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Textbooks as source for conceptional confusion in teaching and learning 'acids and bases' in lower secondary school

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Abstract:
Chemistry teaching and learning bears some subject-specific challenges. For example, explanations and considerations of chemical phenomena drawing on the macroscopic, the sub-microscopic and the representational level. In this paper, we focus on the topic 'acids and bases' where the confusion of these levels leads to numerous misconceptions among learners. One possible source of these problems are textbooks, which can have an important impact on the quality of teaching and learning. To identify scientific and didactical appropriate textbooks for lower secondary classes, we draw on the work of Roseman, J. E., Stern, L. & Koppal, M. (2010), who developed an instrument to analyse textbooks using a conceptual coherence map. To develop our topic-specific instrument, big ideas of the topic were formulated, arranged in a conceptual coherence map, and set in relation with each other. Then we development a coding manual that describes precisely how to apply the different categories while analysing textbooks. The process described is part of a design-based research project with the aim to contribute to better chemistry teaching and learning. We give insight into the process of developing this instrument for analysing chemistry textbooks. Furthermore, it presents some examples for problematic representations from textbooks in the field of 'acids and bases'.

Keywords: 'acids and bases', big ideas, conceptual coherence map, textbook analysis
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Introduction

One major aim of teaching science and chemistry at school is to equip young people with scientific literacy. Scientific literacy should then help learners to grasp how science contributes to the deeper understanding of nature, and enable coming generations to deal with current and future challenges in the field of science and technology. To become scientifically literate, establishing a well-founded knowledge of the conceptual relationships between scientific ideas and the deeper structures connecting these ideas is crucial. Chi, Feltovich, and Glaser (1981) describe this as "*effective organization of knowledge with meaningful relations among related elements*". Learners often have problems with drawing and understanding conceptual interconnections between the big ideas of a topic (e.g. 'acids and bases') because their knowledge is a fragmented accumulation of bits and pieces containing conflicting and naïve notions. The reasons for these problems partly lie in the subject itself, the way how chemistry is taught in school and the way how textbooks present scientific concepts and ideas. In this paper, we elaborate on the question why chemistry learning and teaching is challenging, and describe the development of an instrument to analyse the conceptual coherence of textbooks.

Why chemistry teaching and learning is challenging

Chemistry teaching and learning is challenging because in chemistry "*things are seldom what they seem*" (Johnstone, 1991, p. 75). This text, written by Johnstone nearly 30 years ago, continues such: "*The difficulties of learning*

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science are related to the nature of science itself and to the methods by which science is customarily taught without regard to what is known about children's learning" (ib. p. 75). He elaborates on possible reasons why learners find chemistry hard to learn and points out the relevance of methods and facilities used for teaching, the nature of learners learning, and the nature of the message itself. He resumes that "*almost certainly the problems lie with all three to varying degrees*" (ib. p 76). The nature of chemical concepts cannot simply be derived through direct perceptions. Because, to explain and understand chemical properties and phenomena that we can see, feel or smell (the macroscopic level) we need to refer to processes and conditions that cannot be perceived directly (sub-microscopic level), and to communicate about this we make use of diverse representational figures (symbolic level). These three levels are well-known as the Johnstone-triangle or the chemistry triplet (Taber, 2013). During class, teachers easily switch between these three levels, unaware of the circumstance that for learners it is very demanding to decode which level actually is addressed. Not seldom, learning and understanding is additionally complicated by ambiguous language, e.g. saying 'acid' while addressing an 'acidic solution' or saying 'hydrogen chloride' while meaning 'muriatic acid'. In the first example, the meaning of the word 'acid' is on the sub-microscopic level (particles) whereas the intended meaning 'acidic solution' is on the macroscopic level (substances). The second example is even more confusing because the expression 'hydrogen chloride' can stand for the gaseous substance or for one molecule, while 'muriatic acid' is the aqueous solution of hydrogen chloride. In chemistry classes, we find countless situations like these, where learners are challenged to decode which level the teacher is addressing at this moment. Helping learners to understand chemical phenomena and to make use of this knowledge for decision-making in chemistry related situations means to be particularly clear in communicating on which level the actual considerations are taking place. To do so, a precise and thoughtful language is crucial. University trained chemists and chemistry teachers draw on their professional jargon that often consists of phrases and technical terms that have been developed historically but entail many possibilities for misinterpretations for learners. This applies to teaching in class as well as to writing and designing textbooks and other teaching-material.

Focus on the topic 'acids and bases'

The topic 'acids and bases' is an important part of the Austrian syllabus for chemistry education in secondary schools. On the one hand, it allows for establishing cross-connections to everyday experiences and phenomena, and on the other hand, it is a rewarding example for chemical reactions following the 'donator-acceptor-principle'. The Austrian syllabus follows the definition of acid-base-reactions as proton-transfer-reactions. Corresponding to this, all textbooks for chemistry classes in secondary schools should use the acid-base definition following Brønsted, which addresses acids and bases as particles with certain properties and not as substances (cf. Brønsted, 1928).

At university, we decided for these and other reasons to set emphasis on the topic 'acids and bases' in the pre-service chemistry teacher course "Introduction into Chemistry Didactics". In this course student teachers learn about and reflect upon the challenges of teaching and learning chemistry focusing on this selected topic. Teaching pre-service chemistry teachers for many years, we found that students come to university with profound misconceptions concerning 'acids and bases' and confound the Brønsted model with the Arrhenius model when explaining acid-base-reactions. Research shows that, likewise, experienced teachers tend to confuse different acid and base-models (Arrhenius and Brønsted) (Barke, 2015; Van Driel & Verloop 1999; 2002). These misconceptions turned out to be very persistent (Jenkins, 2013; Lembens & Reiter 2018a; 2018b; Van Driel & Verloop, 2002). After the work of a whole semester focusing on teaching and learning in the field of 'acids and bases' many of the student teachers still struggle with their misconceptions concerning 'acids and bases', they still mix up the macroscopic and the sub-microscopic level and confound different models (Lembens & Reiter, 2018a). Possible reasons for this are, on the one hand, teaching practices in secondary schools and, on the other hand, textbooks.

Problematic (re-)presentations in Austrian chemistry textbooks

In the following, we give a brief insight into the status quo of problematic (re-)presentations in the field of 'acids and bases' in Austrian chemistry textbooks for grade 8 (beginners in chemistry in lower secondary school).

Example "neutralisation reaction"

This take-home message is representative for several textbooks: "*Neutralisation reactions are defined as reactions between a base and an acid that form salt and water*." It is problematic in several aspects:

- Firstly, it is not mentioned that mostly there is no (solid) salt but positive and negative ions in the resulting solution.
- Secondly, it is not mentioned that this happens in (aqueous) solutions, which contain acid particles and base particles.
- Thirdly, it is not mentioned that the driving force of neutralisation reactions is the reaction between protons (hydrogen ions in an aqueous solution, or, to put it more specifically, solvated oxonium ions) with hydroxide ions forming water molecules.

In the same textbook, the following reaction equation is presented (see Figure 1):

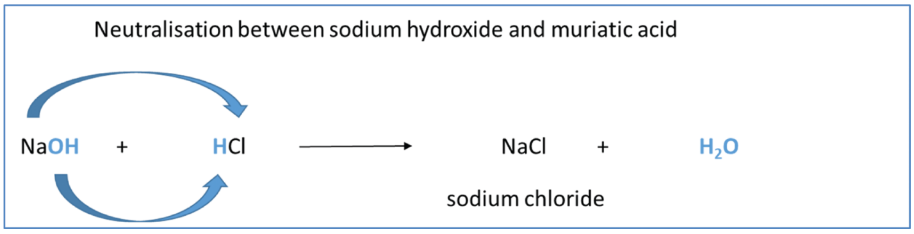

Figure 1: Example for a representation illustrating the reaction equation between sodium hydroxide and hydrogen chloride.

This (re-)presentation suggests to learners

- that sodium hydroxide is a base (correct would be: it is a salt, i.e. an ionic compound, that dissolves in water to form sodium ions and hydroxide ions);
- that hydrogen chloride is muriatic acid (correct would be: it is a gas, i.e. a molecule, that reacts with water to form muriatic acid!);
- that bases always contain an OH-group (hydroxide-group) that forms a water molecule with the H-atom (hydrogen atom) of the acid;
- that sodium chloride, a solid salt, is formed through neutralisation

This representation also exemplifies an instance of confusing the Arrhenius with the Brønsted model.

Example "macroscopic and sub-microscopic level"

The following illustration is typical for several textbooks (see Figure 2).

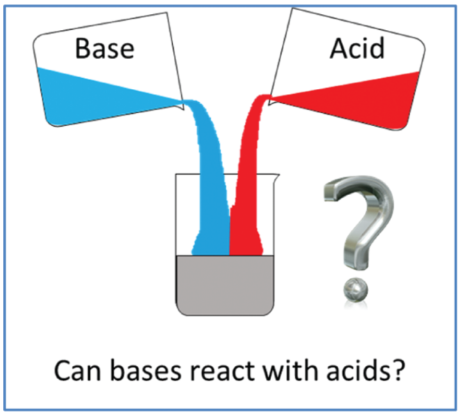

Figure 2: Example for a representation illustrating the reaction between a 'base' and an 'acid'.

This representation misleads learners in several ways:

- Firstly, the liquids in the beakers are labelled with base and acid instead of basic and acidic solution (confounding the substance with the particle level).
- Secondly, the liquids in the beakers are coloured, suggesting that this is the natural colour of acidic or basic solutions.
- Thirdly, the colours of the resulting solution suggests a mixture instead of a chemical reaction, in this case a neutralisation reaction.
- Fourthly, the question beneath the representation is not productive at all.

This is an example for mixing up the macroscopic level with the sub-microscopic level.

Example "pH-value"

In several textbooks, we find illustrations of the colour range of a universal indicator where the lower pH-values (6-0) are labelled "*decreasing acidic strength*". Here the strength of an acid is confounded with a low pH-value. Just as often, we find take-home messages like: "*The so-called pH-value indicates how strong an acid or a base is. The smaller the pH-value, the stronger is the acid*". This last statement is simply wrong. The pH-value is not a measure for the strength of an acid or a base. The pH-value is a measure for the activity of the oxonium ions in an aqueous solution. The strength of an acid or a base is a special property of the particles that are able to release or take up protons. These examples show how negligently textbook authors deal with equivocal terms like "strength" and that not seldom we find scientifically wrong statements in chemistry textbooks.

These examples show some of the problematic (re-)presentations in Austrian chemistry textbooks. Besides these obvious shortcomings, we have to ask how consistently these textbooks do represent the concept of acids and bases in the whole, and how coherent they draw connections between the big ideas within the acid and base concept. This is why we attempt to gain a systematic overview of the quality of chemistry textbooks for secondary school in terms of the correctness of the scientific content and the conceptual coherence concerning the topic 'acids and bases'.

Reasons for a textbook analysis

One of the many factors that influence students' conceptual learning are textbooks. Following Oelkers, textbooks can be seen as the backbone of schooling – they keep teaching clear, reduce the complexity of topics and provide structured tasks (2010, p. 18). Textbooks available in Austria are produced for students' hand. This claim is supported by introducing texts that directly address students and explain how to use the book (cf. Rezat, 2009). But textbooks are not only used by students for learning in class and at home, even more importantly, many teachers use them for lesson preparation and rely on them to "*define both, what and how they teach*" (Harsh, Maltese, & Tai, 2012). For this reason, it is crucial, but not sufficient, that textbooks present the scientific content in a correct and, for the target group, appropriate way. Textbooks also have to support students' learning in perceiving and understanding the conceptual relationships between the core ideas of the respective topic. Then students can use the knowledge and competences acquired for reasoning and decision-making in science related contexts.

Current educational research distinguishes between four different levels of impact-oriented textbook research. These levels are (1) impact on learners, (2) impact on teachers, (3) impact on the public, (4) impact on international relations (Weinbrenner, 1995 cited by Doll & Rehfinger, 2012, p. 25). With our design-based research project, we strive to gain evidence to contribute to answer selected questions on two of these levels.

Impact on learners Is the topic represented appropriate to the learners' level of understanding?

Is the textbook suitable for self-directed learning and critical engagement with the topic?

Impact on teachers Is the textbook a source of information or a learning-media for teachers?

Has the way in which the topic is presented an influence on teachers' beliefs, attitudes or thinking habits?

Roseman and colleagues point out that if we want to make a contribution to improve science learning in school we need to understand "*what textbooks do and don't do on each broad topic at the grain size of specific ideas and the* *interconnection among them*" (p. 49). According to Harsh et al., the coherent presentation of an interrelated set of ideas and connections is an essential characteristic of textbooks that support the development of an integrated understanding of science ideas (Harsh et al., 2012, p. 49). Supporting this, a study shows that maximally coherent texts combined with students' self-explaining strategies can lead learners to detect flaws in their mental models and repair them (Harsh et al., 2012, p. 286).

Considering findings from the research literature, we developed the strong conviction that textbooks are co-responsible for pre-service chemistry teachers' change-resistant misconceptions in the field of 'acids and bases'. Consequently, we strive for getting reliable data about the conceptual coherence of chemistry textbooks. To do so, we decided to start a textbook analysis focusing on the topic of 'acid and bases' to answer the following research question:

> *To what extend do Austrian chemistry textbooks for lower secondary classes present the big ideas of the topic 'acids and bases' in a conceptually coherent and scientifically adequate way?*

To answer this question, the following steps have to be taken:

A. Formulating big ideas of the topic 'acids and bases'.

B. Developing a conceptual coherence map following.

C. Developing a coding manual.

D. Testing and refining the conceptual coherence map and the coding manual.

E. Analysing selected textbooks using the instrument.

In the following, the process of developing and refining our research instrument is described.

Ongoing research and development process

A. Formulating big ideas of the topic 'acids and bases'

Roseman, Stern, and Koppal (2010) argue that "*learning occurs at the grain size of ideas – whether scientifically correct ideas or misconceptions*", they define science ideas as "*propositions that can be investigated and hence supported or refused by data*", and state that these ideas "*can be connected to other ideas*" (p. 49). In science education, the term "big ideas" is well established. For instance big ideas are "*meant to represent the major ideas and concepts which are within the particular science content area*" (Bertram & Loughran, 2012, p. 1028). Loughran and colleagues, who are working with big ideas to capture and develop the professional content knowledge of science teachers, argue that big ideas highlight a number of concepts as being commonly viewed as important for students to learn in order to understand a selected topic (Loughran, Mulhall, & Berry, 2004, p. 378). According to Nilsson and Loughran (2012, p. 707f), "*the notion of Big Ideas offers a way of thinking about how to structure a science topic that is different from the more typical curriculum approach*". In this sense, we challenge all of our pre-service chemistry teachers in the compulsory course "Introduction into Chemistry Didactics" by asking them to develop and discuss big ideas for the topic 'acids and bases'. As mentioned before, we built on the acid-base definition following Brønsted, which addresses acids and bases as particles with certain properties and not as substances (cf. Brønsted, 1928). The formulated big ideas turn out to be quite similar in all the courses. As one step towards developing a conceptual coherence map, we critically reflected upon these big ideas and applied some reformulations to provide maximum clarity. Now these are the formulations of the big ideas of the topic 'acids and bases' we agreed upon:

Big Ideas of 'acids and bases'

1. There are substances that form acidic solutions in water.
There are substances that form basic solutions in water.
or: There are acidic, neutral und basic solutions.

2. An acid is a particle that can release protons (hydrogen ions).
A base is a particle that can take up protons (hydrogen ions).

3. Strong acids show a stronger tendency to release protons (hydrogen ions) than weak acids.

Strong bases show a stronger tendency to take up protons (hydrogen ions) than weak bases.

4. Acid-base-reactions are proton-transfer-reactions.

5. During neutralisation reactions, protons (hydrogen ions; respectively oxonium ions) react with hydroxide ions forming water molecules.

It might be possible that these formulations still bear the potential for further discussions. For example, it is especially difficult to find a wording that avoids anthropomorphism while describing properties of molecules, ions and other participants in chemical reactions. Nevertheless, these formulations turned out to be very useful in developing the conceptual coherence map.

B. Developing the conceptual coherence map

To identify textbooks that present science contents in a coherent and learner-appropriate way, we rely on an instrument developed by Roseman et al. (2010), which is eminently suitable to serve this requirement. This instrument is called "conceptual coherence map". The first step in this process is to define "coherence" for the chosen topic.

In general, coherent textbooks should

a. "present a set of age-appropriate scientific ideas and connections among them;

b. clarify the ideas and connections with effective representations;

c. illustrate the application of the ideas to objects, events, and processes in the real world (i.e. natural phenomena); and

d. avoid the use of unnecessary technical terms or details that are likely to distract students from the main story." (Harsh et al., 2012, p. 50)

Following these recommendations, a maximally coherent representation of the topic 'acids and bases' for grade 8 learners (beginners in chemistry learning) is characterised by the fact that all five big ideas and three related ideas (see Figure 3) as well as the interconnections between them are illustrated and explained in a scientifically correct and adequate way for the target group. At the end of the lower secondary level, learners are supposed to have a basic comprehension of these concepts at disposal. In upper secondary level, learners should additionally engage with mathematical aspects of the pH-value, $K_{a/b}$- und $pK_{a/b}$-value, strength of acids and bases, titration etc., and they should be able to apply this knowledge in relevant contexts. A textbook for upper secondary chemistry classes can, in principle, start with each of the ideas and then, step by step, establish relations to the other ideas using well-chosen examples (phenomena and reactions), while moving from one idea to the next. The following Figure 3 shows the conceptual coherence map of the topic 'acids and bases' which was developed by our working group. This conceptual coherence map contains five big ideas (blue boxes), three related ideas (green boxes), and connecting arrows. The five big ideas can be seen as the core ideas of the concept of acids and bases following Brønsted, whereas the three related ideas provide additional knowledge to underpin the understanding of the concept.

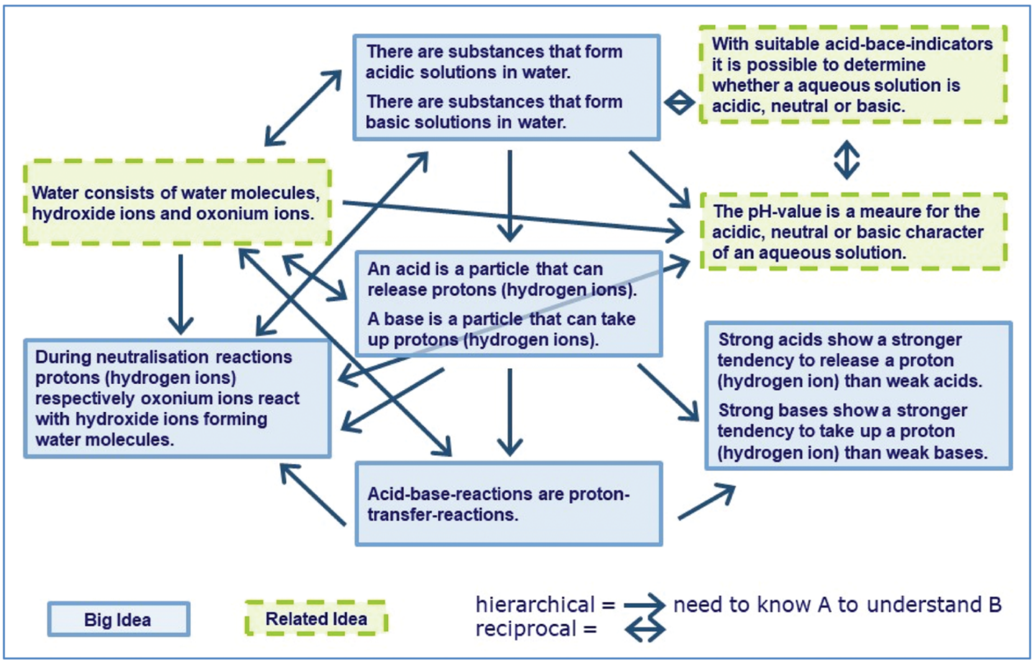

Figure 3: Conceptual coherence map for the topic ‘acids and bases’.

To tell a coherent story of the topic ‘acids and bases’ it is necessary to accentuate the important conceptual connections among these ideas. This is shown by arrows, which symbolise either a hierarchical (single arrows) or a reciprocal (double arrows) relation among the ideas. “Hierarchical” means that one needs to know A to understand B: for example, to understand that acid-base-reactions are proton-transfer-reactions, it is required to know how acids and bases are defined. The “reciprocal” arrows symbolises that one can start from both sides to evolve explanations: for example, to know that water consists of water molecules, oxonium ions, and hydroxide ions, is helpful to understand how acid-base-reactions proceed and vice versa.

Developing this map was not as easy as we at first assumed and it took time to think, time to discuss and time to rethink ideas and arguments. We had several discussions on how to arrange the ideas and to clearly identify the conceptual interrelations among them. Perhaps this is not the final version, but it works pretty well as a fundament for the development of the coding manual.

C. Developing and refining the coding manual based on the conceptual coherence map

To utilise the conceptual coherence map for judging whether a textbook represents the topic ‘acid and bases’ in a conceptually coherent and learner-appropriate way, it is necessary to develop a detailed coding manual. This manual must illustrate and clarify the meaning of the ideas as well as the mode of the interconnections among them, and provide criteria for judging the extent to which the respective textbook actually presents the concepts of the topic in a coherent way. This coding manual is developed to analyse chemistry textbooks for learners in lower secondary schools. The first step is to define the smallest coding unit, which we define as one sentence. In the following Table 1, we give insight into one selected category to illustrate this still ongoing work in progress.

Table 1: Example from the coding manual: Category "Definition of acids and bases".

CATEGORY Definition of acids and bases
The terms 'acid' and 'base' have to be defined clearly through characterising their unique properties. Following the Austrian syllabus and the Brønsted concept this can only be done by addressing acids and bases as particles which are able to release or take up a proton/hydrogen ion.
Application of the category
As "definition" all coding units are classified that either explicitly define or characterise or describe acids respectively bases somehow ("Acids are ..."; "As an acid we define ...", or similar phrasings). These definitions often are highlighted as take home message or put in boxes to stress their importance.
All such "definitions" of the terms 'acid' and 'base' are coded.
Distinction to other categories
The differentiation between the terms "acid" and "acidic solution" respective "base" and "basic solution" is not part of this category.

Subcategory	Subsubcategory	Definition	Application of the category	Anchor example	Distinction to other categories
Compliant to the Conceptual Coherence Map	–	Following Brønsted: An acid is a particle that can release protons (hydrogen ions). A base is a particle that can take up protons (hydrogen ions). Acids are proton acceptors. Bases are proton donators. Brønsted's definition is on the particle level	This subcategory is coded when the following two properties are in place: 1. Acids and/or bases are defined as particles. 2. Acids are described as proton donators, bases as proton acceptors.	"Therefore an acid must be a particle that releases H^+-Ions" (11 p. 50)	This subcategory is not coded when only one of the two properties is presented.
Non-compliant to the Conceptual Coherence Map	Arrhenius	Following Arrhenius: Acids are substances that release hydrogen ions in water. Acids contain always at least one hydrogen atom. Bases are substances that release hydroxide ions in water. Bases contain always at least one hydroxide group. Arrhenius's definition is on the substance level	This subcategory is coded when – acids and bases are defined as substances. – bases are characterised through the presence of a hydroxide group. – it is mentioned that acid-base-reactions always take place in water	"Acids are substances that react with water and produce H^+-ions and acid-rest$^-$-ions. Bases are substances that react with water and produce base-rest$^+$-ions und OH^--ions." (1 p. 62–63)	–

Non-compliant to the Conceptual Coherence Map	Confusion of concepts	Concept confusion is given when more than one of the above mentioned "definitions" are presented without clearly delineating between them. Often the Arrhenius and the Brønsted concept are confused	This subcategory is coded when within one coding unit there are elements of more than one of the scientific concepts (Arrhenius or Brønsted) enclosed without clearly distinguish them	"A proton acceptor is a substance that takes up protons" (9 p. 21)	If elements of more than one concept are mentioned and explicit declared as different and incompatible concepts this subcategory is not coded.
Non-compliant to the CCM	Scientifically incorrect	Scientifically incorrect are all "definitions" that cannot be held to be compatible with the known scientific concepts either Arrhenius or Brønsted	This subcategory is coded when at least one part of the "definition" is not compatible with scientific concepts	"Acids colour universal indicators red." (7 p. 94)	–
Non-compliant to the CCM	No definition at all	–	This subcategory is coded when there is neither a "definition" given nor a description of acids and bases mentioning their generally accepted characteristics	–	–

This extract of the coding manual gives an insight into its structure and character. To reach a satisfactory interrater reliability, it is important to be as clear as possible while describing, clearly delineating, and justifying what should and what should not be within the respective category. Work on the development of the coding manual is still ongoing. Next steps are to test and refine the coding manual (step D) and to analyse the chapter 'acids and bases' in ten selected chemistry textbooks for lower secondary classes (step E).

Summary and conclusions

In this article, we unfolded some reasons why chemistry teaching and learning is challenging and illustrated this by means of the topic 'acids and bases'. Especially, teachers' switching between explanations on the macroscopic and on the sub-microscopic level cause difficulties for learners. Another pitfall is when teachers confound different models, which leads to teaching hybrid models that are inappropriate for explaining and predicting chemical reactions. The consequence of such teaching is that learners are forced to memorise take-home messages by heart, instead of understanding scientific concepts and learning to use them to explain scientific phenomena. Subsequently, students' knowledge often is a fragmented accumulation of bits and pieces.

One of the sources for these problems are textbooks. Not only students use them for learning in class and at home; likewise, teachers rely on textbooks when they plan and prepare their lessons. For this reason, it is essential that textbooks present scientific concepts in a correct and coherent way. To ensure this, in Austria textbooks have to pass an evaluation by an expert group whose responsibilities are, amongst others, to check whether the textbooks are scientifically correct and appropriate in terms of language and didactical elements (cf. BMBWF, 2018). Nevertheless, the presented examples from Austrian textbooks show that, if we hope to enable students to develop a scientific literacy for their personal and civic life, there is urgent need for improvement. The required improvements have to build on evidence from educational research, in this case on a systematic textbook analysis.

We started the attempt to analyse chemistry textbooks for secondary schools with the aim to identify problematic aspects and to develop more coherent curriculum material. The aims of this design-based research project are

- to create evidence about the status of the conceptual coherence of chemistry textbooks,
- to develop conceptual more coherent curriculum material,
- to test and refine this curriculum material, and
- to implement the findings and the material in pre-service and in-service teacher education, as well as in textbooks.

With this project, we strive to contribute to improving chemistry teaching in secondary schools and to help learners develop a conceptual knowledge that is useful to understand chemistry and to apply this knowledge on questions and decision-making in their personal and civic life.

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