Analysing Symbolic Expressions in Secondary School Chemistry: Their Functions and Implications for Pedagogy

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Abstract

Symbolic expressions are essential resources for producing knowledge, yet they are a source of learning difficulties in chemistry education. This study aims to employ social semiotics to analyse the symbolic representation of chemistry from two complementary perspectives, referred to here as contextual (i.e. historical) and functional. First, the contextual account demonstrates that symbolism was introduced to represent compounds according to their elemental composition, to quantify chemistry, and to explain reactivity. Further to this, the functional analysis shows that symbolic expressions entail ~~possess~~ a range of unique grammatical resources to create ~~make~~ specialised forms of knowledge, which cannot be made by natural language alone. It is found that historically the symbolic ~~notional~~ representation was not originally directly related to the submicroscopic domain, nor did it develop sufficient means to offer particulate explanations, although an indirect link could be set up between Berzelian formulae and the submicroscopic theoretical models. It is also found that understanding the quantitative aspects is a necessary but not sufficient condition for effective engagement with the symbolic representation of chemistry. Finally the present study discusses the pedagogic implications stemming from the social semiotic account of chemical symbolism.

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Introduction

Since Johnstone's (1982) formulation of the 'triplet' model (Gilbert and Treagust, 2009, p.6), symbolic representation has been identified as one essential domain for communicating and representing chemical knowledge.~~,~~ Indeed, the ~~whose~~ interaction between the symbolic, the macroscopic, and the submicroscopic domains ~~with the macro domain and the submicroscopic one~~ has become a research paradigm in the field of science education (Talanquer, 2011). While chemical symbolism provides experts with an effective tool to mediate and shift between what can be observed directly and what is happening at the atomic level (Taber, 2013a), it tends to pose two major learning challenges for novices.

First of all, young learners may not understand the complex convention of using different forms of symbolism (Taber, 2009). For example, even a typical symbolic representation found in introductory school chemistry like $2H_2 (g) + O_2 (g) \rightarrow 2H_2O (l)$ features a high level of notational complexity. Effective ~~and effective~~ engagement with this symbolic equation ~~it~~ requires the ability to distinguish the symbols standing for the element ('H' and 'O') from the state symbols ('g' and 'l'), to correctly interpret the meaning of the plus sign and the arrow sign, and to understand the conceptual difference between coefficients and subscripts.

Furthermore, it seems exceedingly difficult for many students to relate symbolic expressions to the particulate nature of matter (de Jong and Taber, 2014). A substantial body of research on learners' understanding of chemical equations has shown that in students' minds symbolic representation is closely associated with the numeric aspects of chemistry rather than with the conceptual aspects (Nurrenbern and Pickering, 1987; Hinton and Nakhleh, 1999; Sanger, 2005). These findings imply that notational signs tend to be perceived quantitatively and have caused considerable debate regarding ~~debates~~ whether an emphasis on the mathematical operation at school has detrimental effects upon students' conceptions about the submicroscopic domain (Bodner and Herron, 2002; Talanquer, 2011).

The present study aims to analyse the symbolic representation of chemistry with a social semiotic approach (Halliday and Matthiessen, 1999, 2004). This approach ~~, which~~ holds much promise to advance current understanding of chemical symbolism, and to illuminate the two interrelated learning difficulties. Firstly, symbolic expressions are inherently signs, and thus a semiotic lens provides a common platform for conceptualising and comparing different forms of representation like symbolism and natural language. In addition, a social-functional analysis may shed light on the strong association between notations and the algorithmic aspects of chemistry and explain why it is difficult for novice learners to relate symbolic expressions to the submicroscopic domain of chemistry.

Theoretical framework

Social semiotics conceives signs as semiotic resources which human beings employ to interpret, create, and act on reality (Halliday, 1978). From a social semiotic perspective, learning science is a meaning-making process wherein young students' understanding of scientific concepts entails the mastery of a set of specialised meaning patterns and meaning relations (Lemke, 1990). The notion of 'meaning' is central to the social semiotic view of science education and so deserves ~~needs~~ further elaboration.

In the first place, within this perspective meaning is both a social and representational phenomenon (Halliday and Matthiessen, 1999). In other words, meaning is shaped by a particular context and constructed in a semiotic expression ~~does not exist independently of either context or semiotic expressions, but tends to co-occur with them at different levels of abstraction in a probabilistic manner~~. ~~For instance,~~ When ~~when~~ human beings communicate through natural language, the shared cultural norms enable them to predict what semantic configurations are more likely to occur. The utterance "We are going to start on the transition metals next week" would seem obscure to a typical number of the public, but is a meaningful communication in the context of one chemistry teacher talking to a colleague who possesses the resources to make sense of the statement. At the same time, the instance of speeches organised in specific linguistic forms and structures provides the participants with concrete means to create and interpret each other's meaning in details. ~~The utterance "We are going to start on the transition metals next week" would seem obscure to a typical number of the public, but is a meaningful communication in the context of one chemistry teacher talking to a colleague who possesses the resources to make sense of the statement.~~ The nominal group 'transition metals', for example, has a 'Classifier + Thing' configuration (Halliday and Matthiessen, 2004, p. 320). This structure makes it possible for the audience to correctly understand the scientific taxonomy of metals that the technical term 'transition metals' implies.

Secondly, meaning is diversified into three generalised semiotic functions (Halliday and Matthiessen, 2004, pp. 29-31): a), the ideational function to represent 'goings-on' or 'state of affairs' in the world; b), the interpersonal function to bring about interactions between the speaker and the audience; c), the textual function to organise related elements into a coherent message. When a teacher addresses a class to say "In today's lesson we will discuss the main characteristics of the transition metals", this statement simultaneously creates three types of meanings. Ideationally, it represents the experience of 'saying'. Interpersonally, the teacher is assigned the role of offering information for the students. Textually, the prepositional phrase ('in today's lesson') gains a greater prominence, as it serves as the point of departure in the flow of information when the message unfolds. Every communicative act serves to construct 'doings and goings-on' or 'state of affairs' in the world as the ideational meaning, to build relationships between participants and take an attitude towards the representation as the interpersonal meaning and to organise related elements into a coherent message as the textual meaning.

Thirdly, meaning is continually created, maintained, and recreated through time. This 'semogenetic' view (Halliday and Matthiessen, 1999, pp.17-18). Accordingly, the meaning potential of scientific discourse underwent constant changes in history when new semantic patterns emerged to facilitate scientific research.is useful to explore how new semantic patterns were formed out of particular social contexts in history. For example, Halliday's (1998) semogenetic analysed the meaning-making patterns of analysis of Newton's *Opticks* （published in 1704） and Priestley's *History and Present State of Electricity* (published in 1767). It was found convincingly demonstrates that scientists in the 18th century significantly increased the use of grammatical metaphor (e.g., to nominalise the verb 'refract' as 'refraction') in their essays to create technical taxonomies and make logical progression for pursuing experimental science.

While the vast majority of existing social semiotic studies focused on the linguistic components of science education (e.g., Lemke, 1990; Halliday and Martin, 1993; Martin and Veel, 1998), it is important to note that language is "one of a number of systems of meaning, that, taken all together, constitutes human culture" (Halliday and Hasan, 1985, p. 2). Recent educational research (e.g., Dimopoulos *et al*., 2003; Bezemer and Kress, 2008; Liu, 2011) has shown that the meaning-based approach is effective for analysing ~~to analyse~~ the specialised functions of individual semiotics other than language and to illustrate how different forms of representation are coordinated to make scientific explanations of phenomena.

Research methodology

The meaning-based approach plays multiple roles in this research: It not only lays down the criterion to select data, but also provides the methods to analyse and interpret the data. Since meaning is both shaped by context and constructed in representation, the present study collected two main sources of data for analysis. The first source of data was derived from historical accounts of the development of chemistry from the late 18th century and the early 19th century when chemical symbolism emerged and later was widely accepted by the scientific community. The primary concern was to explore the ~~semogenetic~~ evolution of specialised meanings in the particular social context rather than to elaborate on the historical details.

The second source of data was canonical symbolic expressions commonly used in introductory chemistry courses for secondary school students. Admittedly, the scope of symbolic representation is not without controversy and it may include all types of signs such as mathematical graphs (Johnstone, 2000). However, this research focuses on the symbolic representation of chemical reactions, a difficult core topic at secondary level (de Jong and Taber, 2014).~~,~~ The data ~~which~~ mainly comprises the signs which ~~to~~ stand for “composition of matter, or its properties and behaviours” (Talanquer, 2011, p.184).

To account for the functions of symbolic representation, the meaning-based approach provides a set of analytical frameworks by linking the grammatical organisation to the semantic configuration.~~,~~ These frameworks have been employed to effectively analyse how language fulfils particular ideational, interpersonal, and textual functions in scientific discourse (e.g., Halliday and Martin, 1993; Martin and Veel, 1998). which were effectively employed to analyse the use of linguistic expressions in scientific discourse (e.g., Halliday and Martin, 1993; Halliday, 1998). While these grammatical frameworks can be used to sort out ideational, interpersonal, and textual meanings, Considering that the present study is primarily interested in the semiotic construction of chemical knowledge, . Accordingly, we focus on ideational meaning making by exploring what particular domain of experience is represented in the symbolic discourse of chemistry.

From a social semiotic perspective, semantic configurations of different complexity are typically related to a constituency hierarchy in the grammar (Halliday and Matthiessen, 1999, pp. 48-50). For example, in natural language the semantic units of figure (configuration of elements) and element are respectively represented in the grammatical ranks of clause and word group or phrase[1]. For example, semantics generally operates at three orders of complexity: element, figure (configuration of elements), and sequence (combination of figures), which are respectively represented in a scale of rank of word group or phrase[1], clause, and clause complex. Table 1 illustrates shows this dialectic relationship between semantics and grammar in language examples of the typical representation of the meaning in the wording.

Table 1 Example of the typical representation of the meaning in the wording

semantic unit		grammatical rank	example
sequence	↔	clause complex	When magnesium burns in oxygen, magnesium oxide is formed.
figure	↔	clause	magnesium oxide is formed
element	↔	word group/phrase	magnesium oxide /in oxygen

Note: Following Martin (1999), the double headed arrow sign stands for the dialectic relationship between semantics and grammar, which mutually construct each other at different levels of abstraction.

Table 1 The dialectic relationship between semantics and grammar in language

semantic unit		grammatical rank	example(s)
figure	↔	clause	magnesium burns in oxygen
element	↔	word group/phrase	magnesium /burns /in oxygen

Note: Following Martin (1999), the double headed arrow sign stands for the dialectic relationship between semantics and grammar, which mutually construct each other at different levels of abstraction. The arrows are sloping down towards “grammatical rank” so as to demonstrate that grammar is less abstract than semantics.

According to Halliday and Matthiessen (2004),~~Of the three semantic units,~~ a figure is the ~~identified as a~~ central semantic configuration ~~one~~ in modelling experience as a flow of events.~~, and~~ It ~~it~~ exploits ~~develops~~ a grammatical resource called ‘transitivity’ to construe the events into a set of process types (i.e., material, relational, mental, verbal, behavioural, existential) at the rank of clause (Halliday and Matthiessen, 2004, p. 170). These process types enable natural language to ~~effectively~~ construe six different domains of experience ~~such as~~ (i.e., doing or happening, being or having, sensing, saying, behaving, and existing).

Each process type or figure consists, in principle, of two obligatory elements: a Process itself and Participants involved in the process, and one optional element: Circumstances associated with the process. The elements of Process, Participant and Circumstance are typically represented in the grammar of a verbal group, a nominal group and a prepositional phrase. An example of the transitivity system is shown in Table 2. A reader may notice that in this example the wording of the clause describing a reaction between two substances treats one substance, magnesium, as Participant, whereas the presence of oxygen is treated as Circumstance. This is a point we return to below.

Table 2 Example of the transitivity system

	magnesium	burns	in oxygen
semantics	Participant	Process	Circumstance
grammar	nominal group	verbal group	prepositional phrase

As Table 2 demonstrates, the transitivity system provides a grammatical tool for analysing the particular domain of experience. The verbal group ‘burns’ represents a Process of happening, inherently associated with which is a Participant realised by the nominal group ‘magnesium’. In addition, the prepositional phrase ‘in oxygen’ stands for the Circumstance of Location to indicate where the Process takes place. Taken all together, these three semantic elements constitute a material process at the rank of clause and construe the experience of what happens to a substance in a place.

It is important to note that there exists no fixed one-to-one correspondence between semantics and grammar. On the contrary, grammar has the potential for ‘rankshift’ (Halliday and Matthiessen, 2004, pp. 9-10), whereby a unit of one rank may be reorganised at a lower level as part of its own rank. One example of rankshift is shown in Table 3.

Table 3 Example of rankshift

	word group	word group	word group
clause	magnesium oxide	is formed	
clause	[[the formation of magnesium oxide]]	is	a synthesis reaction

Note: Following Halliday and Matthiessen (2004), [[ ]] represents a rankshifted clause.

Rankshift is considered a key grammatical resource to remodel experience as scientific knowledge (Halliday, 1998). As can be found in Table 3, when the clause ‘magnesium oxide is formed’ is nominalised as a nominal group ‘the formation of magnesium oxide’ in the clause ‘the formation of magnesium oxide is a synthesis reaction’, the mechanism of rankshift not only functions to create a technical taxonomy by setting up a member-to-class relationship between ‘the formation of magnesium oxide’ and ‘a synthesis reaction’; it also enables the reader to further discuss what has been represented in a prior clause.

On the other hand, rankshift in scientific discourse can pose comprehension challenges for young students (Fang, 2005). For instance, when the clause 'magnesium oxide is formed' is grammatically downgraded, its meaning is compacted in a long word group 'the formation of magnesium oxide' and thus the denser information may become a source of learning difficulty. Further to this, a previous Process of doing ('is formed') is subsequently remodelled as a virtual Participant of entity ('formation'), thereby making the text more abstract to understand.

While the analytic methods such as transitivity and rankshift originated from the pioneering research on natural language (e.g., Lemke, 1990; Halliday, 1998), it should be kept in mind that from a social semiotic perspective, the notion of grammar does not merely refer to a system of formal linguistic rules of correctness, but includes "the structures of relations of elements in a specific mode, and between modes" (Kress *et al*., 2001, p.12). In fact, these analytical methods have been usefully extended to analyse the grammar of mathematical symbolism and explore the functions fulfilled (O'Halloran, 2005). A language-based approach to the symbolic representation of chemical reactions can also be justified by the fact that modern chemical symbolism had a linguistic origin (Crosland, 1962).

The birth of modern chemical symbolism

The modern system of formula notations was first proposed by the Swedish chemist Jacob Berzelius in 1813 and was later generally accepted by scientists in Europe and North America in the 1830s (Brock, 1993). Modern chemical symbols evolved from natural language in that they are usually the first one or two letters of the Latin names of elements (e.g., K for potassium from 'kalium' in Latin; Na for sodium from 'natrium' in Latin).

From a functional ~~semogenetic~~ viewpoint (Halliday and Matthiessen, 1999; O'Halloran, 2005), the semiotic transition from natural language to symbolism was semantically motivated in a particular context. A historical overview demonstrates that while chemistry in the 18th century was well established as a discipline with a considerable body of practical technics, instruments and empirical findings (Golinski, 2003), it lacked important features that would be expected of a natural science today.

First of all, there was a lack of rational nomenclature, which played an essential role in the construction of scientific methods (Comte, 1975, as cited in Bensaude-Vincent, 2002, p. 174). As Brock (1993, pp. 115-116) pointed out, chemicals were arbitrarily named according to one or another property of the substances like provenance (e.g., *Aquila coelestis* for ammonia) and physical appearance (e.g., 'flowers of zinc' for zinc oxide). These less informative names kept obstructing the flow of chemical communication until the end of the 18th century. At that time, ~~when~~ Lavoisier redefined elements as simple substances that could not be chemically broken down. From then on, scientists like Guyton in France and Berzelius in Sweden began to systemise nomenclature solely on the basis of elemental composition (Brock, 1993). 'Spanish green', for instance, was renamed as 'copper acetate'. Seen from a social semiotic viewpoint (Halliday, 1998), this was not simply a process of substituting names.~~,~~ In fact, the new nomenclature ~~but~~ laid down a different criterion to set up technical taxonomies in modern chemistry because a substance's elemental makeup can only be identified through direct experimentation with the aid of sophisticated apparatus.

Secondly, most chemical research up to the end of 18th century had been qualitative with an emphasis on elective affinity between substances.~~,~~ Up till this time ~~as~~ no effective quantitative models were available to facilitate more efficient experimentation or manufacture (Brock, 1993).

After Richter observed that a fixed quantity of acid could be neutralised by different quantities of bases in 1792, scientists in Europe began to measure equivalent weights of different substances (Brock, 1993). This was a considerable step forward in the development of modern chemistry. As stoichiometric research made it possible to assign every substance with a unique combining weight called "proportion, equivalent, or atomic weight" (Klein, 2003, p. 15), the invariant numeric value therefore became a far more reliable attribute to identify chemicals than changeable macroscopic properties like colour and smell.because the stoichiometric research made it possible to set up relations between a substance's weight and its chemical properties, thereby paving the way for attributing the nature of an element to its inherent numeric value.

Another limitation with the 18th century's chemistry was the under-theorisation of reactivity. For example, although Geoffroy's *Table des rapports* of 1718 clearly displayed a wide range of substances' elective affinity, no theory was able to adequately explain why only some chemicals had a disposition to unite together (Weininger, 1998). Inspired by Volta's discovery of galvanic or current electricity and Davy's electrolysis experiments as a new method to decompose chemicals, Berzelius proposed an electrical theory of reactivity in 1811 and identified compounds as the result of attraction between electropositive and electronegative elements (Brock, 1993).

While Although substantive empirical findings had been reported made and novel techniques technics introduced by the end of the 18th century, they could not of themselves remove the above-mentioned limitations alone, for scientific endeavours are "both *material* and *semiotic* practices" (original emphasis, Halliday, 1998, p. 228). Admittedly, natural language was employed in history as a crucial resource to facilitate scientific revolution (Crosland, 1962). Its functional limitations, however, could cause barriers to the further theorisation of chemistry.

For example, a linguistic expression like ‘iron’ has a number of vernacular and scientific meanings.~~,~~ It ~~for it~~ can refer to a piece of equipment to make clothes flat and smooth, a material, a chemical substance, and a chemical element, to name just a few. The ambiguous reference to different domains of experience makes natural language a less effective resource to demonstrate the elemental composition of chemicals. In contrast, the Berzelian symbol ‘Fe’ can hardly be found in everyday life and thus is closely associated with ~~indexical of~~ the field of chemistry. Furthermore, non-systematic ~~unsystematic~~ names such as ‘ammonia’, which contain~~s~~ little information about the substance’s elemental makeup (Taber, 2009), still remain in contemporary scientific nomenclature.

Language also has limitations in its quantification capabilities. As Lemke (1998) pointed out, language is good at making categorical distinctions, but lacks the resource to accurately describe continuous patterns of change. The nominal group ‘sulphuric acid’, for instance, provides clear clues about the scientific classification (e.g., the member-class relationship between ‘sulphuric acid’ and ‘acid’; the part-whole relationship between ‘sulphur’ and ‘sulphuric acid’).~~,~~ However, the name ~~but it~~ fails to demonstrate the numeric relation between the constituents, which~~,~~ ~~however,~~ is clearly represented in the formula H_2SO_4.

The preceding analysis indicates ~~It therefore follows~~ that modern chemical symbolism might have emerged in the early 19th century to carry out three particular functions: to represent compounds according to their elemental composition, to quantify chemical reactions, and to explain reactivity from an electrochemical perspective.~~,~~ All these functions ~~all of which~~ were crucial to further develop Lavoisier’s elemental theories and transform chemistry into a modern science. Accordingly, Berzelius was more likely to use symbols as a reference to simple substances from an empiricist viewpoint than a reference to the real but unobservable particles such as atoms.

In other words, historically, the origin of symbolic representation was not primarily motivated by an intention to reference the submicroscopic domain of chemistry.

However, this does not imply that there existed no link between formula notations and the submicroscopic theoretical models. On the contrary, the following grammatical analysis of the symbolic representation (especially in the section 'The condensed structure of representation') may demonstrate why symbolic representation could be flexibly connected with the submicroscopic domain of chemistry, yet in a limited way.

Grammatical analysis of symbolic representation

As an integral part of scientific communication, chemical symbolism exploits a wide range of grammatical resources to construe meanings, a preliminary account of which is given elsewhere (Liu, 2011)~~a full account of which, however, is beyond the scope of this research~~. The present study only highlights two main grammatical strategies employed by symbolic representation (i.e., two specialised transitivity process types, and the condensed structure of representation). It is argued that these grammatical strategies successfully facilitated the theorisation of modern chemistry based on Lavoisier's empiricist view of elements, but Berzelian formulae lacked sufficient visual-spatial resources to explore the submicroscopic domain of chemical knowledge.

Two specialised transitivity process types

As explained earlier, transitivity is the crucial grammatical system to represent patterns of experience in a clause, which consists of three semantic categories: the Process itself, the Participants in the process, and the Circumstances associated with the process. Natural language develops a full set of process types (i.e., material, mental, verbal, relational, behavioural, and existential) to conceptualise wide-ranging domains of experience (Halliday and Matthiessen, 2004). For example, a material process in everyday life might be to eat; in chemistry a material process might be to react. In the context of science education, it is worth noting that it is common for students (and sometimes teachers) to use the available resources of natural language to refer to how atoms want, wish, like, prefer, etc., that is to describe chemistry at the submicroscopic scale in terms of the mental process (Taber, 2013b)

However, like the situation found in mathematical symbolism (O'Halloran, 2005), the range of process type was substantially reduced in chemical signs. For example, chemical symbolism lacked the resource to represent the mental, the verbal, the behavioural or the existential process[2]. The contracted range of transitivity enabled scientists to maximally exclude common-sense experiences from their symbolic construction of chemical knowledge. On the other hand, two specialised transitivity process types emerged in chemical discourse to produce novel semantic patterns, which were not found in natural language.

The adoption of the operative process

In the grammatical analysis of mathematical discourse, O'Halloran (2000) claimed that a new process type: the operative process was employed in mathematical symbolism to construe the particular domain of experience including addition, subtraction, multiplication, and division. Having grown out of the material process of increasing, decreasing, combining and sharing, the operative process, however, gained the meaning potential to perform on highly abstract and complex quantities, whereas the material process usually represents everyday experience (O'Halloran, 2000).

Historical records clearly show that in chemistry symbolic signs were introduced as a necessary means to indicate the total weight of compounds by adding the number of ‘volumes’ of the constituents. For example, water was symbolised by Berzelius as 2H + O in that water was composed of two volumes of hydrogen and one volume of oxygen (Berzelius, 1814, as cited in Klein, 2003, p. 10). So since its inception chemical symbolism has been co-deployed with algebraic algebra signs to encode mathematical meanings. Further to this, when the elemental symbols were assigned a numeric value no matter what it might be called (e.g., ‘relative combining weight’, ‘equivalent weight’, ‘atomic weight’, or ‘atomic number’), scientists gained additional semiotic resources to quantify chemistry.

For instance, even a seemingly simple symbolic representation like 2H + O contains two operative processes from a social semiotic perspective. The first one is an operative process of addition in which 2H and O are the Participants and the plus sign functions as the Process. The second one is an operative process of multiplication where the multiplication sign as the Process is elided between the Participants of 2 and H. Given that the operative process is the most precise and powerful semiotic resource for calculation (O’Halloran, 2000, 2005), it enables scientists to make quantitative analysis of substances with symbolic representation.

The emergence of the reactive process

Apart from quantification of chemistry, symbolic representation was also employed to address the issue of reactivity. According to Brock (1993), Berzelius explained substances’ elective affinity as an electric attraction between different elements and used the plus sign to indicate the electropositive elements in a compound., So so *oxidum cuprosum* (copper(II) oxide) was represented as Cu + O. From a functional ~~semogenetic~~ perspective (Liu and Owyong, 2011), this semiotic shift facilitated scientists' ability to transform a compound from a stable entity to a dynamic interaction between elemental constituents through a crucial grammatical means called ~~known as~~ 'the reactive process' (Liu, 2009, pp. 134-135).

Similar to O'Halloran's (2005) observations about the operative process, the reactive process might have grown out of the material process in natural language, ~~-~~because both of them construe the experience of 'doing' or 'happening'. However, they have different grammatical configurations to produce particular semantic patterns. Possibly because Berzelius introduced symbolic expressions to represent different elements in a compound (Brock, 1993), the reactive process has developed a multiple-Participant configuration, but ~~-whereas~~ the material process can be actualised by one single Participant.

To follow up from the example 'magnesium burns in oxygen' in Table 2, this particular clause is structured such that 'magnesium' is the sole Participant to actualise the material process, whereas 'oxygen' plays a peripheral role as one part of the Circumstance of Location (Halliday and Matthiessen, 2004). However, ~~By contrast~~, in the reactive process Mg + O_2, both Mg and O_2 ~~the elements of copper and oxygen~~ equally play the semantic role of Participants, while the plus sign functions as the Process. Accordingly, the different grammatical configurations construe the same phenomenon of burning as two different domains of experience.~~:~~ The material process makes common-sense knowledge through direct perception by implying that burning can take place with just one substance. By contrast, the reactive process offers a scientific account by identifying burning as a chemical interaction between different elements. The clause "magnesium burns in oxygen" is therefore open to interpretation by students in ways inconsistent with the chemical concept of reactions. By contrast, ‘$Mg + O_2$’ is more abstract and less readily accessible to novice learners, but can more readily be associated with a process where two substances interact.

It is also ~~Also~~ noteworthy ~~is~~ that in a multiple-Participant configuration, the material process tends to assign one Participant a causing or agentive role.~~,~~ This semantic pattern ~~which~~ seems to be a source of students’ tendency ~~misconception~~ to see one of the reactants in a chemical reaction as the more active - the driver for reaction (Taber and García-Franco, 2010). For instance, ~~those who,~~ when silver nitrate solution was mixed with sodium chloride solution, some learners considered the silver nitrate ultimately responsible for the formation of precipitate. They explained ~~about~~ this phenomenon in terms of one substance acting upon the other: “the silver nitrate acting upon the salt” (Taber and García-Franco, 2010, p. 119). This is reflected in much of the professional language of chemistry of course (references to ‘attacking’ species, for example).~~,~~

However, talking science this way ~~but~~ is problematic for developing a perspective when the reactants are seen as a system that will interact to evolve into another of lower free energy. In terms of the semantic configuration, ~~From a social semiotic perspective,~~ “the silver nitrate acting upon the salt” is a clause of the material process with two Participants: “the silver nitrate” and “the salt”.~~:~~ The former is assigned the more active role to bring out a change, whereas the latter is affected by the change. In contrast, Participants in the reactive process share a co-equal status, as evidenced by the fact that the symbolic expression $AgNO_3 + NaCl$ can be re-presented as $NaCl + AgNO_3$ without any change of meaning.

The condensed structure of representation

Like the symbolic expressions in mathematics (O'Halloran, 2000), chemical symbolism employs a set of specialised resources to condense its structure. Three devices (i.e., the use of symbols with multiplicity of meanings, the ellipsis of the plus sign in chemical formulae, and the multiple levels of rankshift) are selected here to demonstrate how the symbolic structure is maximally condensed to represent reactions in the most economical manner. This makes for effective communication between experts, but offers a dense form of representation that is less readily accessible (compared to natural language, for example) to novices such as secondary students.

The use of symbols with multiplicity of meanings

While historical scholarship suggests that Berzelian symbolism was ~~Berzelian symbolism seems to have been~~ designed ~~in history~~ to represent Lavoisier's empirical concept of elements, within contemporary chemistry research and education it is adopted ~~have interpreted it~~ for a number of different purposes. As Klein ~~Kline~~ (2003) observed, now the symbolic representation can be used in different contexts to stand for macroscopic compounds, small particles in the submicroscopic domain, and atomic weights. However,~~, yet~~ little research attempts to explain how chemical symbols have developed multiplicity of meanings.

It appears that the semantic mechanism of metonymy may have functioned to multiply the meanings of symbolism. Metonymy is a meaning relation where something comes to be referred to by the name of some closely associated entity, such as using the term 'the lab' (as in 'the lab won't like it') to mean those working in a laboratory. Following Horacek (1996, p. 112), linguistic expressions can achieve semantic extension through standard metonymic relations including 'part for whole', 'container for contents', 'producer for product', and 'object used for user'. Given that chemical symbolism grew out of natural language (Crosland, 1962), the metonymic relations were quite likely to play an important role in multiplying the meanings of chemical notations.

For example, the word 'Cambridge', which literally refers to a city in the east of England, has the potential to stand for a famous university in the clause "Cambridge has produced 90 Nobel Prize winners across all categories" through the 'part for whole' metonymic relation. In a similar vein, Berzelius' original symbols for simple substances might have been semantically extended to represent unobservable particles, no matter whether they were chemically indivisible units called known as 'chemical atoms' or physically indivisible units called known as 'physical atoms' (Schütt, 2003, pp. 239-242). Their part-whole relation could be successfully set up, because the concept of atoms proposed in the 19th century was consistent with Lavoisier's empirical view of elements as evidenced by Dalton's definition of atoms as elementarily different particles (Brock, 1993).

The 'container for contents' relation is also an effective mechanism to extend the semantic scope of natural language and symbolism. For example, the noun 'kettle' in 'The kettle is boiling' (Horacek, 1996, p. 112) should not be literally understood as a container, but contextually refers to the water in it. Likewise, in the 19th century both elements and atoms were assumed to have specific weights (Brock, 1993), and thus they constituted weight carriers. Through the 'container for contents' metonymic relation, chemical elements and atoms might have been assigned a numeric value such as relative combining weight, equivalent weight, or atomic weight.

Apart from elemental notations, symbols standing for chemical change like the plus sign and the arrow sign also gained more than one meaning. In the reaction equation $Mg+O_2 \rightarrow MgO$, for instance, the plus sign can be verbalised as "react with", and the arrow sign as "produce" (Taskin and Bernholt, 2014, p. 173). However, when the chemical equation is balanced as

$2Mg+O_2 \rightarrow 2MgO$, both the plus sign and the arrow sign fulfil two different functions at the same time. From a social semiotic perspective, the plus sign not only actualises a reactive process to explain the reaction between magnesium and oxygen, it also simultaneously actualises an operative process of addition to allow the calculation of the weight or the atomic numbers of the two reactants. Likewise, the arrow sign gains another meaning of 'add up to' or 'is interchangeable with' similar to the function of the equal sign in mathematics.

Ellipsis of the plus sign of the reactive process in chemical formulae

As recorded in the historical documents (Klein, 2003, p. 10), Berzelius had symbolised copper(II) oxide as Cu + O before discarding the plus sign and using CuO to represent the same compound as one constituent of the more complex compound of copper(II) sulphate. From a functional ~~semogenetic~~ perspective (Liu and Owyong, 2011), Berzelius' symbolic representation involved two significant semiotic shifts. The first one was a transition from a nominal group in natural language 'copper(II) oxide' to a reactive process in notational signs 'Cu + O'. This transition~~, which~~ enabled scientists to re-conceptualise stable entities as dynamic interactions between elemental constituents. Secondly, the reactive process 'Cu + O' was structurally condensed as a chemical formula 'CuO' through the ellipsis of the plus sign, similar to the ellipsis of the multiplication sign in algebra (Whewell, 1831, as cited in Klein, 2001, p. 28).

Notably, the ellipsis of the plus sign caused a grammatical re-organisation of the symbolic representation. To illustrate, following the grammatical rank scale in language (Halliday and Matthiessen, 2004) and in mathematical symbolism (O'Halloran, 2000), Berzelius' first symbolic representation 'Cu + O' operates at the rank of clause. However, ~~whereas~~ Berzelius' ~~his~~ later expression 'CuO' functions at a lower rank, equivalent to a phrase in language (compare with the examples in Table 1). So the semiotic shift from 'Cu + O' to 'CuO' can be conceptualised as a case of symbolic rankshift as shown in Figure 1.

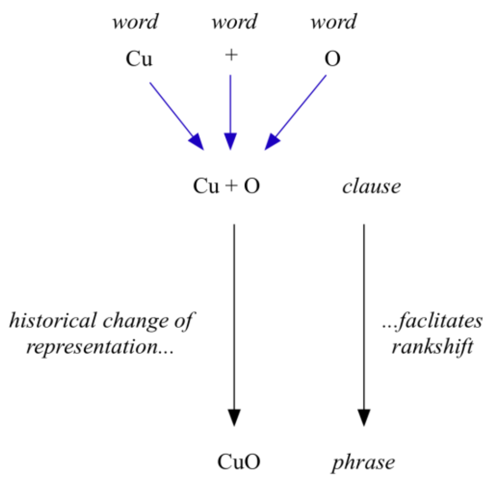

Figure 1 Example of symbolic rankshift

Multiple levels of rankshift

Berzelius' ellipsis of the plus sign provided another effective means to further condense the structure of symbolic representation, and multiple levels of rankshift became possible in chemical symbolism. For example, when the compound of calcium carbonate is symbolised as $CaCO_3$, the formula has complex meanings compacted through multiple levels of rankshift, which is not possible by using natural language. Based on Berzelius' (1814, as cited in Klein, 2003, p. 10) model of symbolic representation for compounds and O'Halloran's (2000) description of ranks in mathematical symbolism, and also following the empirical rule of valency, the multiple rank-shifted configurations in $CaCO_3$ can be shown below in Table 4.

Table 4 Rank-shifted Process/Participant configurations in $CaCO_3$

Rank Level	*Process*	*Participants*
Rank 1: Phrase	+ (reactive/operative)	• Ca^{2+} • CO_3^{2-}
Rank 2: Phrase	+ (reactive/operative)	• C^{4+} • $3O^{2-}$
Rank 3: Phrase	× (operative)	• 3 • O^{2-}
Rank 4: Word		• Ca^{2+}, C^{4+}, O^{2-}, 3

As Table 4 displays, three Process/Participant configurations are grammatically downgraded as phrases at three ranks to encode the specialised semantic patterns in the chemical formula $CaCO_3$. The nuclear configurations at Rank 1 and Rank 2 simultaneously represent the reactive process and the operative process., because For instance, the Process/Participant configuration $Ca^{2+} + CO_3^{2-}$, for example, not only indicates a chemical interaction between two different ions; it also shows their combining ratio (1:1) and other numeric relations.

Similar to the grammatical strategies found in mathematics (O'Halloran, 2000), the multiple levels of rankshift enable scientists to maximally keep the Process/Participant configurations in chemical symbolism, which is crucial to create particular semantic patterns not found in natural language. For example, the Participants such as Ca^{2+}, C^{4+}, and O^{2-} remain intact at the lowest rank in the symbolic formula, thereby clearly representing the compound in terms of its elemental composition. In contrast, the linguistic name 'calcium carbonate' is less transparent, for novice learners may not know the morpheme '-ate' implies the presence of oxygen (Taber, 2009, p. 88).

It is important to note that a nuclear configuration at a lower rank can be remodelled as a new Participant at a higher rank and enters another Process/Participant configuration. For instance, the reactive/operative process $C^{4+} + 3O^{2-}$ at Rank 2 is condensed as a Participant CO_3^{2-} at Rank 1 in the nuclear configuration $Ca^{2+} + CO_3^{2-}$. However, Table 4 also indicates that the multiple levels of rankshift are made implicit due to the ellipses of the plus sign and the multiplication sign, which may cause more comprehension difficulties.

Firstly, implicit rankshift makes it difficult to be aware of a chemical formula's status as a semantic junction (Liu and Owyong, 2011), that is a semantic category formed by conflating content from different semantic categories. As reported by Taber (2009, p. 90), students often fail to recognise $CaCO_3 \rightarrow CaO + CO_2$ as a reaction, because "the calcium carbonate is not reacting with anything". The novice learners seem to assume that the chemical formula $CaCO_3$ is functionally the same as the linguistic term 'calcium carbonate' to stand for a chemical entity without understanding that $CaCO_3$ also functions as rankshifted nuclear configurations in which the Participants (e.g., Ca^{2+}, C^{4+}, O^{2-}) have the potential to be recombined to represent new substances.

Further to this, implicit rankshift poses a challenge makes it difficult to correctly identify the Process/Participant nuclear configurations in formulaic expressions where chemical signs are combined with mathematical symbols. For instance, when asked to interpret the chemical formula 2NaOH, some students visualised it as NaNaOH (Smith and Mertz, 1996). From a social semiotic perspective, it seems that they were uncertain about the order in which the three Participants (i.e., 2, Na^+, OH^-) enter the rankshifted operative and reactive processes. So young learners may interpret 2NaOH as (2 × Na) + OH rather than 2 × ($Na^+ + OH^-$), as they do not know where the implicit brackets go. failed to realise that the Participant 2 actually enters an operative process of multiplication 2×NaOH rather than enters a reactive/operative process $2Na^+ + OH^-$. It therefore follows that without an adequate grasp of the scientific concepts such as valence and ions, it is more difficult for novice learners to can hardly employ the grammatical resource of symbolism to construe chemically valid meanings.

Commented [DYL1]: Prof. Taber's comment: Is it clear which is Participant 2? (i.e. it is not obvious to me!)
This is perhaps a matter of 'where the [implicit] brackets go':
2NaOH
= 2 x Na + OH
but as
2 x (Na + OH)
and not as
(2 x Na) + OH
So I think there is multiplication and addition in either case, but uncertainty about the order (addition first, then multiplication of the sum)

Thank you very much for making this comments. I rewrote this part by incorporating your suggestions.

Most practising chemists and chemistry teachers would not be explicitly aware of the semiotic analysis here in terms of the technical notions such as rankshift. Despite this, advanced education in chemistry involves acquiring an implicit understanding of the communicative potential of the representations used, an understanding which is not available to novices. This is again an aspect of symbolic representation used in chemistry where the affordances offered to the expert may provide a high learning demand for the novice: especially where the expert's use of the communicative potential of the representation has become so habitual that a teacher may not readily appreciate how opaque the symbolism may be to the learner.

The limitations of Berzelian symbolism

Admittedly,~~While~~ Berzelian symbolism was an effective tool to support the development of Lavoisier's theories in the early 19th century so that the chemical properties of a substance could be attributed to its elemental makeup.~~,~~ However, the ~~its~~ condensed structure and the underpinning theories became constrained to represent and explain the chemical behaviours of ~~new phenomena, especially~~ organic compounds, which comprise largely the same components of ~~, namely,~~ carbon and hydrogen.

To take an example, the phenomenon of isomerism found in the 1830s ~~procedurally~~ demonstrates that elemental composition was far from the sole determinant of chemical properties, and the constitution of organic compounds needed to be considered a focus of future research (Brock, 1993). ~~When there was a growing recognition~~ In ~~in~~ the 1860s ~~that~~ the internal arrangement of atoms within a molecule was increasingly recognised to play ~~played~~ a major role in determining the chemical behaviour of organic compounds (Weininger, 1998).~~,~~ Then, scientists began to look for a new semiotic tool to explain material phenomena from the submicroscopic perspective and developed the structural representations.

One famous representation is Kekulé's hexagonal model, which was used to apply the new structural theory to explore the puzzling lack of reactivity of benzene. Before Kekulé introduced his own model, scientists like Couper and Loschemidt had endeavoured to visualise Benzene as $H_2C=C=CHHC=C=CH_2$ following the rules of carbon-carbon bonding (Brock, 1993, p. 264). Compared with the Berzelian formula C_6H_6, Couper and Loschemidt's use of the horizontal straight chain provided more clues about the positional arrangement of the carbon and hydrogen atoms in a molecule., Despite this, the linear structure yet it was not a sufficient means to illuminate the core property of benzene that "all the six carbon atoms must be linked in the same way" (Nye, 1993, p.94). By contrast, Kekulé's hexagonal model had six edges and all its sides were of the same length, thereby providing a feasible interpretation of benzene's extraordinary properties through analogical reasoning.

The historical evolution of the representation for benzene from C_6H_6 to $H_2C=C=CHHC=C=CH_2$ and to the hexagonal model indicates that the three forms of representation lies on a continuum in their semiotic ability to facilitate a submicroscopic explanation for benzene's unique chemical behaviours. Berzelian formulae were the least effective means to illuminate the molecular constitution due to their maximally condensed structures. Keeping the linear structure, Couper and Loschemidt made limited use of the visual resource: the double lines and the horizontal dimension to represent benzene's structure in a more concrete way. However, even if such a representation more accurately represented molecular structure in terms of the linkages between the carbon atoms (e.g., see Figure 2), it was a poor reflection of molecular geometry.

Figure 2 A linear representation of benzene molecular structure

By contrast, Kekulé's structural formulae amply employed the visual-spatial resources such as lines, shapes, angles and dimensions to set up a submicroscopic model to far more accurately explain benzene's lack of reactivity. As a single Kekulé structure implies localised double bonds, the representation that offers greater explanatory power involves the introduction of a new symbolic element of a double headed arrow to represent the resonance between canonical forms. Other representations with this power show the overlap of unhybridised orbitals to form delocalised molecular orbitals. On the other hand, whereas the three representations increasingly exploited the visual-spatial resources to account for the particulate nature of matter, their potential to afford calculation dropped at the same time and only the molecular formula C_6H_6 could enter an operative process such as 100 C_6H_6.

Figure 2 A linear representation of benzene molecular structure

Seen from a social semiotic perspective, each sign system has its unique functional specialization.: Symbolism is unsurpassed for making calculations (O'Halloran, 2000), while visual images are effective to formulate degree, continuous co-variation and graduation (Lemke, 1998). The semantic motivation offers a reasonable explanation why symbolic representation takes a wide range of forms in contemporary chemistry research and education like empirical formulae, molecular formulae, and structural formulae., As none of these representations which is able to afford the whole set of meanings invoked in teaching, so they need to be co-deployed to functionally complement each other. Also noteworthy is that despite their different semiotic power, these forms of representation are all semantically linked to the same compound such as benzene, which makes it possible to make a translation (Cheng and Gilbert, 2009) or a semiotic shift when teaching and learning chemistry.

Summary of findings

Through the lens of social semiotics, the present study demonstrates that the emergence of modern symbolic representation was semantically motivated in a particular historical context of the early 19^{th} century. At that time, when scientists needed an effective semiotic tool to develop the discipline of chemistry as a modern science by ascribing the chemical properties of a substance to its elemental composition, making accurate calculations and explaining reactivity.

The functional analysis of notational signs indicates that symbolic expressions exploited a range of unique grammatical strategies to fulfil these functions, which were not found in natural language. For instance, the reactive process allowed scientists to use electrochemical theories to explain reactivity. The operative process from mathematics provided powerful resources to quantify chemical reactions. The multiple levels of rankshift made it possible to keep the elemental symbols intact as Participants at the lowest rank of a chemical formula, so that the chemical properties of a compound could be maximally ascribed to its elemental composition. In addition, it is found that the mechanism of metonymy might have functioned to extend the semantic scope of elemental symbols from simple substances in Lavoisier's empiricist account, to submicroscopic particles, and atomic weights., Hence, symbolic expressions gained the semiotic power thereby making symbolism an effective means to simultaneously approach both the qualitative and the quantitative aspects of chemical reactions in the most economical way. This of course offers great affordance to the chemist, whilst potentially misleading the novice students about the sense in which a compound might be understood to 'contain' the elements (Taber, 2012).

This research also examines the limitations of symbolic representation. It is shown that Berzelian symbolism lacks visual-spatial resources to build submicroscopic theoretical models because of its highly condensed structure, and thus is less effective than modern structural formulae to reveal the particulate nature of organic compounds. Yet, the condensed form of symbolism has never been (and will not be) excluded from the symbolic representation of organic compounds. One possible reason is that it has the advantage of facilitating calculations and hence functionally complements structural formulae.

Implications for teaching and learning chemistry

We have suggested above that some of the analysis we have offered relates to aspects of how chemical symbolism carries meanings which many experienced chemistry teachers will have come to implicitly understand without ever either engaging with formal ideas from semiotics or considering the historical development of the symbolism. Tacit knowledge can be very important to professional practice, such as in chemistry (Polanyi, 1962/1969). However, by its nature, implicit knowledge cannot be taken into account when teaching novices. Effective pedagogy is more likely where teachers can make aspects of their tacit knowledge explicit so that they can reflect on the nature of that knowledge and the challenges in teaching it. We hope that the analysis presented here will support teachers in reflecting on their understanding of the affordances of chemical symbolism and the ‘learning demand’ (Leach and Scott, 2002) experienced by students when meeting symbolic expressions in chemistry.

As briefly mentioned earlier, young students have two interrelated learning difficulties with the symbolic representation of chemistry. First,~~:~~ novices~~They~~ do not understand the representational convention of symbolism (Taber, 2009). Second~~, and~~ it is extraordinarily difficult for them to associate notational expressions with the submicroscopic explanation of matter (de Jong and Taber, 2014). The findings in this research carry implications for addressing the two issues.

Firstly, the present study finds that symbolic representation develops a range of unique grammatical strategies to encode specialised semantic patterns. This finding implies that the representational convention of symbolism (and other forms of technical representation) in a particular context needs to be taught and learned as a key component of the curriculum. Some learners may manage to decode the symbolism without explicit instruction (and perhaps many chemistry teachers were capable of that themselves), but this is neither an effective nor widespread means of learning. Given that technical representation like chemical symbolism does not simply store transparent meaning but exploits complex grammatical resources for producing knowledge, the representational conventions cannot be easily acquired, but have to be learned systematically. In particular, learning how to effectively engage with forms of representation should be considered equally important as learning scientific content and they are inseparable in science education (Prain and Waldrip, 2010).

The social semiotic analysis of symbolism also carries an implication about how to teach the representational convention. That is, teachers need to lay an emphasis on the functions when offering instructions on the complex convention of symbolism (and other forms of technical representation). It is reported that educators have recently attempted to help young students to familiarise themselves with symbolism by comparing it with natural language (e.g., Goodney, 2006; Restrepo and Villaveces, 2011; Cadeddu *et al*., 2014). This comparison can be productive, because Berzelian notations had a linguistic origin. However, much of the existing research tends to focus on the forms of symbolism. For instance, Nemeth (2006) compares elementary symbols to letters possibly due to their similarity in graphology, which can be problematicmay have problems nonetheless. To illustrate, the letter 'c' is one instance of the smallest unit of graphology in natural language, and it has no semantic significance in the word such as 'cow'. By contrast, the symbol 'C' carries compacted technical meanings, and it is capable of acting as a Participant in the symbolic representation of compounds such as CO. Following a functional standpoint, it might be more appropriate to compare the elementary symbols to nouns in natural language. Likewise, as discussed in the section 'Multiple levels of rankshift', if a chemical formula is considered equivalent to a noun (rather than a rankshifted clause) in natural language according to its form of graphology, it may hinder young learners' understanding of the symbolic representation of reactions.

Furthermore, this research provides a theoretical model and a meta-language to facilitate the instructions on the functions of symbolic (and other forms of) representation. This does not imply that teachers and students should learn the comprehensive theories of social semiotics like a linguist. Rather, teachers are advised to select the analytic tools such as transitivity and rank and guide students to explore how different meanings are constructed in the grammatical organisation. While this suggestion seems to make an additional learning demand, it can be feasible in teaching practice. Firstly, an analytic framework like transitivity is applicable to natural language, visual images and symbolism (Kress *et al.*, 2001; Liu, 2011; Liu and Owyong, 2011), which can not only reduce students' workload to learn technical terms, but also provides the common platform for conceptualising the different forms of representation. Secondly, pioneering studies (e.g., Williams 1995, as cited in Martin, 1999) provided evidence that under the instructor's guidance, young learners (e.g., 10-12 year old students) could attain adequate mastery of transitivity and other basic social semiotic models within a few months and successfully used them to analyse language.

It is found in this study ~~The finding~~ that chemical symbolism was historically designed to serve the function of quantifying chemistry, and the operative process was adopted from mathematics as a specialised grammatical strategy. This finding offers feasible explanations for the strong association between notations and the algorithmic aspects of chemistry. It implies that understanding the underlying mathematical meaning is a necessary yet not sufficient condition for effective engagement with a symbolic representation of chemistry. Hence, students should be encouraged and guided to practice their mathematical skills when learning chemical symbolism. On the other hand, it is important to note that chemical formulae encode varied numeric relations, and failure to recognise this may hinder students' conceptual understanding (Taskin and Bernholt, 2014). Therefore, science teachers should take this issue into account and endeavour to provide students with explicit instructions. For instance, teaching materials need to be designed to clarify the semantic patterns of different positional notations in chemical formulae such as coefficients (denoting the number of molecules and atoms) and subscripts (denoting the number of atoms and the reaction ratio between different atoms).

Apart from the operative process, this research demonstrates that Berzelian formulae also deployed the reactive process to represent the chemical interaction between elemental constituents in a compound. This finding has implications for the discussion on the question "when to learn symbolic language in school"[3]. As the reactive process is a unique grammatical pattern to construe specialised meaning, students' mastery of symbolic expressions entails their understanding of the underlying theories. For example, $CaCO_3$ can be functionally conceptualised as a reduced form of the reactive process $Ca^{2+} + CO_3^{2-}$. Effective engagement with this formula, therefore, requires that young learners grasp the basics of scientific knowledge such as valence, ions, and bonding. This finding points to the needs for science teachers and textbook designers to ensure that a curriculum is properly sequenced. The chemical symbols like Ca, C, O can be introduced to novices at an earlier stage when they start on the topic of elements. However, only after students have adequately understood the theories about chemical reactivity will they be able to effectively use chemical formulae.

Finally, it is found that Berzelian symbols were limited in ability to explain the chemical properties of organic compounds and gradually evolved into structural formulae, and became supplemented by structural formulae to build submicroscopic theoretical models. This finding implies that structurally condensed symbolic representation alone is far from a sufficient teaching or learning tool for students to improve their conceptual understanding at the submicroscopic level. Instead, chemical formulae need to be integrated with other forms of representation such as structural formulae, technical diagrams, three-dimensional models and computer stimulation to explore the particulate nature of matter. This reflects other calls to develop learners' use of multiple forms of representation in learning science (Tytler *et al.*, 2013). Under the teacher's guidance, young learners should be encouraged to compare the different functions of the varied forms of representation and be trained to translate or make semiotic shifts from one form to another. This training facilitates students' ability to set up semantic links between the different forms of signs employed to represent the same target. With adequate experience, students will be less likely to remain stuck in the 'literal' meaning (e.g., the elemental composition, the reaction ratio) of the individual form (e.g., C_6H_6). Rather, they may successfully relate it to other forms (e.g., the hexagonal model) and the underlying submicroscopic explanation.

Conclusion

This study is meant to take a modest step towards the dialogue between linguists, semioticians, and chemistry education researchers and practitioners. For linguists, the unique grammatical patterns of chemical symbolism such as the reactive process and the multiple levels of rankshift found and demonstrated in the present study provide a ‘satellite view’ of language (Kress, 2010, p.15). In other words, only when language is viewed as one among multiple modes of communication can a linguist gain a clearer account of its grammatical features and functional specialisation and understand why natural language alone could not be employed as an effective semiotic tool to facilitate the transformation of chemistry into a modern science in the 19th century.

On the other hand, semioticians, whose research area includes notational systems, often find the existing models too programmatic to analyse multimodal representation like chemical formulae (Tang and Moje, 2010). Based on the shared meaning-making principle (Kress *et al*., 2001) underlying both natural language and chemical symbolism and the fact that Berzelian symbolism grew out of natural language (Crosland, 1962), this study introduces the frameworks of transitivity and ranks from the original field of linguistics to offer an account of symbolic representation. These frameworks have been shown to be effective in illustrating the semiotic landscape of symbolism through the analysis presented above.

Social semiotics also offers chemistry education researchers and practitioners a clear lens through which the structural and semantic complexity of a seemingly simple symbolic representation can be analysed and illustrated. The findings in this study point to the needs for teachers and textbook designers to realise that the different forms of representation in chemistry have specialised but complementary functions and to recognise the significance of semiotic design for young learners' conceptual development. Yet how a particular instance of semiotic design affects students' learning outcomes needs to be addressed by further research to which linguists, semioticians, and chemistry education researchers and practitioners can all make joint contributions.

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Endnotes:

1. According to Halliday and Matthiessen (2004), a word group differs from a phrase in their internal semantic configurations. A phrase has two or more semantic cores, which have different functions and make equally important contributions to the whole unit. For instance, 'in oxygen' is a phrase where the preposition 'in' acts as the semantic role of [Minor] Process and the noun 'oxygen' as [Minor] Range from a social semiotic perspective, and the whole semantic configuration is similar to that of a clause. By contrast, a word group expands from a central word, which is the semantic core. For example, 'chemistry books' is a word group in which 'books' is the central word modified by 'chemistry' because chemistry books are a kind of books (super-ordination). In a similar vein, the name for compounds like 'magnesium oxide' tends to be identified by non-experts as a word group where 'magnesium' functions as the classifier word and 'oxide' as the head although scientists prefer to consider 'magnesium oxide' a symmetrical term because chemically there is no reason to prioritise 'oxide'. This study analyses terms like 'magnesium oxide' as word groups for two main purposes. First, this kind of analysis is similar to novice learners' understanding of compounds and their names and is closely related to their misconception that there is always a more active reactant in chemical reactions (Taber and García-Franco, 2010). It also demonstrates that natural language lacks the sufficient resource to maintain the co-equal relation between elements in a compound, which, however, can be symbolically represented (more details can be found in the section 'The emergence of the reactive process'). Also noteworthy is that a word group like 'burns' may consist of one word, which needs to be the semantic core.

2. Space constraint makes it impossible to offer a full account of these process types, and we only explain about them briefly following Halliday and Matthiessen (2004). The mental process is the resource to represent feeling, wanting, seeing, and thinking (e.g., “Some students like chemistry”). The verbal process construes the experience of saying (e.g., “The teacher told the students a story about the Periodic Table”). The behavioural process is the resource to represent (typically human) physiological and psychological behaviour (e.g., “The teacher coughed in class”). The existential process construes the experience that something exists and is typically represented in the grammatical configuration of “there be…” (e.g., “There are more than 100 elements in the universe”). These process types and their corresponding domains of experience, however, cannot be represented in the grammar of symbolic expressions that have been developed in chemistry.

3. This question was raised by a reviewer of this article.

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