Primary School Students' Understanding of Chemical Bongding and the Particulate Nature of Matter

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Abstract. In this study, we researched whether primary school learners could understand and apply the concepts of the particulate nature of matter and chemical bonding. Thirty Slovak primary school 8th graders (aged 13–14) were investigated using a semi-structured interview protocol that invovled a variety of familiar substances and chemical processes. The properties of the substances and the processes, as well as the chemical processes, could only be explained using the concept of chemical bonding. Most students failed to connect the chemical bonding concept with the issues discussed, and many had misconceptions resulting from an inappropriate mode of instruction and a problematic curriculum.

Keywords: chemical bonding, particulate nature of matter, primary school.

INTRODUCTION

In most countries, students learn about chemical bonding in high school or university. However, in central Europe, the concept of chemical bonding is part of the primary school curriculum. In Slovakia, for example, pupils are introduced to chemical bonding in the 8th grade of primary school, when they are approximately 13 years old. Furthermore, science subjects (chemistry, physics, and biology) are taught separately in central European countries, and little attention is paid to the mutual interconnections between the various concepts.

Research Problem

In the last two decades, research across the world has revealed that many high school and university students have misconceptions about chemical bonding (Barker & Millar, 2000; Boo, 1998; Coll & Taylor, 2001, 2002; Coll & Treagust, 2001 & 2003; Harrison & Treagust, 2000; Karacop & Doymus, 2013; Niaz, 2001). However, only a few studies have involved primary school pupils (Saskova, 1997). Researchers have analysed students' alternative conceptions of chemical bonding, as well as their understanding of different types of chemical bonding and the associated processes. Several reports have focused on students' use of anthropomorphic language and analogies, as well as their mental models of chemical bonding, while other investigations have attempted to enhance students' conceptual understanding.

The findings of Ültay (2015) illustrate the complexity of the chemical bonding concept in education. This author used a context-based approach involving concept cartoons. However, the results were unsatisfying, indicating that chemical bonding is a demanding concept for students at all educational levels, perhaps because it is an abstract construct that students find difficult to visualise. The research also indicated the origins of the misconceptions caused by this inappropriate mode of instruction.

These research findings, together with the results of international evaluation studies, have prompted a vast movement towards improving students' achievement in science through the renewal of national curricula. In this regard, individual countries have devised their own cures. In general though, attention has been targeted at more extensive use of inquiry-based methods (Rocard, 2007). However, in central Europe, and especially in Slovakia, the situation has developed differently. Problematic concepts were simply omitted from the curriculum, without any effort to replace the traditional teacher-centred transmissive approach with a student-centred, inductive–deductive approach.

Repeated attempts have been made to refresh the instructional approach. However, several obstacles have prevented this. Most teachers expect instant success using non-traditional educational methods, and some teachers embrace so-called modern, humanistic, alternative, activating, ecologic, electronic, integrated, and other approaches with a non-critical eye, believing that they have found the 'recipe' for guaranteed educational success. The problem is that these teachers do not change their perspective on the teaching–learning process; they only insert these so-called activating methods into their traditional classrooms. Conversely, some other teachers can be characterised by their refusal to accept any new ideas or changes that might impair their own fixed conception of the teaching–learning process.

These obstacles may have arisen for the following reasons: (1) Slovak teachers are poorly informed about the results of the international evaluation studies and research into misconceptions, and they are therefore unaware that they need to change their approach to teaching. (2) The inquiry-based science approach is often confused with the activating method, and is not viewed as an approach to the teaching–learning process; many local researchers and officials have similar misconceptions. (3) Hardly any instructionally coherent, nationwide teaching materials or appropriate lifelong learning opportunities are available for teachers to learn about these globally recognised educational trends.

Research Focus

In the present study, we investigated the chemical bonding misconceptions of 8^{th} grade students in Slovakia, because this concept is introduced earlier than in most other countries. We asked whether these misconceptions differ when chemical bonding is introduced at an earlier stage of education. Furthermore, we catalogued the specific misconceptions of Slovak students to inform the development of new teaching material that employs student-centred, inductive–deductive education. We also wanted to provide an up-to-date picture of research and development in science education to inform teachers, curriculum developers, and pre-service and in-service providers of professional development.

THEORETICAL FRAMEWORK AND METHODOLOGY

General Background of Research

Chemical bonding is classified as either metallic, ionic, or covalent, and a series of mental models is associated with each bonding type (Coll & Taylor, 2002). In the present study, we paid particular attention to the covalent and ionic bonding types, as well as to the associated octet rule mental model, because these concepts are introduced into the Slovak curriculum in the 8th grade of primary school. More advanced theories are introduced at higher levels of education.

Sample of Research/Participants

We interviewed 30 primary school pupils aged 13–14, with balance in terms of gender and school performance. To maintain interaction among the pupils rather than with the researcher, and thus get better picture of how the students perceived the matter in question, we interviewed five groups of six students each and interviewed these groups separately. Each group was from a different state school in the city of Trnava, Slovakia, and so was taught by a different chemistry teacher. To ensure as much variety as possible among the participants, we used purposeful selection criteria.

Instrument and Procedures

Our methodology was based on research conducted by Coll and Treagust in 2001, although we made some modifications: Firstly, our study involved primary school 8th graders, because chemical bonding is introduced at this stage in Slovakia. Secondly, we avoided direct questions about chemical bonding, because we wanted to know whether pupils could apply the knowledge gained at school to explain real life events.

In a semi-structured interview, we elicited the learners' mental models of the chemical bonding classifications through interactive dialogue between the researcher and the participants. The interview protocol comprised two tasks. Firstly, we showed the participants familiar samples of ionic, molecular, and covalent substances (common salt, sugar, water, and graphite) and asked them to describe how these substances hold together. To avoid influencing the students' way of thinking about the issues discussed, the researchers did not use any words with established scientific meaning before the participants mentioned them. Secondly, we asked about phenomena that are related to the notion of chemical bonding. For example, we asked the learners to explain certain processes (e.g. dissolving) and simply waited for their explanation in terms of chemical bonding. However, we did not determine the borders within which they could think about the process. We adopted this different approach because we were curious about whether pupils connect the macroscopic manifestations of matter with the concepts of chemical bonding and the particulate nature of matter learned at school. The pupils' descriptions of these phenomena allowed the interviewer to probe their familiarity with the chemical bonding models (Coll & Treagust, 2003). We chose familiar events in this part of the interview. For example, we asked students to explain (1) why common table salt is crushed while copper wire simply changes its shape under pressure, (2) the dissolving process, (3) crystallisation, etc. This activity was accompanied by extensive probing and questioning. For instance, we asked:

What does common salt consist of?

What happens if we hit a crystal of common salt with a hammer?

What happens if metal is hit with a hammer?

Why are the results different?

What is the smallest part of the common salt crystal?

What happens if we put a common salt crystal into water?

What will happen if we leave the salt water on the table for a few days?

How are the crystals formed?

What happens if a spoonful of sugar is heated above a candle?

What happens with salt under the same conditions?

Why is the result of these two processes different?

Why are salt, sugar, and graphite solid while water is liquid?

How is it possible that we can use graphite for writing?

Why are we not able to write using iron for example?

To avoid obtaining a limited or distorted representation, we used additional physical and verbal prompts to access maximal detail about the learners' mental models of chemical bonding. For example, if participants introduced the notion of an ion, they were asked to describe what they thought an ion was like and so on.

Learners were also encouraged to draw representations of their mental models of substances' structure during interviews. This method was successfully utilised in the research of Prokop and Zoldosova (2006). We chose the drawing method because it empirically demonstrates the high quality and sophisticated nature of the information that can be collected from young children (Pridmore & Bendelow, 1995). In our case, the use of drawing also prevented the need for direct questions about chemical bonding between particles; we were trying indirectly to gather evidence regarding the influence of the traditional teaching–learning process and syllabus on students' understanding of chemical bonding. Thus, it was important that the pupils' were unaware of our intentions. The pupils were given the following instructions to draw their representations of substance structure: *'Imagine that you are so small that you can step into the salt crystal. What would you see around?'* We asked about sugar, graphite, and water in the same manner.

After a pilot study involving 16 students was carried out in February 2012, the interview protocol was modified so that the learners' mental models were elicited in an open-ended fashion.

Thereafter, the research was carried out from March to April 2012. Thus, the learners had studied chemical bonding 5 months prior the interview. The time shift was purposeful, because we wanted to ensure that the pupils did not know which chemical concepts they should apply when considering the interview questions. We also wanted to reveal how much of information the students remembered after 5 months of non-contact with the chemical bonding concept.

Data Analysis

After the interviews, the transcriptions and drawings were evaluated independently by the two authors of this article. To maintain validity and reliability in the few cases where our point of view differed, we discussed the interview results and drawings until we agreed on the category. We focused mainly on students' mental models of the sub-microscopic world of particles and chemical bonds; specifically, we were looking for evidence that learners:

- (1) worked with the idea of the particulate nature of matter;
- (2) defined the basic particles of common salt as ions, sugar and water as atoms or molecules, and graphite as atoms;
- (3) held correct ideas about substance structure;
- (4) could explain how substances held together;
- (5) could identify the type of bond in a substance based on its physical and chemical properties;
- (6) could apply their knowledge of the chemical bonding concept when reasoning about the physical and chemical properties of substances.

RESEARCH FINDINGS

Particulate Nature of Matter

The group interviews revealed many of aspects of students' conceptions. For instance, in general, students *'don't believe that common table salt is made of organised, ball-like particles or atoms'* because they *'are not able to imagine that.'* However, they are curious about *'how scientists found out that matter consists of ball-like particles'*. Clearly, these pupils were not aware that a substance consisting of spherical particles is nothing like the model of matter introduced by scientists on the basis of experiment. Moreover, the students were not willing to trust the information transferred from a teacher who did not provide any evidence. Therefore, we can see that the students were hungry for constructivist knowledge, whereby they could form conceptions on their own.

Another general finding was that most pupils drew atoms as the smallest parts of salt, sugar, water, and graphite (Figures 1 and 2). We assume that this arose from a vague definition in Slovak curricular materials that *'all substances are composed of atoms.'* But can we say that table salt is made of atoms, rather than ions? From the drawings, it is clear that pupils might have been confused by this definition.

Moreover, nearly all pupils only considered the atom to be the smallest particle in substances that they have come across in classrooms, because they asked the interviewers whether atoms are also *'in wood, stone, people, animals, plants'*, and so on.

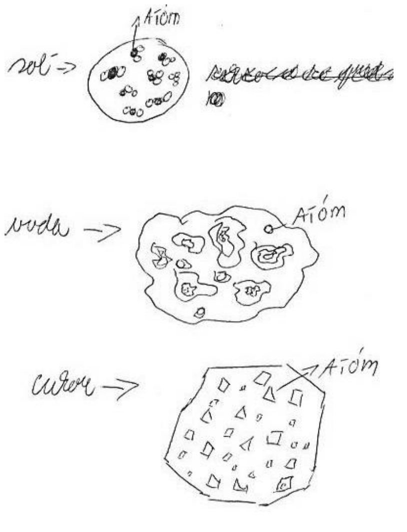

Figure 1. Pupil's drawings of the smallest particles—atoms—in common salt, water, and sugar

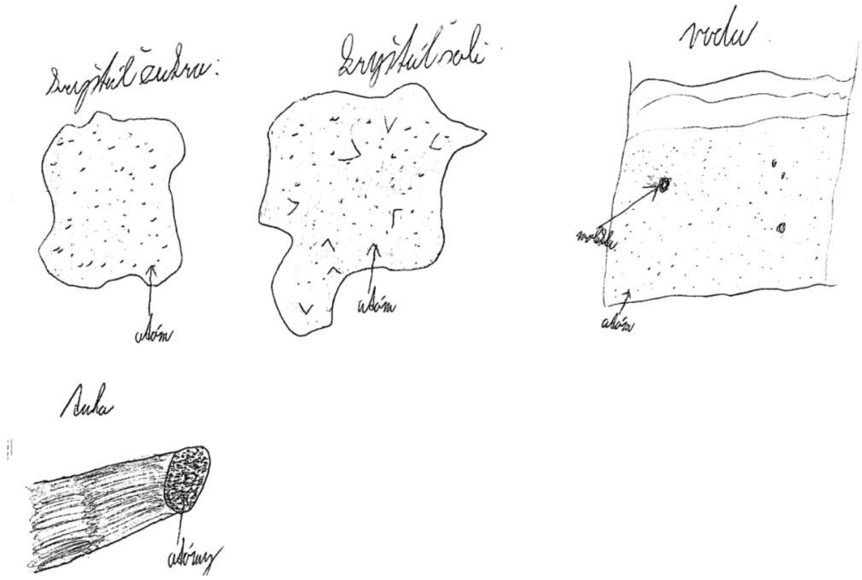

Figure 2. Pupil's drawing of the smallest particles—atoms—in sugar, common salt, water, and graphite

We identified another misconception that we think arises from the lack of modelling activities in chemistry classes: the notion that, in all substances, there are *'other particles'*. The pupils were not able to describe these further. Thus, they considered atoms *'to be part of substances'*, but not something that substances are built from (Figure 3).

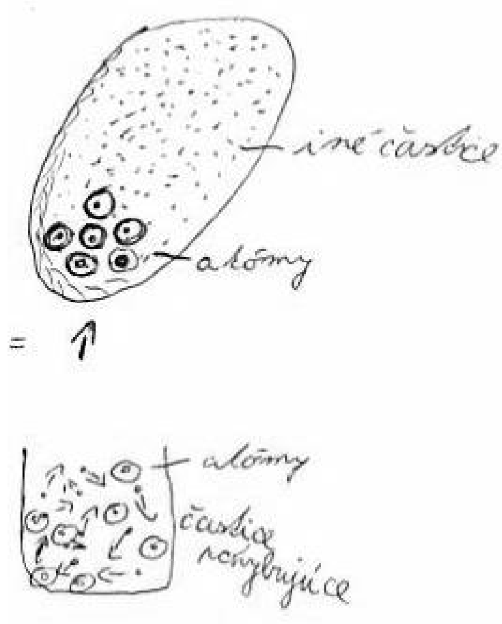

Figure 3. Salt and water consisting of atoms and vaguely identified *'other particles'*

Remarks on the Pupils' Conceptions of Structure

We discovered that, because students are given vague information (*'all substances are made of atoms'*) and no definitions or hierarchy of words like *'particles, atoms, molecules, and ions'*, the learners became confused and used these terms in inappropriate ways. Moreover, they considered these words to be equivalent, and did not perceive particles as being an umbrella term that encompasses molecules, atoms, and ions. They even spoke about molecules as the smallest particles of a salt crystal.

Each groups of students we interviewed had a different teacher, and we found that one group was somewhat different. Pupils of this group marked the particles of salt as ions; they labelled the graphite as atoms and the water molecules as bonded atoms. They were also aware of the right hierarchy of words *'particles, ions, atoms, and molecules'*. We wanted know why there was this difference, so we questioned students further and discovered that their teacher regularly used models of salt, graphite, and water, while emphasising the differences between those models for students. Furthermore, we noticed that learners from this group verbalised their thoughts and knowledge with unerring accuracy and confidence, they were very keen and excited about the topic discussed and admitted that they always look forward to chemistry classes in contrast to students from other groups.

However, none of the groups could adequately explain sugar particles. Pupils stated that sugar consisted of *'something sweet, sugar beet, crystals, ions, core of ion, particles'*. This shows that the pupils did not transmit their general knowledge automatically into a new situation, presumably because few educational materials emphasise the interrelations between the elemental composition of a substance and its physical and chemical properties. In general, pupils in the classes did not presuppose the properties of unknown substances based on those of a known substance. They did not even deduce the properties of elements from their position in the periodic table; instead, they memorised it. This is in contrast to the educational content and methods used by education systems that achieve high levels of success in international studies evaluating the skills and knowledge of students.

Pupils' Conception of Chemical Bonding

Ionic Bonding

Learners indicated various items the smallest part of a salt crystal. For example, they thought that it is *'made of matter, crystals, molecules, atoms, water, organised particles, electrons, neutrons and protons, smaller crystals, nothing—because it's transparent'*, and so forth.

The conception of matter made of *nothing* matches the Aristotelian view emphasising the continuity of matter. In the past, this was in contradiction to Leucippus' and Democritus' atomic theory (Serátor & Linkešová, 2000; Barke, Hazari, & Yitbarek, 2009). Similarly, as in the past, some of the students believed that matter was composed of *nothing*, while others believed it consisted of particles *'because when some surface becomes electrically charged and someone touches it, he gets 'a kick'. So there must be a piece of truth there.'*

With regards to chemical bonding in salt, we asked students about the dissolution process of salt in water and about crystallisation. Pupils did not connect these processes with the electrostatic nature of ionic bonding; they did not even view the bonding as an interaction between oppositely charged species formed by the transfer of an electron, even though they had learned about it. When asked about the different manifestations of heated salt and heated sugar, the students did not think about the process from a chemical point of view. They just stated that they *'can't figure out why there is this difference'*. They failed to connect the different properties of sugar and salt with the chemical bonds in these substances. It seems that, in Slovakia, chemical bonding is taught as something artificial that must simply be taught without any attempt to apply the concepts further.

When drawing small scale salt crystals, students did not connect their particles using any representations of bonding (Figures 2–4). They also confused molecules of water with particles in salt (Figure 5).

Figure 4. Salt crystals and small-scale drawings of ionic bonds

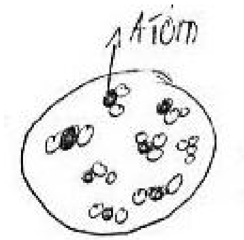

Figure 5. Small-scale drawing of a salt crystal, with molecules of water representing ionic bonding among particles of salt

Covalent Bonding

Learners' conceptions of covalent bonding were elicited using such familiar substances as sugar, water, and graphite. We were not interested in the intermolecular bonds in these substances, because the students had not learned about them yet.

Our questions about sugar uncovered a serious problem of chemistry education in Slovakia. The pupils could not infer anything about the particles of sugar, neither could they explain the different properties of sugar and salt under the same conditions (i.e. heating a spoonful of sugar vs. heating a spoonful of salt).

Our primary intention was to avoid asking pupils directly about the chemical bonding in sugar; we wanted to find out whether students could make the connection by themselves. However learners struggled to conceptualise covalent bonding when considering the properties of sugar. They did not view the atoms of sugar as being connected through electron sharing, even though they had learned about it (Figure 6).

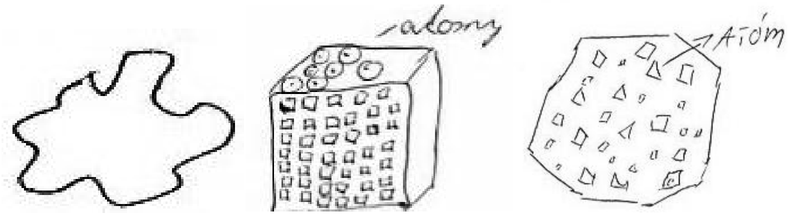

Figure 6. Small-scale drawings of sugar and its bonding

The pupils only learn about the periodic table after they have been introduced to chemical bonding. In this way, they lack the opportunity to connect the properties of e.g. sugar with its elemental composition and related chemical bonding. As we can see, this leads to conceptual chaos, as the pupils cannot meaningfully apply the chemical bonding concept.

Similarly as with sugar, learners described the sensory properties of water first; only later did they start to think about it from a chemical point of view. Nonetheless, students could not answer the question *'What is the smallest particle of water and how is it possible that it holds together?'* Instead, they automatically changed the question into another typical school question *'What can you find in tap water?'* After several prompts from the researchers, the pupils said that *'water consists of hydrogen and oxygen,* H_2O*, chlorine,* and *bubbles.'* We were curious what the pupils thought about the formula H_2O. Their answers were that it is *'a particle', 'a bubble', 'a ball' and 'a molecule'*. Some learners could not *'imagine how it is possible that in water there were ball-like particles. It was funny, because when you look through water it is transparent. So where would the balls be?'* However some other pupils replied that *'there are bubbles, and if you examined water through a microscope you would see them.'*

We assume that the answer *'ball'* is the learners' misinterpretation of a students' book model of matter based on ball-like particles. Unfortunately, as a bubble is similar to a ball, learners conflate those two concepts and come to the mistaken conclusion that the smallest particle of water is a bubble. In this way, Slovak students fell into a common trap associated with models of the submicroscopic world. To avoid this, teachers should work more extensively with models, while constantly emphasising what a model is, how it originated, and what limitations it has.

Students also mentioned the correct term molecule, but when we asked for more details, we discovered that this term is a memorised collocation: *molecule of water.*

Another interesting misconception was revealed through drawings. Some children supposed that *'the smallest particle of a water drop is a living blue ball'* (Figure 7).

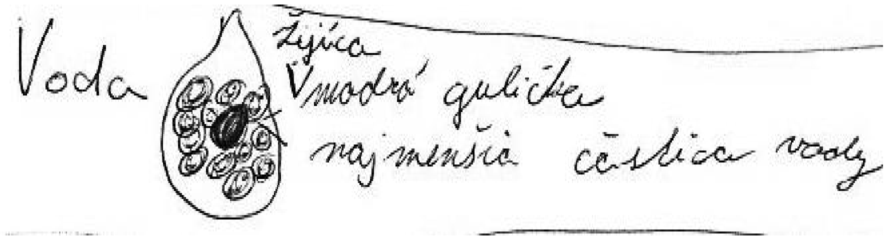

Figure 7. Child's drawing of a water drop with a 'living blue ball' depicted as the 'smallest particle of water'

Learners also explained that '*water holds together'* because of *'some kind of attraction'*, *'gravity'*, or *'ionic bonding'*. Some students thought that chemical bonding in water is *'different from chemical bonding in salt, because water has different properties. So atoms must hold together in a different way.'* One answer that we did not expect was that *'water doesn't have chemical bonds because it's a liquid. Only solids form chemical bonds'*. Here, we can see that pupils' conceptions of chemical bonding range from completely naïve to scientific, despite some uncertainty over terminology.

In the end, learners failed to show a good understanding of chemical bonding, even though they could apply it on an abstract level. It seems that we exposed a large gap in the students' learning that must be filled with appropriate teaching–learning content and methods that would lead students to fully understand and apply the concept of chemical bonding.

Our 8th graders had not learned about graphite in their chemistry classes. We asked them about the composition of graphite and they answered that *'it's made of stones, clay, paint, compressed dust, dust held together by some kind of force, graphite, carbon, C, coal, lattice, molecules, some particles different from atoms and molecules'* and finally *'atoms'*.

We asked whether graphite is made of any element in the periodic table. The pupils concurred with the answer *'No'*. Furthermore, the pupils' description failed to show a good understanding of the particulate nature of matter and the chemical bonding concept as regards this substance. Perhaps this emphasises that learners struggle to apply their existing knowledge to unfamiliar situations.

That said, one group of students that worked with models repeatedly provided more detailed explanations of chemical bonding in graphite: *'Carbon is arranged into layers. Between the layers there is a weaker bond than within one layer, and that is why we can draw with a pencil'*. But not even these students identified the bonds within a single layer of graphite as covalent.

Conclusions

We found that 13–14 year-old Slovak 8th graders have difficulties applying mental models to explain the properties of chosen substances. The models produced by the learners differed significantly from those to which they have been exposed during their chemistry classes. Coll and Treagust (2001) came to the same conclusion, although they were interested in the mental models of learners at higher levels of education. Our research indicated that Slovak learners have no hierarchy for concepts such as *particles, atoms, ions,* and *molecules*, and that they are unaware that the physical and chemical properties of any substance depend on its constituent elements, the types of particles therein, and related chemical bonding. This may be because the learning content is irrationally organised, with the particulate nature of matter being followed by chemical bonding, and only then by the periodic system of elements.

Above, we mentioned several categories to which we turned our attention while analysing the interviews and the drawings of learners. We found that learners had difficulty accepting the particulate nature of matter, even though their abstract thinking seemed to be developed enough that they could apply this idea when the mode of instruction was different. On the basis of their answers, we concluded that a shift toward constructivist-oriented science education would be reasonable.

The second category we focused on was the students' ability to identify the basic particles of familiar substances. Even though this ability is crucial to understanding chemical bonding, our 8th graders were not able to define the basic particles of table salt as ions, sugar and water as atoms or molecules, and graphite as atoms. This showed that chemical bonding is introduced to pupils in a sketchy manner, and that Slovak pupils lack the detail for this concept to be useful to them.

The third category targeted the correct conception of a substance's structure. This category was closely related to the students' ability to explain how a substance held together. We found that learners only *presupposed* some kind of attractive forces among particles, even though they had been exposed to the concepts of ionic and covalent bonding 5 months previously. They were not able to relate these *'some kind of attractive forces'* to the concept of chemical bonding. They struggled to recall the terms and nature of covalent and ionic bonding. The pupils talked as if they had never heard of chemical bonding, so the retention time of the chemical bonding concept is clearly very short in students of the Slovak education system, perhaps because teachers use an inappropriate mode of instruction based on transmission of facts, or because the concept of chemical bonding is not applied further in chemistry classes, even though the periodic table and the properties of compounds follow straight after. Instead, students are encouraged to memorise rather than infer the properties of elements' and compounds'.

The fourth tracked category was the ability of learners to identify the type of bonding in a substance on the basis its physical and chemical properties. This category was not fulfilled by learners either, suggesting that the current teaching model of chemical bonding has been unsuccessful.

Encouragingly, the interviews indicated that Slovak 8th graders do have the cognitive capacity to apply abstract concepts. However, they must be allowed to discover new information and carry out experiments that help them to incorporate abstract concepts into their existing mental scaffold; they must become familiar enough with these concepts to apply them further.

A number of pedagogical models presented in literature involve teaching with analogies, and several authors have suggested better teaching approaches (Coll & Treagust, 2001; DiGuiseppe, 2007; Driver et al., 1994; Naah & Sanger, 2013; Prokop & Zoldosova, 2006; Taber, 1998, 2002).

Implications for Teaching and Learning Practice

Based on our findings, we recommend several courses of action. The first and most important is that chemistry education should shift from a transmissive to a constructivist model of the teaching–learning process. Students must be actively engaged in science, not merely passive recipients of it. Additionally, students must be able to represent what they know, as well as to re-organise and re-create scientific knowledge into personally meaningful concepts and models (DiGuiseppe, 2007).

Furthermore, teachers and curriculum makers should eschew rote learning in favour of deductive–inductive activities, because *'to understand science, students must develop the ability not only to recall scientific knowledge, but also to analyse, utilise, and evaluate it in familiar and unfamiliar contexts'* (DiGuiseppe, 2007). In the case of chemical bonding, this involves determining the properties of elements and compounds on the basis of chemical bonding and vice versa.

Our third recommendation pertains to the goal of science education itself, which we believe should aim to produce *scientifically and technologically literate individuals who can read and understand common media reports about science and technology, critically evaluate the information presented, and confidently engage in discussions and decision-making activities that involve science and technology* (SCCAO, STAO/APSO, 2006 according to Ministry of Education, 2007).

In addition, teachers should constantly emphasise the advantages, origins, and shortcomings of the models they are using. In particular, teachers should avoid using the ball-and-stick model of salt, because students then confuse it with the covalent bonding model. Taber et al. made the same recommendation in 2002.

Our research, and that of Taber et al. (2002), suggests that the *'everything is made of atoms'* approach is a simplification. It is learned, but not readily developed into a more sophisticated understanding.

In summary, our results showed that reducing the content of chemistry education in primary schools has not automatically led to improvments in the students' achievements. On the contrary, it has caused a worsening of pupils' understanding because their knowledge became a collection of transferred facts with no mutual interrelations.

On the other hand, particles and chemical bonding are interesting topics for pupils, and these concepts can be used to develop abstract thinking. Therefore, new teaching–learning materials must be prepared that incorporate our recommendations and thus facilitate teachers' efforts. In the next research stages we will prepare such materials.

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