Analogy and Composition in Early Nineteenth-Century Chemistry:

The Case of Aluminium

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Abstract

Around fifteen years before the chemical substance alumina (aluminium oxide) could be decomposed in the laboratory, it was identified as a compound and predicted to contain a new element called 'aluminium'. Using this episode from early nineteenth-century chemistry as a case study for the use of analogical reasoning in science, this paper examines how chemists relied on chemical classifications for the prediction of aluminium. I argue that chemists supplemented direct evidence of chemical decomposition with analogical inferences in order to evaluate the composition of substances. Since they were established on the basis of relevant similarities in chemical properties, classifications were taken to reflect so-called 'chemical analogies' between substances. In combination with the knowledge that analogous properties indicated similarities in composition, this enabled chemists to infer the composition of experimentally indecomposable substances by analogy. The trust in such analogical inferences, even if they could not be confirmed through experiment, was justified by pragmatic considerations. Whereas the possibility of decomposing a substance depended on the available laboratory techniques, chemical analogies were thought to last independently of internal composition. It was therefore more practical to keep well-established classes of substances together rather than separate them on the basis of experimental results that might evolve as new techniques were developed. Besides highlighting the links between analogical reasoning and classification, this paper also illustrates the importance of analogy in the evaluation of elementary nature in the early nineteenth century.

Introduction

According to the English chemist Humphry Davy (1778-1829):

> "The *body* of natural science… consists of *facts*; its governing spirit is analogy – the relation or resemblance of facts by which its different parts are connected, arranged, and employed, either for popular use, or for new speculative improvements".[1]

For Davy and his colleagues, analogy was one of the key processes by which the mind identified patterns in nature in order to formulate general propositions (Tate 2019). Due in part to the influence of the Scottish philosopher David Hume (1711-1776), whose problem of induction haunted scientific thought, analogy took up an important place in their publications.[2] This makes eighteenth- and nineteenth-century chemical practice a good starting point for exploring the role of analogical reasoning in science.

This paper aims to shed light on the use of analogical reasoning in chemistry, in particular in the identification of chemical elements. While the role of analogical reasoning in physics has been thoroughly explored, a similar investigation with respect to chemistry is relatively absent from philosophy of science. Furthermore, in their survey of eighteenth-century references to analogy in the *Philosophical Transactions of the Royal Society*, Gingras and Guay (2011) have found that analogy was most commonly used as a tool for classification. Yet, whereas recent case studies have shown the role of analogy in conceptual development in synthetic biology (Knuuttila and Loettgers 2014), as evidence in archaeology and the historical sciences (Currie 2016), as a methodological principle helping scientists develop and test hypotheses (Fisher 2018) and in providing reasons to pursue a theory or model in physics (Nyrup 2020), few studies explore the ways in which analogy and classification are linked in scientific practice.

Using the identification of the metal aluminium as a case study, this paper will examine how chemists relied on classifications in order to make analogical inferences regarding the composition of substances and predict the existence of elements that had not yet been isolated. The date of the first isolation of metallic aluminium depends on how one evaluates the attempts of

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[1] Davy stated this in his "Introductory Lecture to the Chemistry of Nature", delivered at the Royal Institution on January 31st 1807, and published in his *Collected Works* (1840, 8:67–68). Emphasis original.

[2] In their survey of mentions of "analogy" and similar terms in the *Philosophical Transactions of the Royal Society*, Gingras and Guay note a significant increase in the use of these terms, starting around 1780 and lasting throughout the nineteenth century (Gingras and Guay 2011, fig. 1).

Hans Christian Ørsted (in 1825) and Friedrich Wöhler (in 1827) at producing the metal and describing its properties (see Ferrand 1961, chap. 1). However, following the work of Humphry Davy on the decomposition of the earths, aluminium had already been known to exist since the 1810s, when it appeared as an element in numerous classifications (for example Berzelius 1811; Thenard 1813; Thomson 1817). Since most histories of aluminium focus on its production as a material from the 1820s onwards, the argumentation that led to its identification as an element has hitherto not been studied in detail.

The prediction of aluminium shows that chemists based their knowledge of the composition of substances on more than just the operations of decomposition they were able to carry out in the laboratory: analogical reasoning also played an important role in identifying which substances were simple and which were composed. On the basis of the principle that analogy in properties indicated analogy in composition, the indecomposable substance *alumina* (aluminium oxide) was viewed as a compound because it belonged to the same class as substances that had been decomposed. The existence of its metallic constituent *aluminium* was predicted in analogy to the metals that were known to compose the substances that were classed with alumina.

Aluminium is not the only element to have been identified and accepted as such long before it was produced in the form of a simple substance. For instance, fluorine was accepted as an element almost 75 years before its isolation (Banks 1986, 16–17). Likewise, following the development of spectroscopy in 1860, new elements could be detected using spectral rays, sometimes years before they were isolated (see James 1988; Scerri 2013). Nevertheless, the story of the identification of aluminium is particularly interesting from a philosophical point of view because its elementary nature was explicitly argued on the basis of chemical analogy. Moreover, this episode not only provides an example of the use of analogy for elaborating and justifying a working hypothesis in early nineteenth-century chemistry, but also illustrates the use of abstract reasoning in the evaluation of elementary nature. Though some historical articles mention the role of chemical analogy as a "heuristic" or a "guiding principle" in resolving questions about the elementary nature of substances (Gray et al. 2007, 43; Ruston 2019, 130), the importance of analogy for the identification of chemical elements has rarely been explored further.

Besides describing how analogy was used, I will also try to elucidate why chemists relied on analogical inferences in this way. I will argue that chemical analogies could serve as a guide in assessing the composition of substances because they were viewed as stable compared to the criterion of experimental (in)decomposability, which continually shifted as laboratory techniques improved. After providing an overview of analogical reasoning based on classification, as well as its justification in early nineteenth-century chemistry, I will describe the acceptance of aluminium as an element in more detail.

1. Analogy, analogical reasoning and classification

1.1 - The importance of relevance considerations

Paul Bartha (2019) defines analogy as “a comparison between two objects, or systems of objects, that highlights respects in which they are thought to be similar”. This definition requires some specification. Analogy is not just any kind of similarity: it is a comparison that establishes a certain similarity as being relevant in such a way that it can serve as the basis for an explanation or further reasoning. For example, one might highlight the many respects in which dolphins are similar to sharks, but this comparison cannot be used to explain why dolphins need to come up to the surface to breathe. On the other hand, a comparison with humans might provide a fruitful analogy: while humans are quite different from dolphins, we share the relevant property of possessing a pair of lungs and therefore being unable to breathe underwater. In other words, it is not the sheer number of similarities that makes a good analogy, but the relevance of the similarities in question. Once identified, such relevant similarities between what are often called the ‘source’ and ‘target’ systems can form the basis of analogical arguments in which it is inferred that the target will likely share further features with the source.

One of the central philosophical issues regarding analogical inferences is whether, and how, they warrant a conclusion. One approach to studying this question has been to develop a formal method for the evaluation of analogical arguments in general. Bartha (2010), for example, formulates two requirements that good analogical arguments have to fulfil. Firstly, there has to be a *prior association* between the known similarities and the inferred property, a relationship of dependency that determines which features are critical for the analogical argument. Secondly, there must be a *potential for generalization,* a reason to believe that the same kind of connection holds in the target domain as well. If there are any significant dissimilarities between the source and target, the argument breaks down.

Others, however, have criticized this approach. John Norton (2018), for example, argues against all attempts at formalization because it is impossible to establish a universally applicable rule that establishes which properties might be passed from the source to the target. Likewise, Alison Wylie (1988) has argued that analogical inferences are warranted not because they conform to some specifically analogous argumentative structure, but because they appeal to a relationship between known and inferred properties that can only be evaluated according to the available background knowledge. Following Wylie and Norton, I will refrain from formulating any general rules for valid analogical argumentation. Rather, I will develop a descriptive account of the ways in which analogical inferences were used and justified in the identification of aluminium. Bartha's terminology can nevertheless be of use in developing such an account because it helps clarify the structure of specific arguments.

According to Norton (2018), any specific analogies might be "captured in a fact that (…) may be explored empirically". Building on this idea, Amy Fisher (2018) has interpreted analogy as a methodological principle, rather than a logical form of argument, and studied how it has facilitated scientific research. She has found that reasoning by analogy helps scientists in the identification of patterns in series of experimental results, the formulation of working hypotheses and the design of further experiments in order to test these hypotheses. The case study presented here will provide an example of the use of analogical reasoning as an 'experimental stratagem' which Fisher has identified. However, it will also complement her work. Focusing on the context of discovery, Fisher mainly highlights the role of working hypotheses in the development of new experiments and the advancement of research programs more generally. Yet, working hypotheses could also be studied as a kind of knowledge in themselves: thus, years before it was empirically confirmed, textbooks and dictionaries of the early nineteenth century already presented the idea that aluminium was an element as a consensus.

Rather than functioning as a confirmation by themselves, I want to suggest that analogical inferences functioned as a type of complementary evidence in this case.[3] In his study of the historical sciences, Adrian Currie (2018, chap. 7) has argued that analogies can function as complementary evidence because they provide epistemic access to causal systems that are otherwise inaccessible. Likewise, analogies between chemical substances provided indirect access to chemical composition in cases where it could not be accessed using experimental means. In order to warrant this type of inference, chemists relied on chemical classifications.

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[3] This is quite different from analogue simulations, where predictions about inaccessible systems are tested in model systems that are formally analogous (on this topic see Dardashti et al. 2015; Crowther et al. 2019).

1.2 - Classification as a basis for analogical inference

In scientific practice, analogy has long been an important classifying principle (see Gingras and Guay 2011). In chemistry, from the mid-eighteenth century onwards, the arrangement of classes of substances was dictated by two principles: analogy and composition (see Klein and Lefèvre 2007, chap. 6). Simple substances were distinguished from compounds, which in turn were separated according to complexity of composition. Within each level of composition, classes were established on the basis of so-called ‘chemical analogy’, patterns of similarities of chemical properties (such as solubility, combustibility, reaction with certain reagents and the formation of a specific kind of oxide or acid) that were considered relevant. As Yves Gingras and Alexandre Guay (2011) have pointed out, classification based on analogy is more than simply listing the common appearances of phenomena: in order for analogy to work as a classificatory tool, one has to show that the empirically grounded similarities are markers of an underlying common nature. In establishing their classifications, nineteenth-century chemists likewise aimed to represent the most significant similarities (see for example Ampère 1816).[4]

Moreover, I argue that analogy and classification are doubly linked: not only are classifications established on the basis of analogies, as (visual) representations of those relevant similarities they can also form the basis for analogical inferences. Once a class is established, it becomes possible to generalize: if a certain feature comes to be associated with a kind of object, for example because multiple members of the kind have this feature, it can be inferred by analogy that all members of the kind share this property. Such an inference is warranted by the idea that the same relation of dependency between the known similarities and the inferred properties will hold for the entire class. In chemistry, Davy (1812, 480) summarized the available background knowledge as follows: “as far as our knowledge of the nature of compound bodies has extended, analogy of properties is connected with analogy of composition”. In other words, if substance A was known to have a certain composition, the analogous substance B would likely be composed of similar constituents. The prediction of the existence of aluminium exemplifies this use of classification as a basis for analogical reasoning: alumina was predicted to be composed of a metal

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[4] The question of identifying similarities that are relevant enough to dictate classifications was also discussed by the English polymath William Whewell (1794-1866) in his *Philosophy of the Inductive Sciences* (1840, book VIII).

(aluminium) and oxygen because it belonged to a class of substances of which multiple members had been shown to be metallic oxides.

2. Analogy, composition and elements in nineteenth-century chemistry

In order to understand why chemists relied on analogical inferences of the composition of chemical substances, rather than strictly basing themselves on the results of operations of decomposition, the context of early nineteenth-century chemistry has to be taken into account. I argue that the trust in these inferences resulted from pragmatic considerations regarding the perceived stability of classifications when compared to the rapidly evolving experimental means of decomposition. Chemical analogy thus enabled chemists to navigate the feeling of uncertainty that resulted from the substitution of the ancient elements with a rapidly evolving list of simple substances.

During the eighteenth century, the broadly Aristotelian view of elements as metaphysical principles was gradually replaced by the idea that the constituents of matter were actually present in compounds and could be isolated as the products of chemical decomposition (see Hendry 2019). In this context, the French chemist Antoine-Laurent de Lavoisier (1743-1794) argued against metaphysical speculations and in favour of defining the chemical element on the basis of the empirical operations of decomposition:

> "[…] if we apply the term elements, or principles of bodies, to express our idea of the last point which analysis is capable of reaching, we must admit, as elements, all the substances into which we are capable, by any means, to reduce bodies by decomposition." (Lavoisier 1790, xxiv).

In other words, Lavoisier defined the element as a *simple substance*. Following a distinction identified by Friedrich Paneth (1962), this notion is often defined in opposition to what has been translated as the 'basic substance' (*Grundstoff*). Paneth coined these two terms to correspond to the two ways in which chemists use the concept of chemical element: elements are seen as indecomposable chemical substances on the one hand, and as abstract, quality-less components of chemical substances on the other (see also Scerri and Ghibaudi 2020). Thus, for example, whereas both sulphur dioxide (SO_2) and elementary sulphur (S_8) contain sulphur as a basic substance, the latter is also a simple substance. Though Lavoisier did not completely eliminate the abstract view of elements (see Hendry 2005), his definition was rapidly adopted and remained ubiquitous in chemical textbooks until Dmitri Mendeleev (1834-1907) distinguished between the terms ‘simple substance’ and ‘element’, reserving the latter for abstract components that could be detected by their atomic weight (Bensaude-Vincent 2019).

From the late eighteenth century until the mid-nineteenth century, the explicit criterion for elementary nature was therefore the impossibility of decomposing a substance through chemical operations. However, this could only lead to a provisional identification of elements, since no amount of failed decompositions could prove that a substance is absolutely indecomposable. Meanwhile, due to improvements in analytical methods used to distinguish between different types of elements in mineral substances, as well as the development of new instruments such as the voltaic pile, the number of known elements continued to increase. It was impossible to know where decomposition would end, implying that the means of decomposition might become so powerful that one day, all simple substances could be decomposed. These two factors resulted in a strong feeling of uncertainty among chemists as well as speculations regarding a possible internal complexity of the elements (Farrar 1965; Siegfried and Dobbs 1968). An additional problem was that results of decomposition were not always reliable on their own. Depending on the framework one adopted, some chemical transformations could be interpreted as either decompositions or combinations (see Chang 2007, sec. 4.1).

Classifications founded on chemical analogy could be a helpful guide in navigating these uncertainties. In some cases, they could provide a counterargument against the worries that newly discovered simple substances might actually be composed: if they could be classed with analogous substances that were generally considered simple, there was no reason to suppose such substances to be compounds. Robert Siegfried (1963) has shown that Davy used this type of reasoning in order to argue in favour of the elementary nature of potassium and sodium. Likewise, multiple studies have shown the importance of the analogies between iodine and chlorine for the acceptance of the latter as a simple substance: only when chlorine could be classed as part of a family of simple substances was it generally accepted as such (see for instance Gray et al. 2007; Hijmans and Llored 2020). In these cases, chemical analogy as represented in classifications supported evidence of decomposition when the simple substances in question had already been isolated. This shows that despite the seemingly ‘operational’ nature of Lavoisier’s definition (as pointed out, for example, by Schummer 2020), elementary nature was not evaluated strictly on the basis of the possibility to decompose a substance.

Moreover, analogical reasoning could help predict the existence of unknown future elements. If an as-yet-undecomposed substance had its place in a class of substances that were commonly admitted to be compounds, it was likely to be a compound as well, and it was therefore justified to take it off the list of simple substances in anticipation of the development of an adequate decomposition technique. Thus, Lavoisier omitted soda and potash from his list of simple substances despite the fact that they could not be decomposed, because their analogy to ammonia meant they were "evidently" compounds (Lavoisier 1790, 178). He also used his theory of the composition of acids to predict the existence of the radicals of muriatic, boracic and fluoric acid, and added them to his table even though they had never been isolated (*ibid*., 233).[5]

The reliance on chemical analogy became most explicit in such cases where a supposed simple substance was predicted to exist and no experimental results could confirm the analogical inference. There were pragmatic reasons for chemists to trust their inferences rather than the results of their attempts at decomposition. As opposed to quickly evolving experimental techniques, chemical analogies were thought to remain stable, and it was therefore not practical to revise classifications each time a decomposition failed. After all, the impossibility of decomposing a substance might simply be due to insufficient experimental means rather than the substance's actual lack of internal composition. In some ways, chemical analogy could therefore be said to be more important than operations of decomposition for the evaluation of elementary nature. As will become clear in the next section, the acceptance of aluminium as an element was similarly justified: alumina had long been classified as part of a well-established group of bodies, and keeping this group together proved more important than strictly adhering to the definition of a simple body as an indecomposable substance.

3. The identification of aluminium as a simple substance

Alumina was first identified in the mid-eighteenth century as the base of a salt called 'alum' that could be found in clay and classified as part of the family of earthy substances. In today's

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[5] Furthermore, Lavoisier added light and heat to his table, even though they had not been isolated as chemical substances. See Perrin (1973) for Lavoisier's use of analogy in establishing his list of simple substances. See Hricko (2021) for a study of the prediction of the boracic radical and its consequences for scientific realism.

terms, the earths were (hydrated) metallic oxides and carbonates, but until the early nineteenth century they were separated from metallic compounds and seen as a subgroup of *salifiable substances*, substances that combined with acids to form salts. Besides the common earths (alumina, yttria, glucina, zirconia, silica), the other subgroups of salifiable substances were the alkalis (ammonia, potash and soda) and alkaline earths (magnesia, barites, lime, strontian). As a class, the earths were generally characterized by the fact that they were incombustible, insoluble in water and they could not be evaporated (Klein and Lefèvre 2007, chap. 7.2). At first glance, these properties might seem rather superficial for the determination of class membership, but it is important to realize that to chemists at the time, it was quite obvious that all salifiable substances were members of the same kind. Despite slight differences from each substance to the next, "these bodies [graduated] into each other so nicely that they [could] scarcely be placed into different classes", according to Scottish chemist Thomas Thomson (1804, 545).[6]

Analogical inferences regarding the possible constitution of alumina date back to the eighteenth-century: because of the resemblance of alum to vitriolic salts that had a metallic base, it was suspected to have a similar constitution. Nevertheless, all eighteenth-century attempts at producing a metal from alumina failed (see Ferrand 1961, 21–2). Despite sharing these suspicions with their predecessors, Lavoisier and his followers did not formulate a precise hypothesis regarding alumina's composition and its potential constituent elements: since it remained impossible to chemically decompose it, alumina continued to be classed as a simple substance. However, this changed around 1810, when alumina came to be seen as a compound and a new simple substance was identified: aluminium, the metallic constituent of alumina. I argue that it was Davy's work on the decomposition of the alkaline earths which caused the shift from mere suspicions on the nature of alumina to the acceptance of aluminium as a chemical element.

3.1. Davy's work on the decomposition of the earths

Humphry Davy frequently mentioned analogy in his publications, and he used it in multiple ways. Despite sometimes dismissing analogy as mere speculation and a figure of speech, he heavily relied on analogical reasoning in order to design and interpret his experiments (Tate 2019).

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[6] The salifiable substances shared a kind of family resemblance rather than a fixed list of properties. This could therefore be seen as an example of a non-essentialist classification (see Winsor 2003). The criteria for distinguishing between the different subgroups of the salifiable substances could vary slightly.

In his view, a “true philosopher” had to understand the connections between facts and put them to use; Davy therefore highlighted his knowledge of analogies in order to increase his authority in scientific debates (Ruston 2019). Furthermore, he relied on analogical reasoning as an experimental stratagem in order to facilitate his research program at the Royal Institution in London (see Fisher 2018). There, between 1801 and 1812, Davy used his voltaic pile (one of the first electric batteries) to decompose as many previously indecomposable substances as possible in order to arrive at the “true elements of bodies” (Davy 1808b, 1).

In the Bakerian lectures of 1806 and 1807, Davy announced the decomposition of the fixed alkalis, soda and potash, and showed that they were compounds of oxygen and previously unknown metals which he named sodium and potassium. Generalizing from this result, he speculated that the property of being composed of oxygen and a metal likely extended to the entire class of salifiable substances. Following Bartha’s (2010) terminology, the prior association which justified Davy’s inference from the known similarities between these substances to their shared composition was the fact that similarities in chemical behaviour generally indicated similarities in composition. Though he did not propose any causal explanation for the relation between composition and properties, knowledge of this simple correlation sufficed. The potential for generalization depended on the fact that these substances were members of the same kind: Davy thus projected the correlation between chemical properties and chemical composition to hold for all members of the class of salifiable substances.

In order to test his hypothesis, Davy first attempted the decomposition of the alkaline earths since they were most similar to the fixed alkalis. By forming an amalgam and distilling away the mercury, he was able to confirm his reasoning and isolate the metals that composed the alkaline earths: barium, strontium, calcium and magnesium (Davy 1808a). The next step was to decompose the remaining salifiable substances, alumina and the other common earths, for which Davy tried many different methods (Davy 1808b; 1810). He fused alumina with potash in a platinum crucible, which he positively electrified using his battery. Upon inserting a negatively electrified platinum rod into the mixture, a lot of light was produced and metallic globules rose to the surface where they immediately burned. When he left the mixture to cool, he saw that the platinum rod was heavily corroded and covered in a thin metallic film, from which alumina could be reproduced in an acidic solution. Next, he heated alumina in a platinum tube and passed potassium vapour over it, which produced tiny metallic particles on top of the remaining alumina.

Davy was also able to fuse together potassium, iron filings and alumina to form a metallic mass that was whiter and harder than iron but still malleable, and from which iron oxide, potash and alumina could be reproduced.

Though the results of these attempts gave some reason to believe that small amounts of aluminium had been produced, Davy did not consider them sufficient to prove the decomposition of the common earths. Nevertheless, in his *Elements of Chemical Philosophy*, he concluded that it "[could] not be doubted" that alumina was an oxide; as to the metallic nature of aluminium, it could not yet be considered demonstrated, but it seemed "extremely likely, both from the facts detailed, and from analogy" (Davy 1812, 356). Before the acceptance of aluminium as a metal can be considered, it is important to analyse the evidence supporting these claims.

3.2. The evidence in favour of aluminium

In Davy's words, the "evidences" of the decomposition of alumina were not "of the same strict nature as those that belong to the fixed alkalies and alkaline earths" (Davy 1808a, 352). Whereas he was able to establish the internal composition of the latter substances through the production of their constituent metals, the internal composition of alumina remained inaccessible and Davy therefore had to rely on analogical reasoning as complementary evidence.

As a family of substances, metals were characterized by a number of properties such as lustre, malleability and fusibility, as well as the tendency to produce oxides (see Klein and Lefèvre 2007, 128). Davy's experiments on the alkaline earths had produced enough of each substance to investigate their properties and show that they were metals. Strontium, barium, calcium and magnesium had a metallic shine and rapidly combined with oxygen to reproduce the alkaline earths. Measuring their weights, Davy was able to show that the metals became heavier as they reacted with oxygen, which meant that the reaction was indeed a combination according to the principle of mass conservation. Thus, the newly isolated substances had enough metallic properties to classify them as metallic simple substances. Moreover, the decomposition of the alkaline earths using the voltaic pile proceeded similarly to the decomposition of the metallic oxides, producing the metal at the negative pole and oxygen at the positive pole. Davy (1808b, 346) therefore concluded that the evidence for the composition of the alkaline earths was "of the same kind" as that invoked in support of the composition of all other metallic oxides.

The same arguments could not be used in the case of aluminium, because the different decomposition methods used by Davy did not produce a definite result. Despite the production of a metallic film and metallic particles, the quantity of metal produced in both experiments was too small to investigate its properties, or to detect any weight change as alumina was reproduced. Therefore, it was impossible to prove that the produced substance was a new metal, rather than a mixture of alumina with potassium or iron. Likewise, the metallic mass that Davy had formed could not definitively be identified. It was likely to be an alloy of aluminium and iron, especially since he had succeeded in producing alloys of calcium and magnesium by the same method; however, it could also have been a mixture of iron, potassium and alumina.

Despite these difficulties, Davy (1810, 66) argued alumina should be classed as a metallic oxide and aluminium, its metallic constituent, as a simple substance. Analogical reasoning provided him with additional arguments. Alumina, zirconia and silica closely resembled the oxides of tin and other oxides that were "abounding in oxygen" and therefore likely had a similar constitution. Moreover, the nature of the alkalis and alkaline earths had already been proven experimentally and Davy therefore argued that all salifiable bases should be classed as metallic oxides, whether they had been decomposed or not. Even if it violated Lavoisier's definition of the element as a simple substance, it was justified to adjust classifications on the basis of this inference because class membership was thought to reflect lasting analogies between substances. As Davy (1808b, 363–4) explained, even if decomposition techniques would one day become so powerful that they might decompose metals, "still the alkalies, the earths, and the metallic oxides will belong to the same class of bodies". Whereas the (in)decomposability of individual substances depended on the available laboratory techniques, and might therefore change as those techniques improved, the relevant similarities among the salifiable substances would not change.

3.3. The acceptance of aluminium as a simple substance

Other chemists readily accepted the existence of the new element aluminium on the basis of Davy's analogical reasoning, despite considering that alumina still remained indecomposable. The Swedish chemist Jons Jacob Berzelius (1779-1848), who first classed aluminium as a metal in 1811, later explained:

> "Since Davy has discovered that the alkalies and alkaline earths are true oxides, we conclude that alumina, zirconia, glucina, and yttria, are likewise oxides, although hitherto nobody has succeeded, so far as I know, in his attempt to separate oxygen from these bodies. Yet no chemist has any doubt about the accuracy of the conjecture, as he sees the analogy between these bodies and the oxides of zinc, manganese, cerium, &c." (Berzelius 1816, 263–4)

The French chemist Louis Jacques Thenard (1777-1857) similarly argued:

> "Before the works of Mr. Davy, these salifiable bases [silica, zirconia, alumina, yttria, glucina and magnesia] were seen as simple bodies; we could even see them as such today, because as of yet no different bodies have been separated out of them; but there are such strong relations between these types of bases and the former salifiable alkaline bases, that is, lime, baryte, strontian, potash and soda, that it is extremely probable that they are all of the same nature. Now, it is proven that the latter are truly oxides: so we must also, by analogy, accept the former to be oxides; (…)." (Thenard 1813, 2: 36-37)

Thenard's textbook was used by the French Ministry of Public Instruction as the model for chemistry teaching, and his classification was copied by most French textbooks of the early nineteenth century (see Bertomeu-Sánchez et al. 2002). Berzelius' textbook *Lärbok i Kemien* ran for many editions and its translations in five languages enjoyed a tremendous success (Jorpes 1970, 94–96). It is therefore likely that Berzelius' and Thenard's views had a wide influence.

The discovery of the internal composition of some of the salifiable substances did not affect the classification of the salifiable substances as such. Thenard (1813) and Thomson (1817) kept the class intact and moved it as a whole from the level of simple substances to that of compounds. The metallic constituents of the common earths, one of which was aluminium, formed a new sub-family of metals that were "admitted as metals only on the basis of analogy" (Thenard 1813, 218).[7] Around fifteen years later this reasoning turned out to be correct when aluminium was eventually isolated. As the English chemist Edward Turner (1834, 501) summed up:

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[7] Thomson eliminated silicon from this family, since it had become clear that it was more closely related to carbon and boron than to the metals (see Partington 1964, 4:150).

> “That alumina is an oxidized body was proved by Davy (...); and it was inferred, chiefly by analogical reasoning, to be a metallic oxide. The propriety of this inference has been demonstrated by Wöhler, who has procured *aluminium* (…) in a pure state.”

These remarks illustrate the frequency with which analogical arguments were invoked by nineteenth-century chemists. While it was Davy’s isolation of the alkaline earth metals which led to the identification of the salifiable substances as metallic oxides, he was far from being the only chemist to rely on analogies as complementary evidence for the composition of substances.

Conclusion

Acting on suspicions regarding the compound nature of alumina, Davy attempted to decompose this substance in 1808 and 1809. Despite judging the direct evidence of the decomposition of alumina as insufficient, chemists concurred in viewing alumina as a metallic oxide and its supposed metallic constituent, aluminium, as an element. This choice was justified because alumina belonged to a class of substances of which multiple members had been proven to be metallic oxides, and chemical analogies were known to correlate with similarities in composition. The classification of alumina as a metallic oxide despite the impossibility to decompose it in the laboratory shows that chemists supplemented direct evidence of chemical decomposition with analogical inferences in order to evaluate the composition of substances. The important role of analogy in such cases was justified by its relative stability: whereas the possibility of decomposing a substance depended on the adequacy of the laboratory techniques at hand, analogy-based classifications were thought to hold independently of such techniques. As the limits of decomposition shifted and more and more substances could be decomposed, the resemblances between the members of a class did not change.

Furthermore, the fact that aluminium was accepted as an element, years before it was isolated in the form of a simple substance, has wider consequences for our understanding of the historical development of the concept of chemical element because it shows that analogical reasoning alone could suffice in the identification of elementary substances. This implies that Mendeleev’s reconceptualization of the concept of element may have been less significant than was previously thought. In a recent paper, Bernadette Bensaude-Vincent (2019, 306) states:

> “Had he relied on Lavoisier's definition of elements, Mendeleev could have made neither predictions nor corrections of atomic weight values. Simple substances, being merely concrete residues of analytic operations, are literally unpredictable. They only have a factual existence, whereas abstract elements can be known in advance and their properties can be induced from those of neighbour elements”.

On the contrary, I argue that the acceptance of aluminium shows that Mendeleev was not the first to rely on classifications for the prediction of unknown elements.[8] Even though chemists of the first half of the nineteenth century explicitly defined the element as a simple substance in theory, they violated this definition in practice by considering elements as abstract entities that stood in relation to one another. This case study therefore illustrates the need to look beyond definitions towards identification practices in order to improve our understanding of the development of the concept of chemical element.

More generally, the case of aluminium exemplifies the use of class membership as a basis for analogical inferences. As multiple philosophers have already indicated, the most important factor for the justification of analogical arguments is the relevance of known similarities to the inferred property. For nineteenth-century chemists, reliance on well-established classifications, together with the knowledge that chemical analogy was correlated with analogy in composition, provided a way to ensure this dependency relation. Yet, an important question which has not been addressed in this paper is whether or not chemists were justified in reasoning in this way. In Bartha’s (2010) classification of analogical arguments, arguments based on classification correspond to “correlative analogies” in which kind formation based on shared features is followed by the inference of further shared properties. According to Bartha (*ibid.*, 203–4), it is justified to make such an inference if the creation of a common kind is based on shared features that are *informative*. In the chemical community of the early nineteenth century, there was an ongoing debate regarding the similarities that were significant enough to dictate the organization of chemical classifications (see Bertomeu-Sánchez et al. 2002). More work is needed on chemical kind formation and the question of whether chemists’ criteria were informative.

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[8] Other examples support the idea that a reconceptualization of the chemical element was not required for the prediction of unknown elements: John Newlands (1837-1898) and Julius Lothar Meyer (1830-1895) both also made such predictions before Mendeleev’s work was published (see Scerri 2007).

However, awaiting further results it is important to note that in the acceptance of aluminium as an element, chemists did not feel the need to justify the criteria according to which they classified substances. The class of salifiable substances and its subgroups were not subject to debate, and the trust of this classification over empirical operations of decomposition was justified by pragmatic, rather than logical considerations. One might therefore say that chemists were justified in their use of analogical inference simply because it worked, as is shown by the eventual isolation of aluminium as a simple substance. Moreover, their trust in analogy had its limits, as is shown by other cases in which failed analogical predictions eventually led to the revision of classifications. The most striking example is the supposed element ‘ammonium’, which Davy predicted to exist as the metallic component of ammonia (see Siegfried 1964). Despite the fact that ammonia had long been classed as one of the alkaline salifiable substances, this classification was eventually questioned, and Davy abandoned his hypothesis in 1812 after actively pursuing it for five years. Later, he stated that he had been “deceived by analogies” and was therefore “resolved to trust nothing but facts” (Davy to Berzelius, 13 October 1813, see Berzelius 1912, 64).[9] This might provide another avenue for further research, and shows once again that eighteenth- and nineteenth-century chemical practice provides an fruitful starting point for the study of analogical reasoning in scientific practice.

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[9] Davy’s attitude towards ammonium was very different from that of Berzelius, who continued to pursue this hypothesis for another ten years (see Partington 1964, 4:167–8).

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