



The role of anthropomorphisms in students' reasoning about chemical structure and bonding

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Abstract

Anthropomorphisms are widespread at all levels of the educational system even among science experts. This has led to a shift in how anthropomorphisms are viewed in science education, from a discussion of whether they should be allowed or avoided towards an interest in their role in supporting students' understanding of science. In this study we examine the role of anthropomorphisms in supporting students' understanding of chemistry. We analyze examples from undergraduate students' discussions during problem-solving classes through the use of practical epistemology analysis (PEA). Findings suggest that students invoked anthropomorphisms alongside technical relations which together produced more or less chemically appropriate explanations. Also, anthropomorphisms constitute potentially productive points of departure for rendering students' explanations more chemically appropriate. The implications of this study refer to the need to deal with anthropomorphisms explicitly and repeatedly as well as to encourage explicit connections between different parts of the explanation - teleological as well as causal.

Keywords: Anthropomorphism, chemical bonding, chemistry education, explanations

Introduction

In this study, we address the potential role anthropomorphisms may play in students' explanations of chemical phenomena. Anthropomorphisms (or analogical anthropomorphisms, or teleological explanations) refer to ascribing human characteristics to non-human objects (Pickett et al. 2000). Although the earlier Piagetian view was that animistic reasoning is an aspect of children's reasoning which, therefore, declines with age (cf. Dorion, 2011; Friedler, Zohar & Tamir, 1993), we now know that anthropomorphisms are widespread at all levels of the educational system (Coll & Treagust, 2001; Nicoll, 2001; Taber & Adbo, 2012; Talanquer, 2013), even among science experts (e.g. Kelemen, Rottman & Senton, 2013; Rundgren, et al., 2012). This has led to a concomitant shift in how we view



anthropomorphisms in science education, from a discussion of whether they should be allowed or banished, towards an interest in what role they may play in supporting students' emerging understanding of science (Dorion, 2011).

An early discussion of the role of anthropomorphisms in chemistry education is found in Taber and Watts (1996). Based on interviews with A-level chemistry students, they suggested that anthropomorphisms may appear in students' reasoning along a continuum from strong, teleological to weak, more metaphorical renderings of a chemical phenomenon. In a later survey, Talanquer (2013) demonstrated the presence of teleological anthropomorphisms in the majority of college chemistry students' answers to questions specifically designed to distinguish between teleological and causal reasoning. He expressed concern that the presence of anthropomorphisms or teleological reasoning creates a false sense of understanding in students, constituting "a cognitively cheap way of satisfying a need for explanation without having to engage in more complex mechanistic reasoning" (Talanquer, 2013, p. 1423). Talanquer suggested that teachers need to engage their students in comparing and contrasting teleological and causal explanations to take advantage of the anthropomorphisms that they inevitably invoke, while making sure that students do not settle for the teleological answers. Similarly, Dorion (2011), based on a significant number of interviews with year 7-10 students, presented firm evidence of various teleological anthropomorphisms in students' reasoning. However, he was able to show that sometimes, seemingly "strong" anthropomorphisms - as defined by Taber and Watts (1996) - coexisted with significant conceptual development within the wider framework of the subject matter (here, diffusion). Thus, Dorion (2011) suggested that, from a science education perspective, anthropomorphisms should be considered heuristic and potential aids rather than hindrances, and that teachers should therefore allow students to develop these alternative explanations.

It is worth noting, however, that the primary empirical evidence for the role of anthropomorphisms in students' scientific and chemical explanations comes from interviews and surveys. Thus, despite at least around 30 years of discussion of their significance, we still lack a robust understanding of how anthropomorphisms may support students' reasoning in the classroom. This study aims to contribute to such an understanding. Specifically, we present analyses from undergraduate students' reasoning in actual classroom work. We analyze both how the students make use of anthropomorphisms and in what ways their use may support acceptable chemical explanations. Our overarching research question is:

- How may anthropomorphisms support first-year university students' explanations of chemical structure and bonding during a problem-solving activity?



Study context and data collection

The data was collected from an introductory chemistry course in a Swedish university during the first semester of the first year. The introductory chemistry course consists of 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 laboratory work is mandatory whereas lectures and problem-solving classes are optional. The recordings came from the second module, structural chemistry, during problem-solving classes. During these classes, the students usually discuss the chemistry content presented in lectures and solve chemical problems related to this content.

Seven groups of 2-4 students were audio recorded during problem-solving activities on three different occasions. The students had previously attended the chemical equilibrium module. The recordings were each between 90 minutes and two hours long and amounted to a total time of nearly 12 hours of student discussions. The first author was present during the data collection but did not participate in the discussions or interact with the students to avoid influencing the research settings. A teacher assistant was present during these classes and acted as a facilitator to support the students. The materials available to the students were a handout that included chemical problems and answers to these problems, a book on general chemistry (Burrows et al., 2013) and the Nuffield Advanced Science: Book of data. The Book of data includes physics and chemistry data suitable for A-Level Physics and Chemistry students. The topic discussed in these problem-solving activities was chemical bonding which included different atomic models (the Bohr atom model and the quantum mechanical model of atomic and molecular orbitals), its application to electron structure, and key concepts associated with chemical periodicity. Some of the main concepts discussed during these problem-solving activities were: electron structure, electronegativity, electron affinity, shielding effect and effective nuclear charge.

Analytical approach

The audio recordings were replayed and transcribed verbatim. Anthropomorphisms were scattered throughout the transcripts but we found eight sequences in which the anthropomorphisms appeared as part of more elaborate efforts to produce chemical explanations. These sequences were then subjected to detailed analysis using Practical Epistemology Analysis (PEA). PEA is an established framework for



analyzing how students' learning proceeds through action in the classroom, and what can be changed in order to support their learning (Lidar, Lundqvist & Östman, 2006; Wickman & Östman 2002; Wickman 2004; Kelly et al. 2012).

PEA includes four main concepts in order to operationalize how students proceed through a learning activity: encounter, gap, relation, and stand fast (Wickman & Östman 2002). Encounter is an operationalization of what it is that students meet and interact with in an activity, such as encounters with written assignments, textbooks, teachers, or peers. The remaining three concepts operationalize how students respond to an encounter. Thus, in encounters, students are said to notice gaps and fill them with relations to what already stands fast. For instance, an encounter with a chemistry textbook may give rise to a gap concerning the meaning of ionization energy, which, in turn, may be filled with the relation "ionization energy – amount of energy required for removing an electron". In order for this relation to fill the gap, terms such as energy and electron need to stand fast, which means that the students do not question their meaning. Otherwise, new gaps may emerge concerning the meaning of these terms. It may of course be that a gap is not filled with any relations, or that those that are established are not working in the sense that they do not help the students proceed. The gap is then said to linger. Gaps that are not filled in a certain encounter may of course be filled in upcoming ones.

After analyzing how students deal with different encounters during the learning activity, i.e., which gaps they notice and which relations they establish to fill them, it is possible to analyze to what extent these gaps and relations lead towards the ultimate purpose of the activity (Wickman, 2004), which in this case was to explain concepts and phenomena related to chemical structure and bonding. Theoretically, we could imagine an instance in which students notice all the relevant gaps and fill these gaps with entirely appropriate relations, such that their reasoning leads directly towards a chemically acceptable explanation. At the other end, we may imagine a group of students failing to establish any working relations to fill the gaps that they notice, or noticing gaps not even close to the issue at stake, or establishing relations which do not connect to accepted scientific knowledge. Normally, however, students' reasoning falls somewhere in between these two endpoints. Thus, although students notice relevant gaps and fill them with working relations, there may be additional gaps that need to be noticed and filled, and the noticed gaps may need to be filled with additional relations. Thus, identifying the gaps that are successively noticed and the relations established to fill the gaps, enables a moment-by-moment analysis of the direction that the students' reasoning takes in relation to what they are expected to learn, and what gaps and/or relations that are potentially missing from their emerging reasoning.



In summary, Practical Epistemology Analysis amounts to analyzing (1) how students' reasoning actually develops during a learning activity, and (2) analyzing how their reasoning could develop differently through other, or additional, gaps and relations. Here, the first part of the analysis was guided by the following two analytical questions:

1. What gaps did the students notice?
2. What relations did the students establish to fill the noticed gaps?

The second part of the analysis was guided by the following three analytical questions:

3. To what extent did the established relations lead towards a reasonable explanation?
4. What additional gaps would the students have needed to notice?
5. What additional relations would the students have needed to establish?

Consequently, we first identified which gaps the students noticed in each of the eight sequences (analytic question 1) as well as which relations the students established as part of producing their explanation (analytic question 2). Since our interest was how anthropomorphisms may contribute to students' explanations of chemical structure and bonding, we made an operational distinction between two kinds of relations which we labeled anthropomorphic and technical, respectively. We defined an anthropomorphic relation as one in which a chemical phenomenon was related to words for describing human characteristics, such as "satisfied" and "happy". We defined a technical relation as one in which a chemical phenomenon was related only to chemical terms, without ascribing human characteristics, such as "noble gases – have full valence orbitals". Third, we analyzed what was missing from their reasoning, and which additional gaps and/or relations might be added in order to produce a more satisfactory explanation (analytic questions 3-5). Notice that the point of departure for the analysis was those instances in which students included anthropomorphisms in their reasoning in the first place. Thus, these anthropomorphisms were part of the emerging explanations, and were therefore retained as we analyzed what else the students needed to establish. In this way, we were able to produce tentative hypotheses concerning how anthropomorphisms may support students' reasoning about chemical bonding.

Findings

In two of the eight sequences analyzed, students produced explanations containing only anthropomorphisms, whereas in the remaining six sequences students also



invoked technical as well as anthropomorphic relations. However, the extent to which these two kinds of relations interacted to support the students' emerging explanations differed. In three sequences, the students managed to produce a reasonable explanation through a fruitful combination of anthropomorphisms and technical relations. This is exemplified below in Excerpt 1. In the remaining three sequences however, students managed less well. This is exemplified in Excerpts 2 and 3. In all three examples, we also provide an analysis of what kind of support these students would have needed to carry through with their explanations. This second part of the PEA led to three tentative hypotheses concerning how anthropomorphisms may support students' chemical explanations. On a general level, the analysis suggests that in order to arrive at a chemically satisfactory explanation, these groups would have needed to establish not only further technical, but additional anthropomorphic relations as well.

Excerpt 1: Continuity between anthropomorphic and technical relations

Our first excerpt is an example of how relations to anthropomorphisms interacted fruitfully with technical relations towards an explanation of the chemical concept of electronegativity. In particular, here both kinds of relations reinforced the students' explanations by being clearly tied to each other.

Emma and Julia were trying to solve the chemical problem: Give the approximate values of electronegativity of noble gases, even though you (probably) won't find them in the tables. Argue for your opinion! Before the excerpt began, they had tried to determine the electronegativity values by providing answers which were poles apart: zero and high.

1 Emma: Zero [sounds doubtful]... no... high is not zero...can't you take... if we could have, find out "electron gain energy" [in English] plus "ionization energy" [in English]

2 Julia: No but you know, it's only to think.

3 Emma: Yeah, it's high... is it, is it enough?

4 Julia: Well no but...

5 Emma: Is it enough what it says in the answer?

6 Julia: Yeah, but what we should think about actually, it says "argue for your opinion". It's actually the noble gases, they are very satisfied [laughs] and happy [laughs].

7 Emma: Yeah.

8 Julia: I mean, they have a full shell... they're cool [laughs].

9 Emma: Yes why?

10 Julia: Because...

11 Emma: They don't want to let go a single bit.



12 Julia: No... so it takes a lot of energy to make an ion from a noble gas.

13 Emma: They fight for their electrons.

14 Julia: Yeah, right... They're among those cool guys [laughs].

Table 1. Summary of the technical and anthropomorphic relations found in Excerpt 1.

Technical relations	Anthropomorphic relations
find out – electron gain energy plus ionization energy	
	high value – satisfied – happy
	they – full shell – cool
	they – don't want to let go
lot of energy – to make an ion from a noble gas	
	they – fight for their electrons
	they – cool guys

The starting point for filling the main gap concerning the electronegativity values of noble gases was by construing a technical relation, viz., to the definition of electronegativity according to Mulliken (Turn 1). This relation, being a quantitative measure, seemed not to be considered enough for solving the problem and the students instead turned to the answer given in the handout (Turn 3), which states: "The noble gases have high ionization energies therefore they have rather high electronegativity values according to Mulliken". As the students realized that they needed to argue for the high electronegativity values of noble gases rather than actually provide a value (Turn 6), they began to construe a number of relations to anthropomorphisms, such as high value – satisfied - happy (Turn 6), full shell - cool (Turn 8), and don't want – to let go (Turn 11). Then, in Turn 12, the students returned to the initial Mulliken definition of electronegativity, but this time through the more qualitative, yet technical, relation it takes - a lot of energy - to make an ion of a noble gas. This relation, in turn, was immediately followed by two additional anthropomorphisms, thus closing the sequence.

It is noticeable here how closely the second technical relation was connected to the anthropomorphisms coming before and after. Indeed, the relation is introduced as a further clarification of the two initial anthropomorphisms, evident through the words "No... So..." (Turn 12). And the following anthropomorphism, equally, is added to the technical relation as a confirmation. We may say, thus, that the anthropomorphisms and the second technical relation here were made continuous with each other in the students' reasoning, such that each reinforced the other.

Turning to the second part of the analysis, i.e., what additional gaps or relations could have made these students' explanation even more satisfactory, we may note that the



students never explicitly connected the relation in Turn 12 to ionization energy, nor did they establish any explicit relation between electronegativity and ionization energy. Thus, one possible way of helping the students "go all the way", as well as making sure that they actually saw these connections, could be to help them notice an additional gap, viz., by asking "what concept captures the notion of an amount of energy needed to make an ion of a noble gas?", which aims at getting the students to establish a further relation between Turn 12-13 and ionization energy. Filling this additional gap would have closed the students' emerging argument for the connection between high ionization energy and high electronegativity of noble gases given in the answer from the handout.

A first hypothesis emerging from this analysis, thus, is that students may produce strong explanations of chemical phenomena through a combination of anthropomorphisms and technical relations if these are actually made continuous with each other. However, they may need help closing their reasoning with explicit relations to the target concepts of the explanation.

Excerpt 2: Anthropomorphisms for making distinctions between concepts

In our next example, Alice and Linda were engaged in answering the question: What does electronegativity of an atom mean? Contrary to Excerpt 1, here the students never managed to make the anthropomorphic and technical relations continuous with each other and, consequently, never arrived at a satisfactory explanation of the electronegativity concept, either from their own or from a scientific point of view. The sequence started by Alice reading the question constituting the main gap aloud:

15 Alice: What is electronegativity? ... Don't you know that? [laughs].

16 Linda: I think...

17 Alice: That it [an atom] wants or doesn't want electrons.

18 Linda: This was the difference between electronegativity and electron affinity... so electron affinity is the ability and need to attach an electron... electron affinity.

19 Alice: The opposite [of electronegativity].

20 Linda: Yeah.

21 Alice: If you have high electronegativity, that's noble gases for instance ...which have full shell.

22 Linda: No, higher electronegativity, for example fluorine and chlorine.

23 Alice: Why?

24 Linda: Here it is... [pause]... Exactly, electron affinity.

25 Alice: Negativity, but then what has...?

26 Linda: Nitrogen, for example, is equal to zero ["plus minus noll" in Swedish]. Not equal to zero ... Right, which question was it?



27 Alice: Three [...] right, that's right. But hey, does a noble gas have low affinity, no, low electronegativity... cause iodine...

[They continue checking electronegativity values for another 21 turns, then change subject].

Table 2. Summary of the technical and anthropomorphic relations found in Excerpt 2

Technical relations	Anthropomorphic relations
	it wants or doesn't want electrons
...difference between electronegativity and electron affinity...	
	electron affinity – ability and need to attach an electron
electron affinity - the opposite [of electronegativity]	
high electronegativity... have full shell	

The students initially attempted to fill the main gap through an anthropomorphic relation, viz., "electronegativity – wants or doesn't want electrons" (Turn 17). This relation did not seem to be satisfactory and they instead tried to fill this gap through a technical relation to the difference between electronegativity and electron affinity (Turn 18). This relation led to the emergence of a new gap concerning the meaning of electron affinity, which, in turn, the students tried to fill with an anthropomorphic relation (Turn 18). However, this relation also applies reasonably well to the electronegativity concept. Therefore, it did not help the students distinguish between the two concepts. They made another attempt to fill the main gap through yet another anthropomorphic relation (Turn 21), followed by continuing attempts to differentiate between the two concepts of electronegativity and electron affinity (Turns 22–27). However, the main gap about the meaning of electronegativity lingered in these two students' reasoning.

Turning to the second part of the analysis, we may say that if the students had managed to fill the gap concerning the meaning of electron affinity (Turn 18), they would have also been in a much better position to fill the main gap concerning the meaning of electronegativity. Put differently, the effort to complement the anthropomorphic relations with a technical relation between electronegativity and electron affinity could have been a potentially fruitful way to explain electronegativity, assuming that the students had managed to distinguish between the two concepts. One might of course argue that the failure to make this distinction could be blamed on the anthropomorphic relations established by the students to



make sense of the two concepts (Turns 18 and 21). However, considering the discussion as a whole, it seems unlikely that additional technical relations or definitions of the two concepts would have helped the students at this point. But what if the students had been supported to continue distinguishing between the two concepts through anthropomorphisms, by being encouraged to construe additional anthropomorphic relations, with the aim of clarifying this distinction in a qualitative manner? In this particular case, the anthropomorphism in Turn 18 could have been more clearly connected to a gap specifically concerning the similarities between electronegativity and electron affinity, and perhaps explicitly developed into the anthropomorphic relation "electronegativity and electron affinity – ability to attach electrons" (cf. Turn 18). Then, the students could have been encouraged to fill a gap concerning the difference between the two concepts, again with the help of current anthropomorphisms. For instance, electronegativity could be related to the ability to "attract" rather than "attach" shared electrons, or the "unwillingness to share electrons equally in a bond", whereas electron affinity could be related to "the tendency for an atom to attach or accept an electron". Finally, after having clarified the difference between the concepts with the help of anthropomorphisms, students could be supported to make these relations continuous with technical ones, such as "how much an atom wants to attract electrons to itself – its electronegativity - helps determining charge distribution in a bond" while "the tendency for an atom to attach or accept an electron – its electron affinity - determines whether a pair of reactants will participate in charge-transfer reactions".

A second hypothesis emerging from the analysis, therefore, is that anthropomorphisms invoked by students may be taken advantage of and developed further, in order to help them better appreciate critical distinctions between chemical concepts, these qualitative renderings of the distinction may be related back to, and made continuous with, more technical definitions of the concepts.

Excerpt 3: Anthropomorphisms for making connections between concepts

Just as Excerpt 2, Excerpt 3 is an example where the students failed to make the anthropomorphic and technical relations continuous with each other. Here, too, the students needed support, not with making a distinction but with clarifying the relationship between two concepts, in this case effective nuclear charge and shielding effect. This excerpt occurred right after Emma and Julia had settled for the answer concerning the electronegativity values of noble gases in Excerpt 1. Next, they spontaneously set out to explain the concept of effective nuclear charge, which they had worked with in the previous problem-solving activity.

28 Emma: But the effective nuclear charge, this, do you remember it? Lower effective nuclear charge.



- 29 Julia: Yeah but it has to do with...
- 30 Emma: It's easier...it's the same thing...but high effective nuclear charge means it also holds on tighter.
- 31 Julia: Mm.
- 32 Emma: But a high shielding number then they willingly let go of electrons. Then they shield.
- 33 Julia: No, but it has nothing to do with shielding but only with how.
- 34 Emma: But effective nuclear charge is atomic number minus shielding.
- 35 Julia: Yeah yeah... no, but it's like this, if it has high shielding, then it's easier to take them [electrons].
- 36 Emma: Yeah, exactly.
- 37 Julia: Yeah... I'm just thinking in my head.
- 38 Emma: It's such an awful lot of different concepts.
- 39 Julia: Because then they're so far away so that it's much that's shielding.
- 40 Emma: Yeah.
- 41 Julia: So, they're sort of...
- 42 Emma: Loose.
- 43 Julia: Yeah...they're gone.

Table 3. Summary of the technical and anthropomorphic relations found in Excerpt 3

Technical relations	Anthropomorphic relations
	Lower effective nuclear charge – easier
	high effective nuclear charge – holds on tighter
	high shielding number – willingly let go – they shield
it - has nothing to do - with shielding	
effective nuclear charge - atomic number minus shielding	
	high shielding – easier to take them
	Far away...much that's shielding
	They – loose - gone

Initially, two anthropomorphic relations were established for filling the main gap concerning the meaning of effective nuclear charge (Turns 28, 30). Then, a relationship between effective nuclear charge and shielding effect was introduced, first through an anthropomorphic relation to shielding (Turn 32), and then through a technical relation including the formula of effective nuclear charge (Turn 34). In the remaining discussion, the students tried to fill this gap concerning the relationship between the concepts (Turn 34) through a number of additional anthropomorphic



relations, such as "high shielding – easier to take them" (Turn 35), and "far away – much that's shielding" (Turn 39). However, the students never really managed to make the technical relation continuous with these anthropomorphic relations, at least not explicitly, and the discussion ended with the main gap lingering.

Turning to the second part of the analysis, we see that if the students had managed to fill the gap concerning the relationship between effective nuclear charge and shielding effect (Turn 34), they would have come a long way towards providing an explanation of effective nuclear charge. As in Excerpt 2, one could argue that the anthropomorphic relations did not appear to help the students to accomplish this. However, also as in Excerpt 2, it seems reasonable to assume that at this point, these students would not have been helped by an outright technical definition of shielding and its relation to effective nuclear charge. Instead, a possible way could be to acknowledge, and even add anthropomorphisms, and then help the students to explicitly connect them to each other and to technical relations. Thus, an additional gap "How does the shielding electrons influence the charge experienced by the outer electrons?" could have been introduced, thereby connecting to the anthropomorphisms already established. In order to fill this gap, the students could then be supported to make the anthropomorphic relations already established in Turns 28, 30 and 35 continuous with each other, specifically, "high shielding - easier to take them" (Turn 35) and "lower effective nuclear charge - easier" (Turns 28 and 30). Then, a more technical gap could be introduced, such as "How does shielding influence the effective nuclear charge?" This gap may be filled by connecting the concepts through both the students' anthropomorphic relations to other anthropomorphic and technical relations in the following manner: "much that's shielding" (Turn 39) - due to the many electrons in the inner orbits - shield the outer electrons from the full positive charge of the nucleus and, so, electrons that are "far away" (Turn 39) and "loose" (Turn 42) - experience or feel less of the positive nuclear charge - refers to the actual or effective nuclear charge.

The third and final hypothesis from the analysis, thus, is rather similar to the second one, and implies that anthropomorphisms invoked by students may be taken further in order to help establish connections between chemical concepts, whereafter these qualitative renderings of the connections may be related back to and made continuous with more technical definitions of the concepts.

Discussion

In this study, our interest was to contribute to a better understanding of how anthropomorphisms may support university students' reasoning in chemistry.



We did this through a two-step analysis considering first how students actually invoked anthropomorphisms in their explanations during regular, problem-solving classes and, second, what would have been needed to make their explanations more acceptable. Two findings from this analysis seem both new and potentially important.

First, anthropomorphisms were primarily invoked alongside technical relations which together produced more or less chemically appropriate explanations. Previous studies of anthropomorphisms in science and chemical education have treated them more holistically, for instance as either anthropomorphic or causal (for instance Talanquer, 2013) and have consequently discussed their pros and cons from that perspective. The distinction invoked here, however, suggests that anthropomorphisms may indeed constitute part of an acceptable chemical explanation, if students manage to make them continuous with what we have labeled technical relations (Figure 1). This suggests that the idea of anthropomorphisms as "first heuristics" (cf. Dorion, 2011) employed by students, may be supplemented by considering the development of students' explanations to occur from those only containing anthropomorphisms, towards those in which anthropomorphisms are more and more tightly tied to relevant technical relations, without ever having to disappear.



Figure 1. A simple model for a chemical explanation constituted by the connection between both anthropomorphic and technical relations.

The second intriguing finding is that the invoked anthropomorphisms constituted potentially productive points of departure for rendering students' explanations more chemically appropriate. This led to the hypothesis that, apart from connecting students' existing anthropomorphisms to technical relations, their explanations may be rendered more chemically appropriate by adding anthropomorphisms. In our examples, we showed how this had the potential to clarify important distinctions and connections between concepts. These distinctions and connections, in turn, constituted potentially important components in the emerging explanations. Of course, we may also envision the option of deepening the technical relations invoked in students' explanations as well. However, here we specifically want to point to the



less intuitive suggestion that a chemical explanation may be made more appropriate by deepening the anthropomorphic relations invoked.

Apart from some new angles on how to view and support university students' chemical explanations, our results also have implications for the assessment of students' reasoning in chemistry. One of the concerns in the literature on anthropomorphisms is that researchers and teachers alike may have trouble knowing what students have actually understood; for instance whether students invoke strong or weak anthropomorphisms (cf. Taber & Watts, 1996). Common suggestions are that students need to be encouraged to compare and contrast teleological and causal explanations, and in general acquire an awareness of what anthropomorphisms do (i.e., work as metaphors) and what they do not do (i.e., provide actual accounts of chemical phenomena) (cf. Taber & Watts, 1996; Talanquer, 2013). While we entirely agree with these suggestions, our results indicate that teachers (and researchers) may also choose to encourage students to explicitly make anthropomorphisms and technical relations (or, if you will, teleological and causal explanations) continuous with each other. We provided concrete examples of such explicit continuity in the three examples presented. Such an approach may relieve at least teachers, if not researchers, from the burden of deciding what students actually intend with a given anthropomorphism. Instead, the invoked anthropomorphism is employed as a means of successively producing, together with the student, as clear an explanation as possible, through encouraging explicit connections between different parts of the explanation - teleological as well as causal.

This study examined students' anthropomorphic reasoning in action during problem-solving classes during a first-year university course in general chemistry. As such, it supplements previous studies on the subject, all of which have investigated students' use of anthropomorphisms through interviews (Taber & Watts, 1996; Dorion, 2011) or surveys (Talanquer, 2013). We thereby now know that anthropomorphic reasoning occurs reasonably frequently in authentic learning settings. At the same time, studying anthropomorphic reasoning in such authentic contexts may actually have contributed to the new findings presented here. Although this is a small, qualitative study, it thus presents evidence both of anthropomorphic reasoning in actual learning settings, and of potentially productive ways of making use of these anthropomorphisms in chemistry teaching. As such, the findings and suggested hypotheses are worth taking into consideration both for university chemistry teachers trying to help their students make sense of such difficult notions as chemical bonding, and for future research on students' teleological and anthropomorphic reasoning in science.

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