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Developing an approach for teaching and learning about Lewis structures

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ABSTRACT
This study explores first-year university students' reasoning as they learn to draw Lewis structures. We also present a theoretical account of the formal procedure commonly taught for drawing these structures. Students' discussions during problem-solving activities were video recorded and detailed analyses of the discussions were made through the use of practical epistemology analysis (PEA). Our results show that the formal procedure was central for drawing Lewis structures, but its use varied depending on situational aspects. Commonly, the use of individual steps of the formal procedure was contingent on experiences of chemical structures, and other information such as the characteristics of the problem given. The analysis revealed a number of patterns in how students constructed, checked and modified the structure in relation to the formal procedure and the situational aspects. We suggest that explicitly teaching the formal procedure as a process of constructing, checking and modifying might be helpful for students learning to draw Lewis structures. By doing so, the students may learn to check the accuracy of the generated structure not only in relation to the octet rule and formal charge, but also to other experiences that are not explicitly included in the formal procedure.

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Chemistry education; problem-solving; Lewis structures

Introduction

In this study, we present detailed analyses of the processes through which first-year university students learn to draw Lewis structures during problem-solving activities. As part of these analyses, we introduce a theoretical account of the procedure for drawing Lewis structures taught in introductory chemistry courses. Through this combined theoretical and empirical work, we aim to contribute to an understanding of how the steps of the formal procedure interact with each other as well as with different experiences actualised by the students in their reasoning, such as knowledge of chemical concepts, processes and properties. Such an understanding is vital for suggesting improvements to the teaching of Lewis structure.

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Lewis structures have an important role in the communication and visualisation of chemical processes, structures and phenomena. This simple representation is a basic tool for chemists for predicting the geometry and some physical properties of chemical compounds, as well as for explaining their reactivity. Thus, developing an ability to draw this representation, understand its dimensionality and how it may be used is a fundamental aspect of becoming a professional chemist. Because of this, Lewis structures are emphasised as a significant content already at the introductory level in courses involving chemical structure and bonding (Tro, 2011; Zumdahl & Zumdahl, 2007).

Generally, learning and teaching Lewis structures have been procedural. As seen through a large body of research literature and textbooks, it is commonly introduced to students in the form of a step-by-step procedure for drawing these structures (e.g. Ahmad & Omar, 1992; Ahmad & Zakaria, 2000; Miburo, 1998; Nassiff & Czerwinski, 2015). In its details, this procedure may appear in different ways in different textbooks, but it commonly includes some basic steps. A typical procedure thus involves summing up the valence electrons, determining the central atom which is the least electronegative, drawing the skeletal structure showing the positions of the atoms, adding electron pairs for completing the octet rule for all atoms and finally calculating the formal charge.

However, drawing this representation and using it for deriving useful information about the molecules have long been recognised as challenging tasks for the students (Ahmad & Omar, 1992; Brady, Milbury-Steen, & Burmeister, 1990; Cooper, Grove, Underwood, & Klymkowsky, 2010; Nicoll, 2003; Pardo, 1989; Shane & Bodner, 2006; Shultz & Gere, 2015). Students are usually able to draw Lewis structures of simple molecules but the more complex the molecules get, the greater the challenges in constructing accurate structures (Ahmad & Omar, 1992; Cooper et al., 2010; Pardo, 1989). Especially, the choice of the central atom and completing the octet rule seem to be challenging for the students (Ahmad & Omar, 1992; Brady et al., 1990; Nicoll, 2003; Pardo, 1989). Students also have difficulty in determining the number of bonds in the structure, tending either to form too many bonds or to 'run out' of electrons with which to form bonds (Nassiff & Czerwinski, 2015). When dealing with structures with multiple bonds, students tend to form less bonds than required which leads to a structure with less than an octet (Pardo, 1989). This was particularly observed by Cooper et al. (2010) concerning oxygen and nitrogen. In their study, students' generated structures showed that nitrogen and oxygen either had electron deficiency or expanded octet. The students also 'missed' taking account of the positive or negative charge of the molecule when calculating the valence electrons, instead adding it at the end, thereby generating a radical. Miscalculation of the formal charge is an additional problem reported in the literature when drawing Lewis structures which results in high formal charges (e.g. Pardo, 1989). Moreover, students have to deal with many exceptions such as when certain elements (such as third period elements) can exceed the octet rule (Malerich, 1987; Suidan, Badenhoop, Glendening, & Weinhold, 1995). Then, students end by using 'trial and error' for drawing the correct structure (Ahmad & Omar, 1992).

As a way for abridging and simplifying the process of drawing Lewis structures, a considerable body of research suggested methods or improved procedures in different ways for making this process more manageable (e.g. Ahmad & Omar, 1992; Brady et al., 1990;

Miburo, 1998; Nassiff & Czerwinski, 2015; Pardo, 1989; Purser, 2001). Most of these efforts focus on changes in some parts of the formal procedure. For instance, Nassiff and Czerwinski (2015) suggested providing students with the correct skeletal structure due to beginning students' limited experience in determining the correct positions of the atoms. They also suggested that students should complete the octet on each atom instead of initially completing the octet on the terminal atoms. However, several scholars have argued that the problem goes much deeper than this. It seems as if students rely on memorisation rather than understanding the rules of the procedural approach for drawing Lewis structures (Cooper et al., 2010; Shultz & Gere, 2015). This, in turn, is likely due to the fact that they have not yet developed an extensive base of experiences of chemical compounds and structures (Kozma & Russell, 1997). In short, students in these early stages of their studies lack the practice that experts had through series of manipulations, successful and unsuccessful, in generating chemical representations of different kinds. As a consequence, students rely on following the procedure more or less mechanically.

Apparently, then, a central problem for students as they learn to draw Lewis structures is that additional information is often required to complete the task, that this information is usually not explicitly made part of teaching the formal procedure and, thus, that students often do not have access to it (Cooper et al., 2010). This information, moreover, obviously needs to be connected to the formal procedure in different ways. An important question is therefore what kind of additional information students need for drawing Lewis structures, and how they may learn to use this information in the practice of drawing these structures, that is, in connection to the formal procedure. This is, we argue, both a theoretical and an empirical question. Theoretically, it concerns how we may conceptualise the formal procedure in ways that makes it easier for students to learn. Empirically, we need to better understand the details of how students deal with the procedure and its relation to other experiences in the actual activity of drawing Lewis structures in relation to specific settings and the often contingent routes that learning takes (Hamza & Wickman, 2009; Wickman & Östman, 2002).

Our research questions are:

(1) How do students employ the different steps of the formal procedure as they engage in drawing Lewis structures during problem-solving activities?
(2) How do the different steps interact with each other and with other experiences that the students invoke as they engage in drawing Lewis structures?

Theorising the procedure of drawing Lewis structure

The step-by-step procedure for drawing Lewis structures can be found in virtually every chemistry textbook (e.g. Atkins & Beran, 1992; Atkins & Jones, 2005; Burns, 1999; Tro, 2011; Zumdahl, 1996; Zumdahl & Zumdahl, 2007), and is also present in the research literature (e.g. Ahmad & Omar, 1992; Ahmad & Zakaria, 2000; Nassiff & Czerwinski, 2015; Packer & Woodgate, 1991). It typically contains a sequence of steps which, although differing in number and details, share basic characteristics. This is, of course, because the procedures reflect a set of underlying principles that are based on shared knowledge within the chemistry community. To illustrate this, we present three different procedures, two procedures drawn from textbooks in chemistry and one procedure from an article.

As can be seen in Table 1, the procedures are similar to a large extent concerning where the main steps appear in the each procedure. However, some discrepancies can be found in the order of the steps and how detailed and comprehensive the different steps are. Moreover, individual steps, such as the formal charge, are not included in all procedures.

Then, by a closer examination of these and other versions of the procedure for drawing Lewis structures, it is possible to distinguish three main components common to these procedures. At first, there is an initial element of *construction*: Construct a Lewis structure by calculating the total number of valence electrons, draw the skeletal structure and distribute remaining electrons. Second, there is more or less implicitly an element of *checking* the structure: Check the accuracy of the structure mainly in relation to the octet rule and, in some instances, to formal charge on the different atoms. If this check turns out well, the structure is correct and the process is completed. However, if the check indicates inaccuracies, then a third element is invoked, namely *modification*: Modify the structure by moving electron pairs to form multiple bonds. It is obvious from a reading of the texts that this reconstruction is expected to go on until the check confirms the suggested structure and distribution of bonds. However, it is equally evident that this iterative process is almost always presented implicitly, usually through a series of examples (cf. Zumdahl & Zumdahl, 2007).

Table 1. Three procedures for drawing Lewis structures presented, one column for each procedure.

Procedure 1 Tro (2011)	Procedure 2 Zumdahl and Zumdahl (2007)	Procedure 3 Ahmad and Omar (1992)
(1) Write the correct skeletal structure for the molecule. Two guidelines to consider: first, hydrogen atoms are always terminal and second, the more electronegative atoms in terminal positions.	(2) Use a pair of electrons to form a single bond between each pair of bound atoms.	(2) Construct a skeletal structure by drawing a single bond that connects the central atom to each terminal atom. (1) Choose a central atom which is the least electronegative.
(2) Calculate the total number of valence electrons of all atoms in the molecule.	(1) Sum up the valence electrons from all the atoms in the molecule.	
(3) Distribute the electrons among the atoms giving octets (or duets in the case of hydrogen) to as many atoms as possible. Start with the bonding electrons and then the lone pairs on terminal and lastly lone pairs on the central atom.	(3) Arrange the remaining electrons to satisfy the duet rule for hydrogen and the octet rule for the second-row elements.	(3) Add unshared electron pairs to complete the octet rule on each terminal atom.
(4) If any atom lacks an octet, form double or triple bonds as necessary to complete the octet by moving lone pairs to form bonds.	(5) If the number of electrons is not correct or the octet is not fulfilled, then move lone pairs to form multiple bonds.	(4) Try to complete the octet rule on the central atom, if it is not complete, by moving unshared electrons from the terminal atoms to form multiple bonds.
	(4) Then the authors pose the question: Is the structure correct? In order to answer this question: Check (a) the total number of valence electrons and (b) the octet rule for each atom.	
		(5) Calculate the formal charge. As far as possible, zero (or minimum) formal charge should be achieved by converting one or more unshared electron pairs into bonding pair.

Note: The corresponding steps from each procedure are presented in the same row.

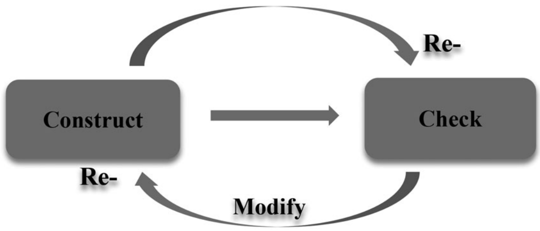


Figure 1. A model of the general procedure for drawing Lewis structures.

Consequently, the different procedures found in the literature may be modelled as all consisting of a pattern of three central elements or phases, namely construct, check, and modify through additional reconstruction and rechecking. The first two elements, moreover, may be considered to ideally constitute an initial, more or less linear phase of the procedure, whereas the last element, modification, may be seen as an iterative phase of reconstruction and rechecking.

As can be seen in Figure 1, the sequence of rechecking and reconstructing could be iterated until a structure that fulfils both the octet rule on all atoms and minimised formal charge is achieved.

The usefulness of the presented model for how the formal procedure may be conceptualised is that it may help us perceive the challenges that students face in learning to draw Lewis structures in a more coherent and structured way. In addition, the model is able to account for challenges that are already known from the literature. The conceptualisation is further elaborated in the analytical approach, as it is converted to an analytic tool for investigating how students used the formal procedure and how the different steps of the procedure interacted with other information invoked by the students.

Methodology

Setting and data collection

The study was conducted on undergraduate students enrolled in an introductory chemistry course at a Swedish university. The introductory chemistry course includes four modules: equilibrium, structural chemistry, reactivity and biochemistry. It provides a broad introduction to physical, inorganic, organic and biochemistry. Each module includes a set of lectures, laboratory work and problem-solving classes. The empirical material was drawn from problem-solving classes from two of the four modules: structural chemistry and reactivity which the students attended after the initial equilibrium module. Four pairs of students, who voluntarily participated in this study, were audio and video recorded on two different occasions resulting in eight sessions of discussions of problem-solving. As our intention was to examine students' learning in authentic environment, no specific instructions were provided before and during the data collection. The students were solving problems given in a handout provided in the course. In the structural chemistry module, the answers to the problems were provided in the same handout. Additional material available was Nuffield advanced Science: book of data and a book in general chemistry (Burrows, Holman, Parsons, Pilling, & Price, 2013). The book of data contains physics and chemistry data suitable for all A Level Physics and

Chemistry students. It includes formulas, equations and tables of physical and thermochemical properties of elements, inorganic compounds, and organic compounds. Teacher assistants were available as usual in these activities mainly for providing support to the students if they needed it.

The problems discussed were:

(1) Determine the oxidation numbers of the atoms in the following molecules. In some cases, different models are listed. HSO_4^-, PO_4^{3-}, NO_3^-, NH_4^+, HF, $Fe(CN)_6^{4-}$, MoO_4^{2-}, H_2O_2
(2) Draw Lewis structures and determine the formal charge for all atoms as well as determine the hybridisation of the central atom in following molecules. SO_4^{2-}, NH_3, C_3H_8, CO_2, CO_3^{2-}, HSO_3^-, SF_6
(3) Draw Lewis structures comprising all the resonance forms (all you can come up with) for the following molecules. C_6H_6, NO_3^-, CO_3^{2-}, SO_4^{2-}

The answers to these problems were provided in the same handout. The answers to all problems included the Lewis structures of the different molecules. The students turned to the answers provided only after they had first tried to solve the problems on their own, as a way of checking their answers. Since the purpose of the present study was to investigate how students go about drawing Lewis structures as part of problem-solving activities, all data analysed came from passages where the students dealt with these structures before they turned to the answers provided in the handout.

Empirical data consisted of students' conversations, the student-generated diagrams of Lewis structures as well as other sketches produced during these conversations (e.g. Kindfield, 1993/1994; Rundgren, Chang Rundgren, & Schönborn, 2010). Student conversations were video and audio recorded and subsequently transcribed verbatim. The student-generated diagrams were collected and reproduced from the video recordings. Thorough and repeated readings of all transcripts were made. This was followed by a detailed analysis of 16 instances of students' discussions concerning the students' actions when drawing Lewis structures.

The first author conducted all initial analyses. These analyses were then discussed and further analysed among the authors on multiple occasions until agreement was reached. Finally, the findings were also discussed with an independent researcher at the department for additional confirmation of the quality of the analysis.

The formal procedure taught in the course

The formal procedure introduced to students that were part of this study is basically similar to other common procedures presented in the literature and general chemistry books. As most of these procedures, it relies on completing the octet rule and achieving minimised formal charge. It was presented to students in a lecture through the molecules of CO_2, N_2O and SO_4^{2-}. The students were taking notes during the lecture. The steps were as follows:

(1) Calculate the total number of valence electrons in the molecule, including the charge

(2) Draw the skeletal structure which connects the different atoms together with single bonds.
(3) Distribute the remaining electron pairs on the different atoms to fulfil the octet rule
(4) Check if the octet is complete, if not consider moving lone pairs to form multiple (double or triple) bonds
(5) Lastly, calculate the formal charge

The students were also taught through examples that steps 4 and 5 could be repeated until a structure that fulfils the octet rule on all atoms and minimised formal charge is achieved.

The teacher demonstrated the steps for drawing Lewis structure of CO_2 as follows:

Step 1 – The sum of valence electrons $\underset{\text{C}}{4}+2\cdot\underset{\text{O}}{6}+\underset{\text{overall charge}}{0}= 16\ e^{-} \rightarrow 8$ pairs

Step 2 – The skeletal structure was as follows: O—C—O

Steps 3 and 4 were completed simultaneously where all electrons were distributed as double bonds and lone pairs to fulfil the octet on all atoms $\langle O{=}C{=}O\rangle$

Step 5 – The formal charge was calculated for all atoms. $\langle\overset{0}{O}{=}\overset{0}{C}{=}\overset{0}{O}\rangle$

Then the teacher carried on by drawing another skeletal structure for CO_2 as a way for showing the students how to evaluate this Lewis structure in relation to the octet rule and formal charge.

Step 2 – C—O—O

Steps 3 and 4 were completed simultaneously attaining the structure $\langle C{=}O{=}O\rangle$

Step 5 – The formal charges was calculated for all atoms $\langle\overset{-2}{C}{=}\overset{+2}{O}{=}\overset{0}{O}\rangle$

This procedure fits neatly into the model that we described earlier (Figure 1). At first, *construct* the structure by following steps 1–3, then *check* the octet rule (step 4); if it is complete, calculate the formal charge (step 5). But if the octet is not complete, *modify* the structure by moving electron pairs to form multiple bonds. Then again, check the octet and calculate the formal charge (steps 4–5).

Operationalisation of the model for drawing Lewis structures

Our interest was to analyse in detail how students employ the different steps of the formal procedure and how these steps interact with other experiences that the students may draw upon when drawing Lewis structures. In order to accomplish this task, we operationalised the theoretical model of the formal procedure presented in Figure 1 for a systematic description of the sequence of the steps of the formal procedure and their interaction with other experiences. Figure 2 summarises the developed model in relation to the formal procedure and other experiences. The construction phase consists of steps 1–3 of the formal procedure. This phase is followed by a checking phase of steps 4 and 5. When the octet is not fulfilled (step 4), a modification is considered. This modification is in the form of reconstruction (step 3) and a recheck (steps 4 and 5). The modification phase is iterative since it could be repeated until all atoms are given full octet and minimised formal charge. We also used the model to explore how other experiences interacted with the formal procedure (Figure 2). Figure 2 also shows how the model may be

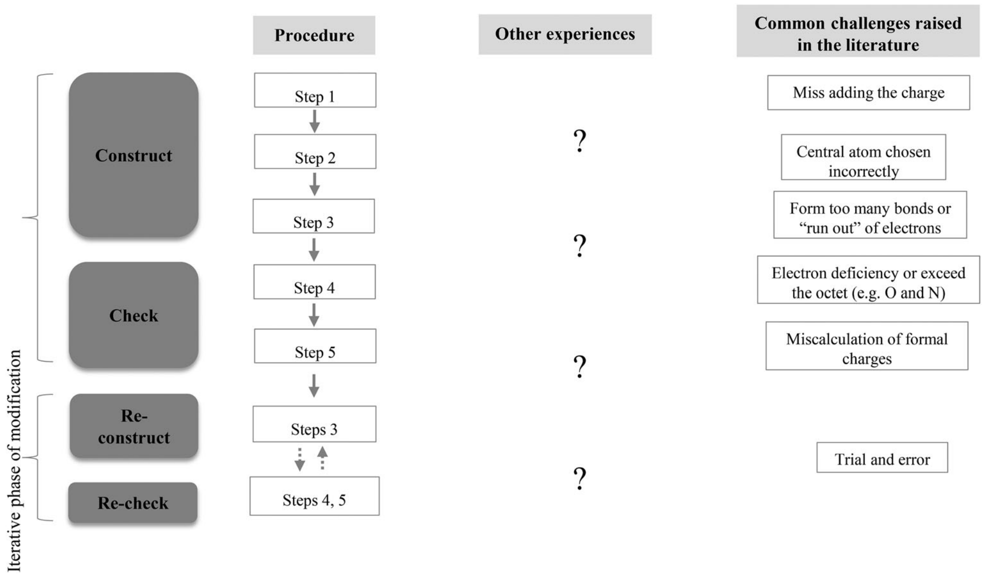


Figure 2. The operationalised model of drawing Lewis structures in relation to the steps of the formal procedure and common challenges raised in the literature.

employed to categorise challenges already known from the literature as a way of adding support to its usefulness as an analytic tool for the purposes of the present study.

Analytical approach

In this study, we were interested in analysing in detail students' actions for drawing Lewis structures during authentic problem-solving activities. Thus, we needed to conduct the analysis in relation to the particular setting which the students were part of, which in this case included the actual assignments given in the problem-solving activity and the expectation that the students employ the formal procedure taught in the course. Moreover, we wanted to see how student actions concerning this formal procedure interacted with other knowledge and experiences drawn upon during the conversations. Thus, the unit of analysis is students' actions as part of a specific activity (Wertsch, 1993).

Practical epistemology analysis (PEA) was developed by Wickman and Östman (2002) for analysing how the different parts of an activity interact in students' actions, and how these interactions lead students' reasoning in different directions. This analytical tool is based on Dewey's principle of continuity of experience (1938/1997) and sociocultural perspective on learning (e.g. Harré & Gillet, 1994; Wertsch, del Río, & Alvarez, 1995). The point of departure of practical epistemology (PEA) analysis is the purpose of the activity as carried out by the individuals involved. Here, the overarching purpose was to draw Lewis structures of different molecules. PEA includes four operational concepts: *encounter*, *stand fast*, *relation* and *gap* (Wickman & Östman, 2002). Individuals *encounter* each other and the environment (e.g. textbook, students' diagrams) and in a way that it influences the individuals' actions towards other individuals and towards the environment. In these encounters, *gaps* occur constantly. Gaps may be filled with *relations* to what *stands* *fast* (i.e. not questioned by the participants). For instance, if the gap 'What is the total number of valence electrons of CO_2?' is noticed, it could be filled with relations to the number of valence electrons of carbon and hydrogen, provided that valence electrons and hydrogen stand fast in the conversation, that is, no one questions the use of these words. When individuals succeed to fill a gap by establishing relations to previous experiences the activity will carry on. However, the students may notice gaps and fail to fill them with relations. In these cases, the gap is said to linger and the activity will be interrupted. So, the progress of the activity depends on which gaps that are noticed and how they are filled with relations. Gaps that are not filled in a certain encounter may be filled in upcoming ones (Wickman & Östman, 2002).

Through the different gaps and relations that the students established, we identified the individual steps of the formal procedure and other experiences when drawing Lewis structures. This analysis enabled us to describe in detail how students used the steps of the formal procedure in interaction with other experiences. By combining this analysis with the theoretical model of the formal procedure (Figure 2), we could describe systematically how students constructed, checked and modified the structure in relation to the formal procedure and other experiences. Moreover, through this procedure, we were able to identify important gaps that were not noticed by the students.

We illustrate this analytical approach through the following example:

Adrian and Linus were engaged in drawing Lewis structure of SO_4^{2-}. The following excerpt is part of a longer discussion when drawing this structure.

1. Adrian: Draw Lewis structure and determine the formal charge for all atoms as well as determine the hybridisation of the central atom in the following molecules [reading problem 2 in the handout], SO_4^{2-}
   [Browse in their notepads]
2. Linus: We look at valence electrons … oxygen has 6 valence electrons … 4 times 6 plus [writing in his notepad] … sulphur … [Looks at the periodic table on the wall] it should be …
3. Adrian: The periodic table is here [shows in the book of data]
4. Linus: Yeah but you can see it here [looks at the periodic table on the wall] … 4 … 8 maybe
5. Adrian: It's 6
6. Linus: Is it 6?
7. Adrian: I think so … yeah cause … don't you remember S1F6 [in problem 2]
8. Linus: Yeah right … then it's totally 4 times 6 plus 6, 30 [using a calculator] 30 electrons, and it's 15 electron pairs

The excerpt began with a relation to the purpose of the activity which is drawing Lewis structure of SO_4^{2-} [Line 1]. Initially, the students need to construct the structure (Figure 2). In order to do that, they began with calculating the total number of valence electrons in the structure, step 1 [Line 2]. Consequently, a gap concerning the number of valence electrons sulphur has, was noticed [Line 2]. In order to fill this gap, several relations were established. First, a relation to the periodic table [Lines 3 and 4] followed by the relations '4 … maybe 8' [Line 4] and 'it's 6' [Line 5]. This led to the re-emergence of the gap [Line 5]. In order to fill the gap, a relation to the molecule of SF_6 that they encountered earlier in the same problem-solving activity was established [Line 7]. As they succeeded filling the gap, the students could complete the first step in the formal procedure [Line 8].

As the example illustrates, the students initiated the construction phase by carrying out step 1. During the process, the students noticed gaps and filled them with relations. However, the gap regarding the charge of the molecule was left unnoticed. The students did not count in the charge of the molecule when calculating the total number of valence electrons. Consequently, they counted 15 electron pairs to distribute while it should be 16. In this way, we observed not only gaps noticed and filled with relations but also gaps that the students failed to notice or failed to fill.

The transcripts involved molecules that were discussed more or less exhaustively by the students. Molecules that generated considerable discussions among the students were CO_3^{2-}, NO_3^- and HSO_3^- as they included multiple bonds. The molecules of SO_4^{2-}, and NH_3 were also discussed by the students but to a lesser extent, as these structures were introduced to students in a lecture. Finally, as drawing Lewis structures that includes only single bonds (e.g. C_3H_8 and SF_6) was hardly an issue for the students to draw, no discussions revolved around these structures. In the end, a total number of 16 instances in which students dealt exhaustively with drawing Lewis structures emerged from the data. These were examined in further detail to explore the development of drawing Lewis structures in relation to the pattern described. In the next section, we present five representative examples from the 16 analysed in detail. The issues that arose in these five examples are representative of the 16 cases.

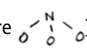
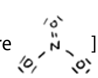
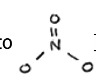
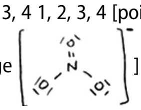
Results

A general observation through students' conversations was that although the formal procedure taught in the course was central for drawing Lewis structure, its use was dependent on several situational aspects. Commonly, the use of the individual steps of the formal procedure was contingent on experiences of chemical structures, and other information such as the characteristics of the problem given. The students typically constructed, checked and sometimes modified the structure in relation to the formal procedure and the situational aspects.

The five examples illustrate different patterns in the use of individual steps of the formal procedure and their interaction with other experiences.

Example 1

Example 1 illustrates how our students both constructed and checked the Lewis structure in relation to the formal procedure as well as to other experiences. They constructed the structure by carrying out steps 1 to 3 and then they checked its accuracy in relation to step 4 and other features of familiar structures. The Lewis structure of NO_3^- and its resonance form were discussed (problem 3).

1 Leo: Is it nitrate ion, is it? 1 2 3 [drawing the skeletal structure ] … or is it a double bond?
2 Kevin: It's 24 [the total of valence electrons], 12 pairs
3 Leo: 24?! nitrogen is 5 [valence electrons], 6 [counting in the charge]
4 Kevin: 6 times 4, 24 [calculating the valence electrons]
5 Leo: Yeah 24, it might be double [bond]
6 Kevin: Yeah probably … it has to be a double bond because it's resonance [drew the structure ]
7 Leo: Mm [changed the initial structure to ] but it's so strange, nitrogen would only take
8 Kevin: Nitrogen would take four [bonds], like this, 1, 2, 3, 4, 1, 2, 3, 4 1, 2, 3, 4 [pointing at the electron pairs around each oxygen, then added square bracket and the charge ] it should be correct
9 Leo: Right, cause it can … it needs only three to

10 Kevin: Is there something wrong?
11 Leo: No, it should be correct but … I'm just confused because I'm thinking that nitrogen would take, that it can take three electrons but it's wrong cause … it's oxygen who is the oxidant here, so it doesn't matter but it [nitrogen] can only take three electrons
12 Kevin: we could use something less [electronegative] … .
13 Leo: Yeah like hydrogen, ammonia … Let's check if hydrogen has less than nitrogen … 2.1 … where is nitrogen? [Searching for the electronegativity values in the book of data] oxygen has 3.5, hydrogen has 2.1 and nitrogen has 3.0 … it should be correct

The students started by constructing the structure of the nitrate ion, steps 1 to 3. To begin with, they drew the skeletal structure that showed the positions of the different atoms in the molecule, step 2 [Line 1]. Consequently, a gap regarding the presence of a double bond in the structure was noticed. Leo and Kevin carried on with the process by establishing a relation to step 1 of the formal procedure, namely calculating the total number of valence electrons in the molecule [Lines 2–5]. In order to fill the gap noticed earlier, the students established a relation to resonance. This concept was part of the purpose of the activity by figuring in the formulation of problem 3 [Line 6]. Here, resonance was invoked as a clue indicating the presence of a double bond. Consequently, an addition of a double bond was made followed by distribution of the remaining electron pairs in the structure according to step 3 [Line 6]. Leo did the same through a revision of the initial structure [Line 7]. After constructing the structure, Kevin checked its accuracy by carrying out step 4 which involves the fulfilment of the octet rule [Line 8]. Although the octet rule turned out to be fulfilled, this check seemed not to be enough for the students. This can be seen through the consequent gap noticed [Lines 7, 9]. Then another check was made through a relation to the electronegativity values of hydrogen in NH_3 compared to oxygen and nitrogen in NO_3^-. As a result, the students confirmed the structure with no need for a modification.

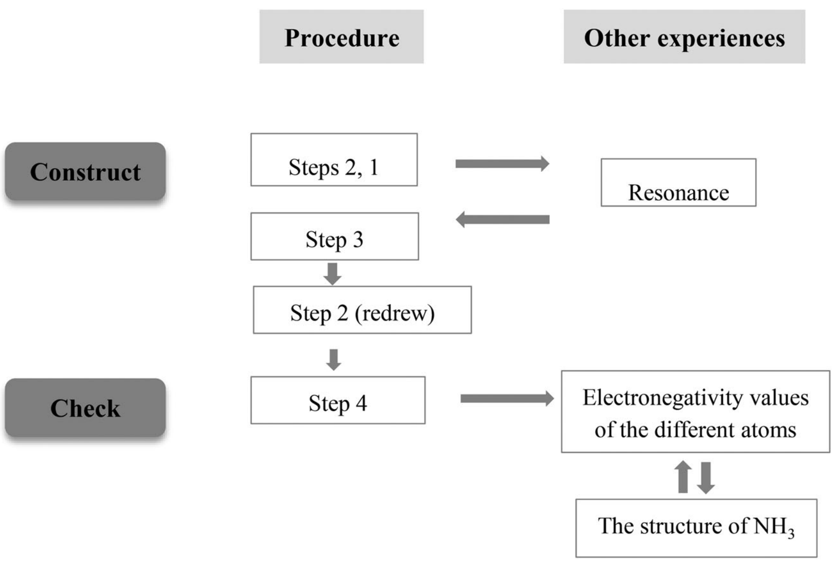
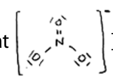


Figure 3. The pattern of drawing Lewis structure in relation to the formal procedure and other experiences.

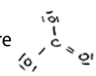
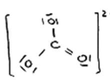
As we can see in Figure 3, the steps of the formal procedure were used and interacted with other experiences, such as resonance and the structure of NH_3, for constructing and checking the structure. The students constructed the structure by following steps 1–3 of the formal procedure. However, the steps were not mobilised sequentially. Moreover, another experience, that of resonance aided the students constructing the structure. The checking phase consisted only of the octet rule (step 4) derived from the formal procedure, whereas step 5, formal charge, was not employed by the students. Step 4, moreover, was conducted in interaction with two other experiences, the electronegativity differences of oxygen and nitrogen in analogy to hydrogen in NH_3. There was no modification phase (Figure 3), since the checking phase turned out well. Another point to note is that the relation to resonance stood in direct conflict with the students' earlier experience regarding the number of bonds nitrogen could form, namely three (NH_3) which generated the gaps in lines 7 and 9. Thus, the need for checking the accuracy of the structure in relation to another experience than the procedure was required.

Example 2

As in example 1, Diana and Frida in example 2 used the steps of the formal procedure together with other experiences when drawing Lewis structure of CO_3^{2-}. However, this was true only for the checking phase. The construction phase, on the other hand, was completely accomplished through an analogy to a familiar structure (Figure 4). As the purpose of the activity was to draw Lewis structure of carbonate ion, CO_3^{2-} (Problem 2), the students established several relations to features of the familiar structures of NO_3^- and NH_3 which they had drawn before in the same problem-solving activity.

14 Diana: Now it's CO_3^{2-}. It's the same thing but with carbon instead [pointing at ]

[They carried on drawing the structure]

15 Frida: it's exactly the same thing [generated the Lewis structure 
16 Diana: But with carbon
17 Frida: But
18 Diana: 2- should be [Drew ]
19 Frida: I was wondering [unclear] … aha these two become 2- [pointing at the oxygen atoms that are single bonded to carbon in the structure]
20 Diana: Why not this one 2- [Pointing at NO_3^-] … it's only 1-. Let's check it out [Browse in her notepad]
21 Frida: Because there are, there are 12 pairs [counted the total number of electron pairs in the structure of nitrate ion] … no, what?
22 Diana: It's exactly the same only it's …
23 Frida: [Looking on the periodic table on the wall] But N has five [valence electrons] and C has four [valence electrons]
24 Diana: Yeah N has, N can actually … three, like, it was this … that it can bind to three [pointing at the structure of NH_3 in her notepad] but it can bind to four, it could be this … if you have four so … since this one [pointing at NH_3] is actually neutral, it has a charge of zero, if you add one more [bond] here [pointing at the nitrogen atom in NH_3] … add one more, yeah

The students constructed the structure of CO_3^{2-} directly in relation to the familiar structure of nitrate ion, NO_3^- that they drew earlier in the same problem-solving activity [Lines 14–16]. They drew the skeletal structure and distributed the electron pairs of the carbonate ion in accordance with the reference structure of nitrate ion. Then a gap regarding the charge of the carbonate ion was noticed [Line 19]. In order to fill this gap, a check was

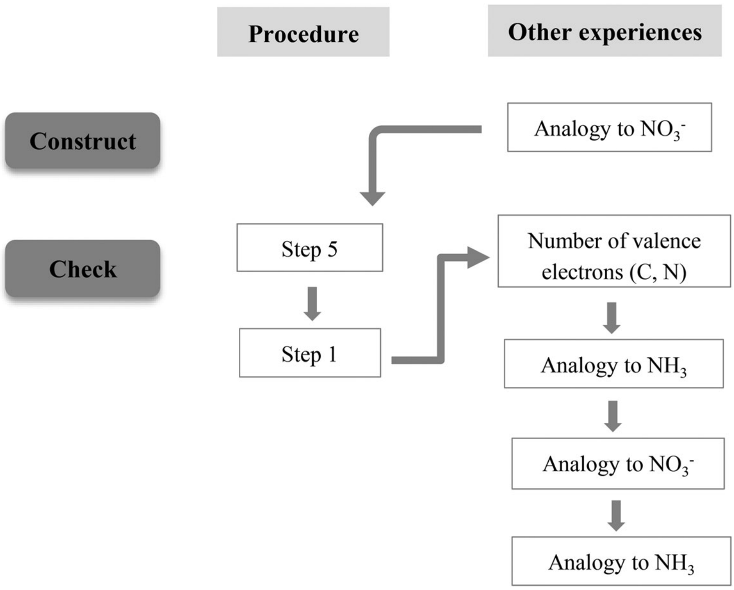


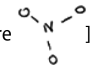
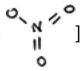
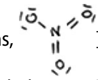
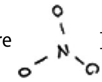
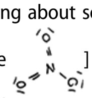
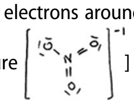
Figure 4. The pattern of drawing Lewis structure in relation to the formal procedure and other experiences.

made in relation to step 5 of the formal procedure which is calculating the formal charge [Line 19]. As a result, a second gap concerning the charge of the reference structure, NO_3^- was noticed [Line 20]. In order to fill this gap, the students turned back to step 1, calculating the number of valence electrons in the structure [Line 21] as a check and balance of electrons. This relation was followed by a relation to the difference between the valence electrons of carbon and nitrogen [Line 23] and lastly, a relation to the structure of NH_3 [Line 24]. The analogy that students made to NH_3 aided them in filling the gap related to the charge of the NO_3^-. Therefore, no modification was required.

We can see in Figure 4 that the students managed the construction phase only with an analogy to the familiar structure. As determining the skeletal structure, the distribution of electrons (bonds and lone pairs) was mobilised in relation to the reference structure of NO_3^-. The checking phase was made through individual steps of the formal procedure (steps 5 and 1) in an interaction with further analogies. However, step 1 was not mobilised here according to the formal procedure but for the purpose of checking the total number of valence electrons in relation to the reference structure. Moreover, checking the octet rule (step 4) was not carried out since it was mobilised in accordance with the reference structure. It is also important to note two things, first that the main gaps noticed were related to the formal charge. Second, the structure of the nitrate ion was used and re-actualised in the process of drawing Lewis structure of CO_3^{2-} which was seen in the second gap [Line 20]. And again, for filling this gap, an analogy to an additional structure (NH_3) was made.

Example 3

Whereas in examples 1 and 2 there was no need for a modification phase, example 3 illustrates an instance where the students failed to see that modification needed to be considered. The discussion concerned the Lewis structure of NO_3^- and its resonance forms (Problem 3).

25 Diana: Next is NO_3^- .... [started by drawing the skeletal structure ]
26 Frida: What does it look like? Diana, what does it this look like?
27 Diana: N has five four five, three four five [looking at the periodic table on the wall, then adding bonds to the structure, ] like this and like this, and like this [distributing lone pairs on oxygen atoms, ]. Here is one [Resonance form] and then we have a lone [electron pair, pointing at the single bonded oxygen]. One resonance form … isn't it just … like this, Look … [continued drawing another two resonance forms by changing the positions of the double bonds]
28 Frida: [drew the skeletal structure ] 24 plus 5 [calculating the valence electrons]
29 Diana: What did you say? 24 plus 5
30 Frida: 29 divided by 2
31 Diana: What are you doing? We're only supposed to draw the different resonance forms
32 Frida: I don't know, I like to do this, counting [Talking about something else]
33 Frida: [distributed the electron pairs in the structure ] is it just like that?
34 Diana: Yeah, I guess so, or maybe it's possible that this one [point at nitrogen atom] may have a free …
35 Frida: I'll take a look … cause we had it the other day [Browse in her notepad] [They are looking at the different resonance forms of NO_3^- in Frida's notepad from previous lecture]
36 Diana: But …
37 Frida: It doesn't matter
38 Diana: But we get 1 2 3 4 5 6 7 [pointing at the electrons around the single-bonded oxygen] we will get negative [charge] anyway [completed the structure ]
39 Frida: I counted 29 [valence electrons]
40 Diana: What is it then?
41 Frida: It's 23 [valence electrons]
42 Diana: Oh, you mean four …
43 Frida: I didn't know that … [corrected the calculation of the number of valence electrons]
44 Diana: But we have two [double bonds], why don't they have two? … right it supposed to have these [square brackets on the second resonance form], it should be …
45 Frida: it doesn't matter at all
46 Diana: well we have …
47 Frida: it doesn't matter, it's the formal charge that is moving around

Diana started immediately constructing the structure of NO_3^- by drawing the skeletal structure and distributing the electron pairs, steps 2 and 3 [Line 27]. While Frida constructed the structure by carrying out the steps 1–3 more thoroughly, she drew the skeletal structure, step 2 [Line 28], calculated the valence electrons of the molecule, step 1 [Lines 28–30] and then distributed the electron pairs in the structure, step 3 [Line 33]. A potential gap concerning the miscalculation of the total number of valence electrons was not noticed. Besides, it did not agree with the number of electrons distributed in the structure. Moreover, a gap concerning the two double bonds in the structure was not noticed either. Instead, the students carried on checking the accuracy of the generated structure. First, they checked the generated structure against the accurate structure drawn in an earlier lecture [Line 35]. Then they checked the structure in relation to the formal charge, step 5 [Line 38] and considered this as sufficient for confirming its accuracy. Subsequently, the gap regarding the miscalculation was noticed [Line 39] and immediately filled [Lines 39–42]. Then, despite that the gaps concerning the two double bonds in the

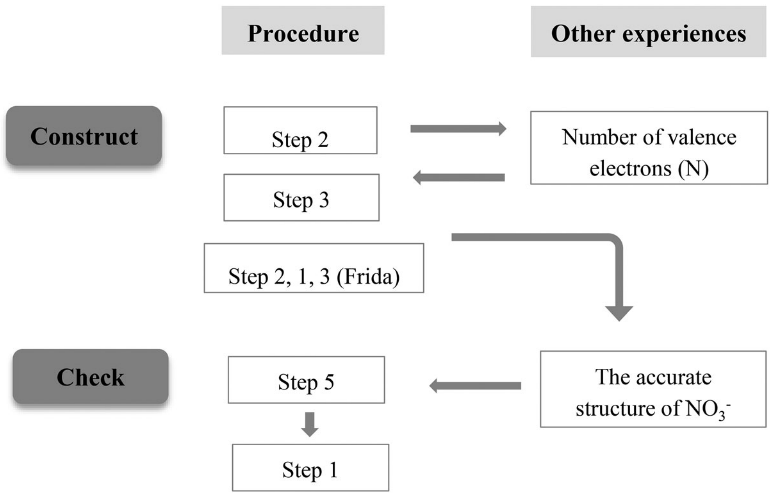


Figure 5. The pattern of drawing Lewis structure in relation to the formal procedure and other experiences.

structure were noticed [Lines 36, 44], they were filled with the unproductive relation 'it doesn't matter' [Lines 37, 35]. So, the students settled with the generated structure.

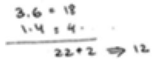
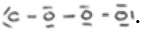
This example thus repeats several patterns present also in examples 1 and 2. As in these cases, the students constructed Lewis structure and then checked its accuracy in relation both to the steps of the formal procedure and to other experiences (Figure 5). Also similar to these two examples, the checking phase was only carried out through one of its two steps. In this case, this was done through step 5 (formal charge), whereas step 4 (octet rule) was not employed. However, unlike examples 1 and 2, here, checking only one of these steps was not sufficient. As a consequence, the students never filled the gap concerning the two double bonds in the structure [Line 44] with productive relations. This in turn explains the reason for not modifying the structure by moving a bond to lone pair. Checking the structure in relation to the octet rule (step 4) on all atoms (nitrogen in particular) might have aided the students in filling this gap.

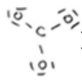
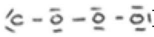
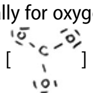
Thus far, we showed instances where drawing Lewis structure may be contingent on other experiences. In these instances, the students constructed the structure by using steps 1–3 of the formal procedure together with other experiences (examples 1 and 3) or only in relation to experiences to familiar structures (example 2). The checking phase was mainly conducted through either step 4 (example 1) or 5 (examples 2 and 3) together with experiences to familiar structures. The modification phase, finally, was not considered either because the checks, although not formally complete, still corroborated the structure (as in examples 1 and 2) or because the students would indeed have needed to check through both steps, as in example 3.

Our two last examples illustrate how students not only constructed and checked the structure but also modified it. The modification phase involved a reconstruction and recheck of the structure in an iterative manner. However, this iteration was shown to be a complex task for the students.

Example 4

In this example, the students not only constructed and checked the structure of the carbonate ion, CO_3^{2-}, but also considered modifying it. The modification was made in the form of a change of the skeletal structure. However, the unsuccessful checks only towards the octet rule (step 4) made the reconstruction phase very challenging for the students.

Before the excerpt began, Sally calculated the total number of electron pairs in the molecule as follows:  pairs (problem 2). Then she constructed the structure . Sally constructed the structure by following the steps 1–3 of the formal procedure. She calculated the number of valence electrons (step 1), drew the skeletal structure (step 2) and then distributed the electrons pairs (step 3). Then a gap concerning the way the different atoms in the carbonate ion, CO_3^{2-} are bonded to each other was noticed.

48 Alex: What are you drawing?
49 Sally: CO_3^{2-} … if we place C in the centre [drew ]
50 Alex: C has to be in the centre
51 Sally: What did you say? No, C doesn't have to be in the centre. You have to try And see what fits best
52 Alex: Of course it has to be in the centre, because oxygen is more electronegative otherwise it will be very strange, if it's straight [referring to ]
53 Sally: Why does it have to be strange?
54 Alex: Cause now you have … you have like, three oxygen that pull each other pretty hard
55 Sally: Mm
56 Alex : And carbon is there and … doesn't know what to do
57 Sally: But it has just to give away its electrons to oxygen, isn't it enough? Does it have to be in the centre?
58 Elias: [counting the electrons around each atom] the octet rule won't be fulfilled if it's [carbon] in the centre
59 Sally: No, right
60 Alex: But the octet rule can't always be fulfilled
61 Elias: But it was especially important for C, O and N
62 Alex: Yeah, it's true
63 Sally: Yeah exactly, especially for oxygen it has always to be fulfilled … the octet rule is fulfilled for oxygen anyway but not for carbon []
64 Elias: Yeah if we place carbon in the centre
65 Sally: Mm
66 Elias: I put out lone electron pairs on oxygen atoms to satisfy the octet rule [pointing at oxygen atoms in the structure at line 40]
67 Sally: No, ok
68 Elias: You can't simply satisfy the octet rule for both of them [carbon and oxygen] if we place carbon in the centre
69 Sally: No, let's try out a bit …

Before the excerpt began, Sally constructed the structure of CO_3^{2-} by following the steps 1–3 of the formal procedure in order. Immediately thereafter, she modified the structure by constructing another structure where carbon is the central atom [Line 49]. Most probably, Sally checked the accuracy of the structure in relation to the octet rule (step 4) which apparently was not fulfilled. Therefore, she reconstructed the structure by assigning carbon as the central atom. As we can see, the gap noticed [Line 51] by the students was related to the skeletal structure of the carbonate ion (step 2). In order to fill this gap, a relation in terms of a difference between the electronegativity values of oxygen and carbon was established [Line 52]. It seems as though Alex, unlike Sally and Elias, knew that the least electronegative atom is supposed to be in the centre. As a result, this relation was not useful for determining the skeletal structure. Instead, again, Sally and Elias rechecked the accuracy of the structure with carbon in the centre in relation

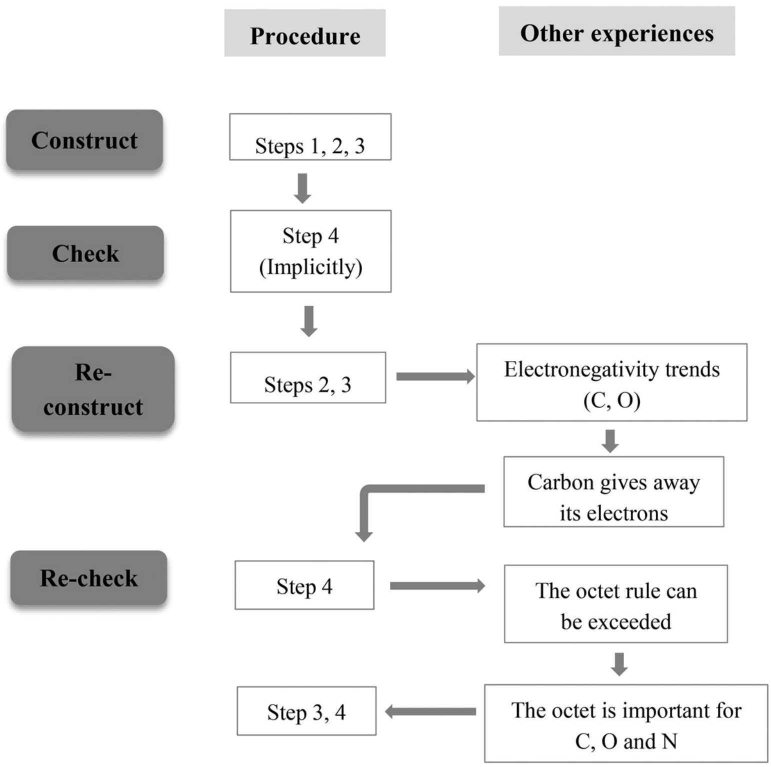


Figure 6. The pattern of drawing Lewis structure in relation to the formal procedure and other experiences.

to the octet rule, step 4 [Lines 58, 63, 66, 68]. According to them, completing the octet for both carbon and oxygen is important [Line 61] but it could not be completed in the structure with carbon in the centre; therefore, this modification was not fruitful. So, the discussion ended with a lingering gap about determining the skeletal structure.

As can be seen in Figure 6, the initial construction and check of the structure were only in relation to the formal procedure. But since the check towards step 4 (octet rule) did not turn out well, reconstruction and recheck were made. However, they did not yield an accurate structure despite the relations to other experiences such as the importance of the octet rule for both carbon and oxygen. Obviously, other experiences were required. First, the importance of electronegativity differences between atoms was needed for reconstructing the skeletal structure. Second, step 4 of the formal procedure which involves moving lone pairs to form multiple bonds. Moreover, a gap concerning the check of the formal charge was not noticed (step 5). By calculating the formal charge, the students might have considered a reconstruction in the form of moving a lone pair to form a double bond, this as a way for reducing the formal charge on carbon to zero and completing its octet at the same time.

Example 5

Similar to example 4, the students in our last example constructed, checked and considered a modification. Here too, the modification was made through a reconstruction of the skeletal structure which was shown to be challenging too. Whereas in example 4 the students used other experiences besides step 4 (octet rule) in the iterative phase, here, the students relied completely on the formal procedure through the whole process. A recheck towards other experiences (e.g. the number of bonds an atom can form) was required in order for the iterative phase to be productive.

As the purpose of the activity was to determine the oxidation states of the different atoms of H_2O_2 (Problem 1), the students showed the need for drawing the Lewis structure of the molecule. Before the excerpt began, Sally started with calculating the total number of valence electrons in her notepad $\begin{array}{r}12\\ 2\\ \hline =14 \Rightarrow 7\end{array}$ pairs (step 1), while Elias directly drew the skeletal structure $H-O\equiv O-H$.

70 Elias: But then I wonder a bit about this one [pointing at $H-O\equiv O-H$]
71 Sally: Yeah this one … cause it has to be 7 [electron pairs]
72 Elias: What? Aha
73 Sally: Or?
74 Elias: Seven what? you're writing down ok
75 Sally: Electron pairs
76 Elias: 2 times 6 [valence electrons of oxygen] and then 2 times 1 [valence electrons of hydrogen], 14 [electrons, wrote in his notepad]. Ok, we should put out 7 [electron pairs] … I put 1, 2, 3, 4 5, [pointing at the structure $H-O\equiv O-H$] I put out only five
77 Sally: exactly, me too
78 Elias: But then you could put out a lone electron pair on each oxygen [pointing at the oxygen atoms]
79 Sally: No, because of the octet rule
80 Elias: Aha right
81 Sally: You should put them on H … or maybe you can change the positions if it helps [drew $H-O-H-O$ and erased it immediately] … it must be that there will be extra charge on H, +2 two, I Guess [pointing at $H-O\equiv O-H$]
82 Elias: Ok, but
83 Sally It could be that … for example [drew $H-\bar{O}=\bar{O}-H$] … or, I don't know, we should try a bit
84 Elias you're right, maybe it could be like this [Line 83]
85 Sally [distributed remaining electrons $\bar{H}-O\equiv O-\bar{H}$] But it will be very much charge on hydrogen. Something is wrong

The discussion began with noticing a gap [Line 70] concerning the construction of Lewis structure of H_2O_2, particularly step 3 [Line 70]. In order to fill this gap, a relation to the total number of valence electrons in the structure was established [Line 71]. As we notice, the students did not notice the gap concerning the number of bonds oxygen can form or not form but carried on in the process. Elias carried out step 1 by calculating the number of electrons in the structure [Line 76]. Then, they carried on trying to distribute the electron pairs in the structure, step 3 [Line 76] with a simultaneous check of the accuracy of the structure. This check was made in relation to steps 4 and 5 of the formal procedure. First, allocating a lone pair on each oxygen atom [Line 78] which stood in direct conflict with the octet rule [Line 79]. Alternatively, they tried allocating the lone pairs on hydrogen atoms which according to them stood in conflict with the formal charge on hydrogen [Lines 81, 85]. Since the students could not fill the gap concerning the distribution of electron pairs (step 3), they modified the structure by reconstructing it [Lines 81, 83] as way for filling the gap. However, they did not check the accuracy of these structures. So, despite that the students checked the accuracy of the structure in relation to steps 4 and 5 of the formal procedure, they failed to fill the gap.

As Figure 7 shows, the students employed only the steps of the formal procedure during the whole process which was shown to be insufficient for generating the accurate structure of H_2O_2. The construction phase was made according to the formal procedure (steps 1–3)

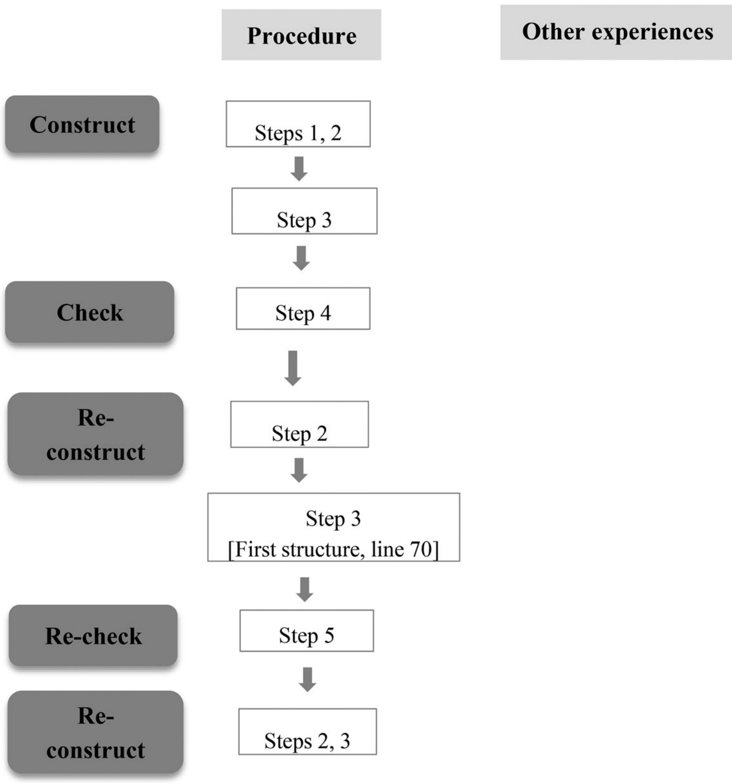


Figure 7. The pattern of drawing Lewis structure in relation to the formal procedure and other experiences.

followed by a check towards step 4 (octet rule). This check did not turn out well; therefore, an iteration was conducted. A reconstruction (step 3) followed together with a recheck (step 5). Again the recheck did not turn out well which led to another reconstruction, this time by drawing another skeletal structure. These iterations of reconstructing and rechecking seemed not to be productive. Despite the check towards the octet rule and formal charge, the students did not succeed to fill the gap concerning the distribution of electron pairs in the structure [Lines 70, 85]. This is because another gap not connected to the formal procedure was left unnoticed, namely the number of bonds oxygen can form or cannot form. A check towards an experience regarding the maximum number of bonds an atom can form might have aided the students in filling the second gap instead of reconstructing by drawing another structure.

Summary of the results

To sum up, as seen in Figure 8, the students in this study typically constructed, checked and sometimes modified the structure. Examples 1–3 showed how the steps of the formal procedure were used in interaction with other experiences for constructing and checking the structure. Moreover, the steps of the formal procedure were not carried out in order neither all of them were employed for drawing Lewis structures. In these instances, no

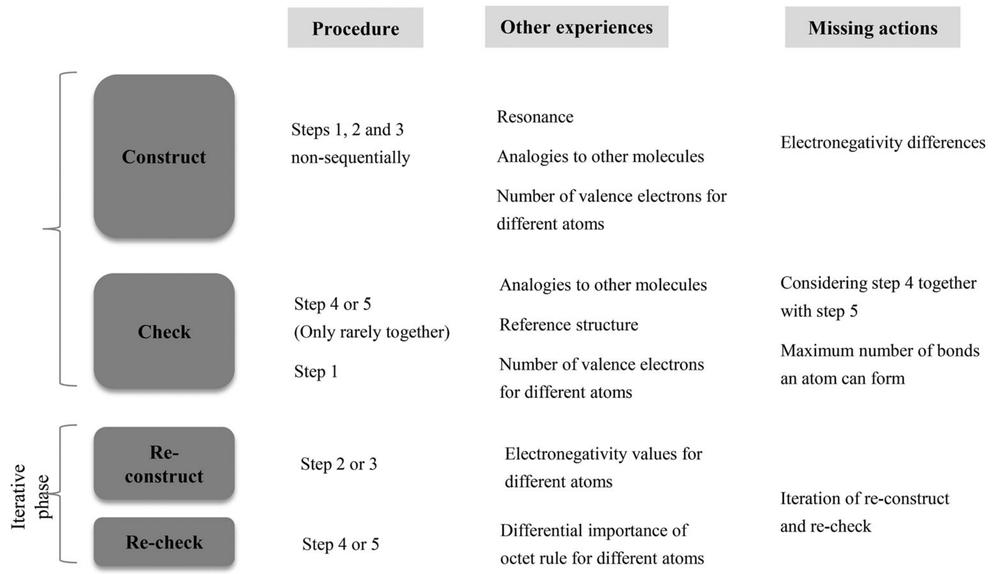


Figure 8. A summary of the different experiences and knowledge used by the students when constructing and checking the structure as well as in the iterative phase. Missing actions are those experiences and knowledge that were needed but not used for drawing Lewis structures.

modification was conducted. In examples 1 and 2, other experiences together with the steps of the formal procedure aided the students in constructing and checking the structure and accordingly, the modification was not needed. However, in example 3, a gap concerning the number of bonds was not filled. A check towards step 4 might have aided the students in filling this gap and accordingly in modifying the structure. In examples 4 and 5, the students not only constructed and checked the structure but also modified it. The modification phase was conducted in the form of iteration of reconstruction and recheck. In example 4, the reconstruction was made by drawing another skeletal structure followed by a recheck through step 4 (octet rule) and other experiences. However, this was not enough for generating the accurate structure. A gap concerning step 4, which involves moving lone pair to form double bonds, was not noticed. A check towards the formal charge might have aided the students in noticing this gap. Lastly, example 5 shows that the formal procedure alone was not enough for drawing Lewis structures. The iterative phase was problematic due to the fact that the students failed to fill the gap concerning the distribution of all electrons (step 3). A recheck towards other experiences (e.g. the number of bonds an atom can form) would have been required in order for the iterative phase to be productive. Moreover, the students would have needed to use both the octet rule and the formal charge for checking the accuracy of the structure, which our students did not do.

Discussion

In this study, we sought answers for how students employ the steps of the formal procedure when drawing Lewis structures (first question) and how these steps interact with each other and with other experiences (second question). In order to do that, we developed a theoretical account of the process of drawing Lewis structures based on a number of shared features between the various versions of the formal procedure. Using this theoretical account as an analytic tool enabled us to model the interaction between the steps of the formal procedure and other experiences, and so discern certain patterns in students' reasoning.

Similar to other studies (e.g. Brady et al., 1990; Cooper et al., 2010; Pardo, 1989), our results showed that drawing Lewis structures is complex and difficult for first-year university students. This complexity seems to be connected to difficulties both with employing the steps of the formal procedure systematically and with knowing what knowledge and experiences to draw on as well as when to include this knowledge and experiences for drawing correct Lewis structures.

Our students' approaches for drawing Lewis structures correspond to general approaches and strategies for solving chemical problems (e.g. Bodner & Herron, 2002; Christian & Talanquer, 2012; Kraft, Strickland, & Bhattacharyya, 2010). Some studies categorised students' approaches and strategies as rule-based reasoning if the students relied on rules for solving problems and case-based reasoning if the students recalled familiar processes and structures. Similarly, in some instances in our findings, the steps of the formal procedure were employed exclusively; in other cases, the students managed without recruiting these steps at all. And in yet other cases, the steps interacted with other experiences.

Likely, the approaches chosen by the students to solve chemical problems are influenced by the ways such problems and their handling are introduced to the students. And since drawing Lewis structures has been strongly characterised by a procedural approach with emphasis on the octet rule and formal charge, this might explain our students' reliance on the procedure to a large extent. Besides, students' approaches may also have been influenced, to some extent, by the particular examples, such as molecules that contain nitrogen (e.g. NH_3, NO_3^-) and oxygen (CO_3^- and H_2O_2). In these molecules, the number of bonds nitrogen and oxygen form depends on the molecule in question. However, judging from how the approaches were distributed between students and molecules in our data, the missed actions indicated in Figure 8 primarily correspond to general problems that were also reported in the literature, Figure 2 (Ahmad & Omar, 1992; Brady et al., 1990; Cooper et al., 2010; Malerich, 1987; Nassiff & Czerwinski, 2015; Nicoll, 2003; Pardo, 1989)

Moreover, drawing upon features of familiar structures is a well-known way of dealing with a new problem (e.g. Coll & Treagust, 2001). Such analogies made it easier for the students to both construct and check the structure and accordingly no modification was required. Our results support the idea that beginning students benefit from drawing upon familiar structures until they establish a broader base of experiences of chemical structures and, consequently, that such analogies should be considered as important scaffolds for students (cf. Coll & Treagust, 2001).

Beyond this view on general approaches for solving chemical problems, our findings provided insight into how students draw Lewis structures in regard to our model, namely, construct, check and modify. In relation to this model, our analysis revealed that other knowledge and experiences than the formal procedure often proved crucial in the checking phase, as in this phase, the students had the opportunity to check the accuracy of the structure. Interestingly, this became evident in the analysis of which gaps that were not noticed (Figure 8) by the students or which relations were not established, for instance the number of bonds certain atoms can form and electronegativity differences. These experiences are commonly gained from earlier encounters during their chemistry studies. A question to be asked, then, is how students are supposed to recognise such additional knowledge as relevant to invoke. For instance, how are students to know in which compounds nitrogen forms three as opposed to four bonds, or know that the number of bonds nitrogen forms is situational in the sense that it depends on the nitrogen compound in question, or that the least electronegative atom is not always in the centre (e.g. NH_3, Cl_2O)? The students in our study, unlike experts, had not yet developed an extensive experience regarding processes and structures (Kozma & Russell, 1997; Nassiff & Czerwinski, 2015). In addition, the struggle in the iterative part in the modification phase could be traced back to the checking phase, as gaps in the checking phase were noticed and not successfully filled with relations and/or necessary gaps left unnoticed. This likely influenced the ways in which students went about modifying the structure.

How, then, can we help students learn to draw Lewis structures in more informed and insightful ways, rather than mechanically follow a step-by-step procedure? In order to achieve that, we suggest our model of construct, check and modify as a new conceptualisation of drawing Lewis structure. This model opens up for opportunities to consider explicitly what knowledge, apart from the stipulated steps, that may help in the process of drawing Lewis structures. Moreover, this may increase students' awareness of the role of the different steps and when and how to invoke them with other necessary chemical knowledge. Moreover, we might enhance the possibilities where the students learn to notice gaps (Figures 2 and 8) and accordingly modify it towards a correct structure, for instance, too many bonds formed or problems of distributing all electrons (Nassiff & Czerwinski, 2015). If the students overlooked an excessive number of bonds in the construction phase, they may learn to check their structure towards other experiences such as considering the maximum number of bonds an atom can form.

In the end, we believe that this is how professional chemists approach this as well as other tasks. Helping new students to arrive their through more meaningful paths may be an important contribution to introductory chemistry education.

Disclosure statement

No potential conflict of interest was reported by the authors.

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