number of pairs of properties would show—being wholly composed of iron and being wholly composed of lead, for example.

The wisest move for the combinatorialist is simply to concede this point. This does not mean abandoning the principle of recombination, just restricting its role. The hope then would be that, by conjoining the principle with an account of properties, objects and their relations (which Armstrong, for one, provides elsewhere: see

Armstrong [1978]), it would be clear why certain properties were incompatible, and why a certain object could not exhibit a certain property. What kind of account this could be is not my concern. My interest is just in the principle of recombination as a constraint on possibility.

The second objection appeals to an intuition (one, it would be fair to point out, which may not be shared by everybody). It is this: we want to allow for the logical possibility of *alien* properties, objects and relations—i.e. those which are not identical to or composed out of actual properties, objects or relations—but this is ruled out by combinatorialism, as characterized here. Now, as far as objects are concerned, it is highly counterintuitive to suppose that the world could not have contained more objects than it does. There simply seems no good reason to deny that, e.g., a given couple *could* have had a fourth child, even though as a matter of fact they only had three. And it does not seem plausible to suppose that this counterfactual fourth child must be a recombination of actual simple objects. Why should there not have been more simple objects than there in fact are? Let us suppose, then, that the combinatorialist is prepared to concede this point, too. It would be perfectly coherent to maintain that there could have been alien objects, whilst denying that there could have been alien properties. (On a bundle theory of objects, these alien objects could be viewed simply as recombinations of actual properties.) But what of the intuition that there could have been alien properties? Of course, by recombining actual properties, we may produce all kinds of complex properties that are decidedly *outré*, but that will not satisfy the intuition we are dealing with here. The point is that there could be alien *atomic* properties, ones not reducible to other, actual ones. We may not have a clear idea of what such properties would look like, indeed it may be beyond us to imagine them. But we do not have to imagine them in order to postulate the possibility of their existence, although in the absence of any content supplied by the imagination, the thought remains a rather abstract one.

Conceding the possibility of alien atomic properties (hereafter just ‘alien properties’) does not immediately appear to be an option for the combinatorialist, and I suspect that committed combinatorialists will simply stand their ground and deny that the intuition has to be taken seriously. But there is another response, and that is to take the principle of recombination to define the range of what we intuitively think of as *physically* possible properties, and regard alien properties as, at best, merely logically possible. Because of, by now familiar, worries about the definition of ‘physical’, let us provide the following broad characterisation: the *physically possible worlds* are those where the laws that constrain the behaviour of concrete objects in those worlds are the same as those obtaining in the actual world. The revised principle of recombination can now be stated as follows:

> An unactualised property is physically possible iff it is constituted by a physically possible recombination of actually existing properties.

The reference to ‘physically possible’ on the right-hand side is necessary, since there are certain logically possible combinations of properties that would conflict with actual laws. The appearance of the same term on both sides of the biconditional does not vitiate the principle, since it is not intended as a definition of physical possibility. What it defines, rather, is simply the range of unactualised but physically possible properties.

The revised principle of recombination implies that no physically possible world contains alien properties. And this is really very plausible, given the intimate connection between laws and properties. Could we, for example, coherently talk of a world in which none of our laws of thermodynamics obtained, but in which water had the same boiling point as it does in the actual world (that is, really the same, not just called the same)? We could, indeed, characterize properties by reference to laws:

> Properties are identified *a posteriori* by scientific theories, construed as Ramsey sentences: i.e. as saying for example that there are properties C, F and G such that in C-circumstances all F-events have such-and-such a chance of being followed by G-events. If that statement is true, then there are such properties, and there is such a law, of which those properties are constituents. And being a constituent of some such laws is…..all there is to being a property. (Mellor [1991b]. p. 175.)

It follows from this that a world with alien properties is also a world with alien laws.

Alien properties, on this view, may be logically possible, but by definition they are not physically possible.

(What of contracted worlds, those that contain no alien properties, but only a subset of actual properties? Will those worlds be physically possible? They will if 'physically possible worlds' includes those worlds whose laws are a subset of actual laws.)

What we have now arrived at is a very modest, and therefore, I hope, plausible, form of combinatorialism: one that appeals to the principle of recombination simply as a constraint on what properties are physically possible. It is this modest combinatorialism that provides a missing premise in the argument for the reduction of chemistry, and which suggests a response to the two objections to physicalism articulated in the previous section.

4 Combinatorialism and the Bohr model

Let us begin by adopting the fiction that the Bohr model of the atom is correct. To spell out the fundamental tenets of the model: the atom of each element has a nucleus containing both protons (of positive charge) and neutrons (of no charge), the combined number of which determines the atomic weight of the element (or, more precisely, the atomic weight of that isotope of the element). Orbiting this nucleus are one or more electrons (of negative charge), whose number is equal to that of the protons (so the atom as whole is charge-neutral). These electrons occupy fixed orbits, or 'shells' around the nucleus. The first shell contains a maximum of two electrons, the second a maximum of eight, the third a maximum of eighteen, etc. Given this model, can we derive the periodic law, and other patterns among the elements? Here are some questions and their answers in terms of the model. Why are the noble gases (helium, argon, neon, etc.) so unreactive? Because their outer shells contain the maximum number of electrons, and so are the most stable. Why do the alkali metals all have a valency of 1? Because elements with the same number of electrons in the outer shell share the same valency, since the gain or loss of the same number of electrons is needed to return them to the most stable state, and the outer shells of the alkali metals all contain one electron. (The dispositional property of valency can in fact be identified with the categorical property of the number of electrons in the outer shell.) Why do the rare earths have such similar properties when they have different atomic weights? Because, although they have a different number of electrons in their inner shells (and so a different number of protons in the nucleus) the number of electrons in the outer shell is the same.

I have spoken in terms of 'questions' and 'answers', but our encounter with the asymmetry problem may make us suspicious of the suggestion that there is an asymmetric relation between the electronic configuration of the atom of a given element on the one hand and the chemical properties of that element on the other, with the former determining the latter. What, traditionally, was the basis of the assumption of asymmetry here? It almost certainly had to do with explanatory asymmetry: the Bohr model proposed to *explain* chemical properties. If the model had simply been an electronic representation of periodicity, then it would not have had a strong claim to explanatory depth: it would simply have substituted one form of periodicity for another. There would have been no more reason to regard the electronic configuration of an element as explaining its position in a periodic ordering, than to regard the length of each period as justifying the maximum number of electrons per shell. What, in part, gave the Bohr model explanatory depth was its ability to explain, in terms of a few basic principles, a range of phenomena. For example, Moseley's discovery that the frequency of X-rays emitted by elements exposed to cathode rays was a function of atomic number showed that atomic number was not merely the abstract property of position in the table, but corresponded to an intrinsic property of the atom. This led to a reformulation of the Periodic Law in terms of atomic number rather than atomic weight. The Bohr model also had greater predictive power than the Periodic Law alone. From his rules concerning electron arrangements, Bohr was able to predict that the as-yet-undiscovered element number 72 would not be a rare earth, but one of the transition elements. Further developments of the Bohr model, and in particular the discovery of two more quantum numbers—the magnetic quantum number and the spin quantum number—made the restriction on the maximum number of electrons in each shell less arbitrary. The numbers for each shell fall out as a consequence of Pauli's *exclusion principle*, that no two electrons have the same four quantum numbers, together with the relationship between the first three quantum numbers. (Whether the arbitrariness has simply been transferred, however, is a moot point. What, for instance, is the deeper justification for the exclusion principle?) Finally, the model is ontologically parsimonious, in that each element is built up from its predecessor by the addition of a single electron—the *aufbau* principle.

We have, however, been careful to distinguish epistemological/explanatory issues from ontological ones. Whether the Bohr model has explanatory power is one question; whether it identifies more fundamental properties than the chemical properties is quite another. The asymmetry problem remains unresolved. What I want to outline in the remainder of this paper is a case for ontological reduction, one that does not depend on the fortunes of any given attempt at epistemological reduction.

If the Bohr model were correct, then we would have an answer to the mystery so clearly expressed by Mendeleev: the discreteness of chemistry. For each element has a unique successor and (with the exception of hydrogen) a unique predecessor in the periodic table: there is not even the possibility of an infinite number of intermediate elements. Why is this? Because the variation in the number of electrons and shells between elements is itself discrete: there are no intermediate positions between having two electrons in the outer shell and having only one.

Now consider the related, but philosophical, question: what distinguishes the physical possibility of intermediate elements from their mere logical possibility? (That there is a clear distinction here follows from the observation that the physical possibilities form a discrete series, whereas the logical possibilities form a continuous series.) We can now answer this in combinatorial terms: the physical possibilities are defined by recombinations. Recombinations of what? According to the Bohr model, recombinations of the properties of and relations between electrons, relations that define both the number of electrons and their locations in the shells of the atom. The logical possibilities need not be so restricted.

Combinatorialism is a form of reductionism about *possibilia* (although, given the concession that the principle of recombination cannot be regarded as a theory about possibility, it does not follow that combinatorialism is reductionist about possibility). That is, talk of non-existent *possibilia* is made true by virtue of actual objects and their properties. This now suggests an answer to the asymmetry problem for physicalist reductions: granted that some property *F* can be identified with some physical property *G*, what makes it the case that *G* is a more fundamental property than *F*, that *F* is determined by *G*, and not *vice versa*? Here is a combinatorial criterion:[7]

> A property type *F* is ontologically reducible to a more fundamental property type *G* if the possibility of something's being *F* is constituted by a recombination of actual instances of *G*, but the possibility of something's being *G* is not constituted by a recombination of actual instances of *F*.

Applied to the chemical case, the property of being element *N* is (according to the Bohr model) reducible to the property of having a certain number and distribution of electrons, because the possibility of anything's being *N* is definable in terms of a recombination of those properties and relations that define actual electron distributions, but not *vice versa*. It would make no sense, for example, to define possible electron distributions in terms of recombinations of actually occupied positions in a periodic table. Thus, the combinatorial criterion, together with an electronic model of periodicity, implies a genuine ontological reduction of chemical properties.

5 Objections

What does the argument of the previous section establish? Very little, it might be argued. Here are two objections. First, is the argument committed to the Bohr model or not? Either way, there is a problem. If it is committed to the model, then it is (as admitted) premised on a fiction. Crucial components of the model—for example, the idea of fixed orbits, and the attribution of quantum numbers to individual electrons—were rejected by the new quantum physics of the 1920s. So even if the argument is valid, and the principle of reduction to which it appeals correct, we can have no faith in its power to lead to a true conclusion. Replacing the Bohr model with a more sophisticated quantum theory will not help, since the argument would still depend on the suspect thesis of epistemological reduction. But, on the other hand, if the argument attempts to distance itself from the Bohr model and any successor, and talk instead completely agnostically of 'whatever it is about the fundamental structure of matter that grounds the periodic law', then it runs straight into our first objection to physicalism, the vacuity problem.

Second, the argument locates the chemistry/physics distinction in the wrong place. Even allowing the model to be an approximation to the truth, the appeal to electronic distribution became, during the course of the twentieth century, a part of chemistry, not something outside it. Thus Eric Scerri:

> …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 chemistry. (Scerri (1997), 236.)

So the real issue in the debate over whether chemistry can be reduced to physics is whether the Bohr model can itself be reduced to, or replaced by, something more fundamental.

Let us consider the first objection. Of course, as it was presented, the argument of the previous section did make explicit appeal to the Bohr model, and so is squarely impaled on the first horn of the dilemma. But it does provide a stepping stone to another argument, an argument for ontological reduction that is independent of a commitment to epistemological reduction. Such an argument will not, obviously, commit itself to the truth of any given theory of the atom. But it cannot avoid contact with all theoretical issues. As the second objection shows, the thesis of the ontological reduction of chemistry must be accompanied by a view of what chemistry's concerns are, and that cannot be done in a completely theory-neutral way. Now, it is not necessary to define where the margins of chemistry lie: those have shifted both with and since the Chemical Revolution.[8] But since the thesis of ontological reduction is about properties, we do have to have a clear conception of what is to count as a chemical property. I shall take the identity of an element, as defined by its position in a periodic ordering, and its associated macroscopic properties (capacity to form compounds of a given composition with other elements, solubility, etc.) to be paradigmatically chemical properties. About these properties we can be unapologetic realists. A periodic ordering is a classification rather than a theory, so this conception of chemical properties is as theory-neutral as it can be. Below this level, the theoretical content, and corresponding pressure to be instrumentalist, increases. The question of the ontological reduction of chemistry (or at least the question I am interested in) is the question of whether these paradigmatically chemical properties reduce to more fundamental properties.

What counts as ‘more fundamental’? One criterion is the combinatorial one of the previous section: the more fundamental properties are those properties combinations of which generate the range of physical possibilities of the less fundamental properties. Now, we illustrated this by reference to the Bohr model, but it was simply an illustration—a purely fictional one, if you like. We have a reason to suppose that the chemical properties are not the most fundamental ones even if we are not willing to subscribe to any given theory of the atom. And that reason lies in the fact that the series of elements, conceived as a series of physical possibilities, is a discrete, not a continuous one. But there is no *a priori* reason why it should be discrete, and no *a priori* reason why different elements should combine in fixed proportions. The chemical properties of matter could have varied continuously. We might, perhaps, just accept it as a brute fact about the world that the series of elements was discrete. But if there were a finite number of properties, combinations of which generate the physical possibilities represented by the periodic table, then variation would necessarily be discrete rather than continuous. We can believe in the existence of these fundamental entities and properties without subscribing to any particular account of them (e.g. an account in terms of electronic configuration), but such accounts at least show us the way in which chemical properties could be determined by more fundamental ones. The point is that, given the principle of recombination, unless these more fundamental properties exist, unactualised elements would not be physical possibilities.

How then does the argument avoid the second horn of the dilemma, the vacuity problem? The problem was that there was no way of characterising the physical that did not make physicalism false or trivial. It is quite unilluminating, for instance, to say that chemical properties reduce to those properties that determine all properties, for that is compatible with the possibility that chemical properties are among the most fundamental. But it is not at all unilluminating to say that *chemical properties reduce to those properties variation in which is discrete, and combinations of which constitute the series of physically possible chemical properties*. That is not trivial, but neither does it give a hostage to theoretical fortune.

6 The missing premises and a disanalogy with mind

We may now state our combinatorial argument for the ontological reduction of chemical properties in full, as follows:

(1) *The discreteness of chemical ordering*: the periodic ordering of the elements is discrete, i.e. between any two elements there is a finite number of physically possible intermediate elements (0 being the limiting case).

(2) *The denial of plenitude*: some places in the periodic ordering represent physically possible but unactualised elements.

(3) *The principle of recombination*: an unactualised property is physically possible iff it is constituted by a physically possible recombination of actually existing properties.

(2) & (3) $\rightarrow$ (4)

(4) There are properties $p_1 \ldots p_n$, recombinations of which constitute the series of unactualised but physically possible elements (i.e. the unoccupied positions in the periodic ordering).

(5) The physically possible but unactualised elements are not constituted by recombinations of actually occupied positions in the periodic ordering.

(4) & (5) → (6)

(6) The physical possibility of $p_1 \ldots p_n$ is not constituted by recombinations of actually occupied positions in the periodic ordering.

(7) *The combinatorial criterion for ontological reduction*: A property type *F* is ontologically reducible to a more fundamental property type *G* if the possibility of something's being *F* is constituted by a recombination of actual instances of *G*, but the possibility of something's being *G* is not constituted by a recombination of actual instances of *F*.

(1), (4), (6) & (7) → (8)

(8) Chemical identities are ontologically reducible to more fundamental properties, variation in which is discrete.

Although the conclusion is silent about what the more fundamental properties are (and so is invulnerable to objections to the Bohr model and its successors), it is saved from vacuity, first by distinguishing those properties from the more abstract property of occupying a certain place in a periodic ordering (a distinction implied by (6)), and secondly by giving them a well-defined role, that of forming a discrete series of combinations which fill the gaps in the table. The asymmetry problem is answered by premises (4) and (5). What makes $p_1 \ldots p_n$ more fundamental is that combinations of them constitute the possibility of the higher-level property of having such-and-such a position in a periodic ordering, and not vice versa. (5) follows from the definition of an element as a substance that cannot be decomposed into simpler substances. [9] Recombinations of occupied positions in the periodic ordering may define mixtures or compounds, but not unactualised elements.

Does the conclusion support the reduction of chemistry to physics? If the kind of reduction here is of the epistemological kind, then no. Even if the relevant properties were discovered, there might remain obstacles to complete epistemological reduction. In any case, there is the terminological issue of what is to count as 'physics', and the vacuity problem once again rears its head. But the conclusion may well capture the component of truth in the assertion that chemistry reduces to physics.

Can similar arguments be constructed to support ontological reductions in other fields? Possibly, but there is one field in which we could not plausibly offer a similar argument, namely psychology. Where mental states are concerned, there are of course many unactualised possibilities, but here there is no interesting distinction to be drawn between the merely logically possible and the physically possible. And it would be very odd, certainly, to suggest that the range of mental possibilities exhibits a discrete structure. So one moral of the story may be that different kinds of argument for ontological reduction are suitable for different contexts.

Now that the missing premises have been made explicit, they may provoke objections. But my purpose in this paper was simply to bring them out into the light, not to ward off all predators.[10]

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Notes

[1] If so, he does not explicitly appeal to it. Another, less philosophical, line of thought might have been this: it is reasonable to suppose that there remain some undiscovered elements, and those elements would have to occupy the gaps in the table (unless they are all heavier than the heaviest known element, which would be against the balance of probability). However, what Mendeleev actually says is that, prior to the formulation of the periodic law, there was no particular reason to suppose that there were elements waiting to be discovered.

[2] Thus, whether or not it will ever be manufactured (and claims in 1999 to have manufactured it were later withdrawn) element 118 is—or would be—a noble gas. Elements 122-153, which are represented in some versions of the table, were dubbed 'superactinides' by Glenn Seaborg, after whom element 106 was named. The difficulty of identifying very heavy elements in the products of nuclear bombardments is largely due to the extreme shortness of their half-lives.

[3] Not all of Mendeleev's predictions corresponded to reality, however, such as 'ether', which was placed by him above hydrogen in the table.

[4] For Mendeleev, the periodic ordering was one of atomic weights, although it was later replaced by one in terms of atomic number. Being intermediate in terms of weight is not the same as being intermediate in terms of number (although they coincide in most cases).

[5] It is, in fact, debatable whether ontological reduction is weaker than epistemological reduction. Strictly, *p* is weaker than *q* if *q* entails *p*, but not *vice versa*. Now epistemological reduction does not actually entail ontological reduction, since the physical properties might causally determine, without actually constituting, the chemical ones. Conversely, one might take ontological reduction to imply the in principle reduction of chemical laws to physical ones. However, I take ontological

reduction to be weaker by virtue of making no assumptions about scientific theory.

[6] Physicalists about the mind, for instance, have been influenced by Davidson’s (1970) defence of ‘anomalous monism’, which actually derives the identity of the mental and the physical from (among other propositions) the *denial* that there are any psycho-physical laws. (Such laws would be required, it seems, in order to reduce psychological laws to purely physical ones.)

[7] I am not suggesting that this criterion follows from the principle of recombination. One could take a combinatorialist approach to physical *possibilia* and still offer a different account of reducibility. But since combinatorialism is reductionist about *possibilia*, the criterion is a natural extension of the theory.

[8] A very ambiguous term. It is often associated with Lavoisier (who was to lose his head in a rather more violent revolution), his systematisation of chemical nomenclature, and the replacement of the phlogiston theory of combustion with the oxygen theory. But I have in mind an earlier event: the appearance in 1661 of Robert Boyle’s *The Sceptical Chymist*, and its introduction of the modern conception of an element.

[9] This is perhaps the most theoretical component of our characterisation of chemical properties. That there are fundamental substances could, however, be justified on *a priori* grounds by appeal to finitism, as follows: finitism asserts that there is no actual infinite existing in nature; were substances indefinitely decomposable into other substances, then there would be such an actual infinite; therefore there are fundamental substances.

[10] An earlier version of this paper was given to a history and philosophy of science seminar at Leeds. I am very grateful to those present for their comments. I should also like to thank two anonymous referees for this journal for their detailed and helpful suggestions.

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For example, we might describe a chair as ‘nothing more than’ its constituent atoms and their arrangement. This, even if justified (in that there is no further component of the chair not captured by the description), does not obviously justify the further suggestion that the chair can be *reduced* to the constituent atoms. After all, although we can define the chair in terms of a collection of atoms, we can equally define the atoms as parts of the chair. And although the properties of the chair are constrained by the properties of the atoms, the reverse is equally true. (Location is an example: if the chair is moved, the atoms perforce move with it.) Yet there is a tendency, in cases of entities standing in the part-whole relation, to take the parts as more fundamental than the whole. But there are other reductionist assertions that have nothing to do with the part-whole relation: the reduction of mental states to the physical, for example.