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THE CREATIVE POWER OF PAPER TOOLS IN EARLY NINETEENTH-CENTURY CHEMISTRY

> The invention and use of tools have played a large part in consolidating meanings, because a tool is a thing used as a means to consequences, instead of being taken directly and physically. It is intrinsically relational, anticipatory, predictive. Without reference to the absent, or "transcendence," nothing is a tool. (John Dewey)[1]

INTRODUCTION

Chemical formulas, such as H^2O for water or C^2H^6O for alcohol, were introduced by the Swedish chemist Jacob Berzelius in two articles published in 1813 and 1814.[2] From the late 1820s onward, Berzelian formulas began to spread, at first in organic chemistry, then in increasingly different forms in other chemical domains. The various epistemic functions of this sign system have been largely ignored by historians and philosophers of science. To date, we have no detailed analysis of their application in chemical practices. In many historical overviews, Berzelian formulas are mentioned, but only to characterize them as precursors of structural and stereochemical formulas that do not deserve much attention in their own right.[3] There are various reasons for this neglect. Many historians of science conceive of Berzelian formulas as representations of an atomic theory which was much better represented by verbal language or by Daltonian diagrams. Others have claimed that they were surrogates for names, and expressed sheer empirical findings, namely stoichiometric and volumetric laws. In both cases, Berzelian formulas figure as a passive medium for pre-existing knowledge. For example, the French philosopher François Dagognet wrote about them:

> The first mode of writing, which merely translated speech by applying letters and vocal symbols, hardly offers any advantage (in comparison with spoken chemistry which it perpetuates). ... this stenography will occupy or invade chemistry during the first half of the nineteenth century until that moment (rather near) when its insufficiencies will become obvious. At the beginning of the nineteenth century it was mainly preached by Berzelius who established the rules of its application.[4]

According to Dagognet, only the introduction of structural formulas in the 1850s significantly altered modes of inscribing in chemistry. While he ascribed a generative role in knowledge production exclusively to structural and stereochemical formulas, he conceived of Berzelian formulas almost as a hindrance to progress.

Dagognet's assertion that Berzelian formulas were unambiguously "vocal symbols" which "hardly offered any advantage" was the outcome of a formal semiotic analysis to the exclusion of any historical analysis of the actual application of this sign system in chemical practice. In contrast to Dagognet and others, I argue

U. Klein (ed.), Tools and Modes of Representation in the Laboratory Sciences, 13–34.

in this paper that European chemists applied Berzelian formulas as enormously productive tools on paper, or "paper tools." In the first part of this paper, I analyze the constitutive role played by chemical formulas in Berzelius' elaboration of the "theory of chemical proportions" between 1813 and 1814, which went hand in hand with his introduction of the new sign system. In the second part, I question the familiar classification of Berzelian formulas as "symbols" that can be clearly distinguished from icons. Based on the argument that Berzelian formulas conveyed a "building-block image" for contemporary readers, I study their application as paper tools in organic chemistry during the 1830s, concentrating on chemists' construction of models of binary constitution. Finally, I discuss the notion of paper tools by comparing it with that of laboratory tools.

1. MODES OF REPRESENTATION AND MEANING

In his 1813 and 1814 articles introducing chemical formulas, Berzelius was concerned mainly with the elaboration of what he called "laws of chemical proportions" and a "doctrine" or "theory of proportions." Since 1807 he had been carrying out quantitative analyses of chemical substances, and of inorganic compounds in particular. These experiments, together with the ongoing attempt to assign a unique, invariant relative combining weight (also called "atomic weight") to each chemical element, had contributed to his growing conviction that there were general laws which determined the number of possible "proportions," though many chemists were still skeptical since this assumption contradicted Berthollet's theory of affinity. Berzelius wrote: "I do not know how far chemical philosophers will allow them [the laws of chemical proportions] to be well founded; but, in hopes that the laws of chemical proportions which I have endeavored to establish will be one day examined and admitted, I will continue in this paper my research ..."[5] Berzelius followed a double strategy in order to achieve his goal. He continued experimentation while at the same time attempting to elaborate a chemical theory from which the "laws of proportion" could be deduced. John Dalton's atomic theory offered one possible route. Yet, some "anomalies" occurring in this theoretical framework, along with speculations about mechanical properties of the submicroscopically small atoms which were far from being subject of experiments at the time, prevented Berzelius from accepting it wholeheartedly. Instead, he tried to go his own way by developing a chemical theory which he called the "theory of chemical proportions." In his attempt to elaborate a theoretical alternative to Daltonian atomism, Berzelius made a particular experience; he encountered the limits of the available sign systems. Ordinary language, which was the most common sign system chemists used for theoretical purposes, was also the language of philosophers and of atomic theories forged in the natural philosophical tradition. Speaking of "atoms" would therefore immediately invoke the idea of invisibly small bodies, defined by their orientation in space, size, shape, and other mechanical properties, which chemists could not link to their laboratory practice. Daltonian diagrams, which represented simple atoms by circles and composed atoms (later "molecules") by juxtaposing them, had the same effect.

Berzelius' confusion about language can hardly be overlooked in his writings. In one of his journal articles introducing chemical formulas he describes them as signs denoting "something quite analogous to the corpuscular hypothesis of Dalton"[6] without being able to explain exactly what constituted this analogy and how far his theoretical entities differed from those in Dalton's theory. The fact that Berzelius also states in the same article that his formulas denote a "determinate quantity" of a substance, i.e., an observable, macroscopic entity,[7] and in other articles that they represent "chemical proportions"[8] and "elementary volumes"[9] supports my interpretation. All of these terms were linguistic alternatives which, on the one hand, avoided the mechanical-philosophical connotations of the term "atom" Berzelius wanted to eliminate.[10] On the other hand, the semantics of these alternative terms posed new obstacles.

"Chemical proportions" and "elementary volumes" were terms used in the formulation of the stoichiometric laws and the law of combining gases. In this context, the two terms unambiguously referred to measurable relationships of macroscopic substances. How did these magnitudes fit with "atoms" in the sense of submicroscopic particles? I propose to interpret the theoretical entities of Berzelius' "theory of chemical proportions" as scale-independent portions of elements and compounds.[11] The distinction between scale-independent chemical portions and submicroscopically small atoms may be strange for today's readers, and even for today's chemists who are used to thinking in terms of submicroscopic particles. However, this was different in the first half of the nineteenth century when the most fundamental category of chemical practice – that is, of experimentation and classification – was that of a chemical substance. Chemists spoke, for example, of copper, sulfuric acid, nitrous gas, etc. without considering the shape of the body composed of copper, or the size of the vessels containing sulfuric acid or nitrous gas. They were interested in the qualities of the substances, what colors they had, how they smelled, what characteristic effects they exhibited when mixed with reagents, what kind of reactions they underwent and what reaction products were produced from them, what relative combining weights they had, and so on. In sum, "chemical substance" was (and is) a category which abstracted from the mechanical properties of bodies, such as shape, spatial orientation, and also size. It was a scale-independent category. The quantitative concept that was superimposed on "chemical substance" had to be scale-independent as well.

Given the fact that there were no linguistic terms or diagrammatic representations available to express this chemically specific reference in an unambiguous way, the new formulaic sign system designed by Berzelius appears in a new light.[12] It was perfectly suited to represent unobservable portions of chemical elements (and of entire compounds) identified by their unique and invariable combining weights. It is not coincidental that Berzelius elaborated his theory of chemical proportions, for which the name "theory of chemical portions" might be more appropriate, in conjunction with the introduction of his chemical formulas. There was no two-step process in which the theory came first and the formulas afterwards. Rather, the formulaic system became a tool to forge a theory which overlapped with Dalton's atomic theory without being identical to it. The difference between an submicroscopically small atom and a discrete chemical portion was both produced with and embodied by chemical formulas. The mode of representation was not an exterior medium for a pre-existing conceptual referent, a kind of receptacle for some content, but a constituent of meaning.

Dagognet has pointed out that "scientific symbolism" is characterized by an inverse quantitative relation: "la minceur d'un signifiant, l'universalité et les capacités du signifié."[13] While he believed that exclusively graphical formulas, which were introduced in the second half of the nineteenth century, were semantically dense scientific signs, I assert that this holds for Berzelian formulas as well. Apart from their theoretical meaning as signs for scale-independent chemical portions, Berzelian formulas also encapsulated more traditional chemical concepts including pure "chemical compounds" made up of "elements" and the stoichiometric and volumetric quantitative relations of these elemental constituents. Moreover, in specific theoretical contexts they could also signify atoms in the sense of submicroscopically small particles. Their large "capacity of inscription"[14] made these signs applicable in various practical and theoretical contexts. This corresponded to the algebraic form and syntax of Berzelian formulas, which are the subject of the next section.

2. ICONIC SYMBOLS

Throughout the literature about chemical formulas a sharp distinction has been made between Berzelian formulas, on the one hand, and structural and stereochemical formulas, on the other. Berzelian formulas have been viewed as algebraic, linguistic, or symbolic signs, the other two as graphical, pictorial, or iconic. This dichotomy fits a popular distinction made by semioticians between language-like or logical types of signs, which are arbitrarily related to their objects and have a compositional semantics, and image-like or iconic signs, which represent their objects by virtue of being isomorphic to them. The distinction goes back to Charles S. Peirce's famous triad of "symbols" (arbitrarily linked with their objects), "icons" (similar to their objects), and "indexes" (physically connected with their objects).[15] In the following I argue that the distinction between icons and symbols does not work for Berzelian formulas.[16]

Berzelian formulas consist mainly of letters and numbers, the numbers preceding the letters or being superscripts of them. The letters, such as O (Oxygenium), S (Sulphur), or Cu (Cuprum) were taken from the Latin names of the substances. In addition, Berzelius often used dots instead of O for oxygen, letters combined with dashes to denote two "atoms" of an element, as well as the plus sign and parentheses to combine letters and numbers. For example, in his introductory article of 1814 Berzelius represented the composition of sulfuric acid by the formula $S + 3\,O$, but also by SO^3, which he viewed as identical in meaning with the former formula. The plus sign could be omitted in the case of the simplest compounds consisting only of two elements, such as SO^3, but Berzelius always used it for denoting compounds consisting of more than two elements; for example, the formula for copper sulfate was $SO^3 + CuO$, and that for alum $3(AlO + 2\,SO^3) + (Po + 2\,SO^3)$. The reason for this was that the formulas not only represented the elemental "composition" of compounds but also their binary "constitution," that is, the internal association of the elements to form two composed "immediate constituents" (see below). The partition of the formula into two partial formulas simultaneously separated and linked by the plus sign signified that copper sulfate was not immediately composed from the three elements sulfur, oxygen, and copper, but from sulfuric acid and copper oxide, and that these two "immediate constituents" were stable enough to be isolated experimentally in chemical analyses. In the case of more complicated compounds, such as alum, parentheses were necessary to denote the binary constitution. The two parentheses in the formula for alum 3 $(AlO + 2\ SO^3)$ + $(Po + 2\ SO^3)$ signified that its two immediate constituents, obtained through analysis, were aluminium sulfate $(AlO^2 + 2\ SO^3)$, itself consisting of the two components aluminium oxide and sulfuric acid, and sulfate of potash $(Po + 2\ SO^3)$, which again is shown as being made up of the two components potash and sulfuric acid.

Berzelius explicitly mentioned that he used parentheses "as is done in algebraic formulas."[17] Letters, numbers, superscripts, the plus sign, and parentheses were inscriptions of an algebraic mode of representation par excellence. Furthermore, Berzelian formulas were read progressively, just as algebraic notation. Like many other chemists of the time, the mathematization of chemistry and thereby the enhancement of its reputation was one of Berzelius' main goals. Yet Berzelian formulas were not completely lacking in imagery. A letter was not merely shorthand for the name of an element and a sign for its theoretical combining weight ("atomic weight"); it also stood for a discrete portion of an element.

Owing to the one-to-one correspondence between a letter and the denoted portion of element, letters had a certain "graphic suggestiveness."[18] With respect to algebraic notation in general, Rudolf Arnheim has given cogent expression to what is meant here:

> In the strictest sense it is perhaps impossible for a visual thing to be nothing but a sign. Portrayal tends to slip in. The letters of the alphabet used in algebra come close to be pure signs. But even they stand for discrete entities by being discrete entities: a and b portray twoness. Otherwise, however, they do not resemble the things they represent in any way, because further specification would distract from the generality of the proposition.[19]

The letters of the alphabet in algebraic notations, Arnheim says, come close to "pure" or arbitrary signs, since they do not resemble in any way the signified objects. The letters of Berzelian formulas did not resemble the mental image of an elemental portion – if there was such a mental image at all. Yet, the fact that a letter is a visible, discrete, and indivisible thing (unlike a written name) constitutes a minimal isomorphy with the postulated object it stands for, namely the indivisible unit or portion of chemical elements.

Further, the composition of a Berzelian formula from letters as syntactic elements corresponded to the composition of a chemical compound from portions of chemical elements. Hence, a Berzelian formula conveyed a building-block image of the chemical compound (see Figure 1). In accordance with this, the plus sign did not merely signify mathematical additivity of the relative combining weights (also "atomic weight") of the chemical portions, but also chemical additivity of elemental portions constituting a chemical compound. This becomes particularly clear when we compare the Berzelian formula models of binary constitution, for which Berzelius coined the term "rational formulas," with his raw formulas or "empirical formulas."[20]

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Tools and Modes of Representation in the Laboratory Sciences
Klein, U. (Ed.)
2001, XVI, 264 p., Hardcover
ISBN: 978-1-4020-0100-0