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Molecules Are Not Enough! Overcoming Students' Overgeneralization Tendencies by Comparing and Contrasting

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Abstract: Many students assume a molecular structure for all substances, even after being instructed on the topic. But why do students struggle to understand key concepts like chemical bonding? One of the reasons is students' tendency to overgeneralize: Students wrongfully transfer characteristics from familiar (*e.g.*, molecular substances) to lesser-known concepts (*e.g.*, ionic compounds). In this article, possible reasons behind this commonly observed tendency are discussed and a possible didactical solution is proposed. Comparing and contrasting approaches increased students' ability to distinguish between similar concepts in mathematics. The method of comparing and contrasting is therefore applied by simultaneously introducing the three types of chemical bonding to effectively tackle students' overgeneralization tendencies.

Keywords: Chemical bonding · Chemistry education · Comparing and contrasting · Overgeneralization

Dr. Adrian Zwyssig studied chemistry at ETH Zürich and obtained his master's degree in 2016. From 2018 to 2023, as part of his doctoral dissertation at ETH Zürich, he conducted research in the field of chemical education to diagnose and promote the understanding of chemical bonding among high school students. He is currently teaching chemistry at a Swiss Gymnasium (part-time) and conducting research as a postdoc at ETH Zürich (Prof. E. Stern). His research interests include cognitively activating learning and teaching methods, didactic questions, as well as the understanding of concepts, mental models, and (mis)conceptions of learners in the field of chemistry.

Introduction

What is a sodium chloride crystal composed of? Unfortunately, from the perspective of chemistry educators, many students will answer this question with 'sodium chloride molecules'. Many students wrongfully assume a molecular structure for all substances even after being instructed on the three types of chemical bonding intensively. In a more general sense, this means that students tend to incorrectly transfer characteristics from molecular to ionic substances, something we call overgeneralization. In this article, I first want to shed some light on possible reasons for the occurrence of such overgeneralization tendencies in chemistry in general. Therefore, I elaborate on humans' tendency to overgeneralize and present further reasons why chemistry might be especially susceptible to this tendency. I then discuss students' overgeneralization of covalent bonding and the typical challenges this tendency poses to further chemistry learning. In the next part, I will summarize the limited research conducted on students' learning and understanding of chemical bonding. Next, I present relevant research from the field of mathematics education concerning comparing and contrasting as a way of how to tackle similar challenges in mathematics.[1] And lastly, I present a method of how to better overcome overgeneralizations by using a comparing and contrasting approach to teaching about chemical bonding.

Overgeneralization is in our Human Nature

Where does this tendency to overgeneralize come from? The simple answer is: humans are prone to overgeneralize. On many occasions, it is beneficiary to build categories and generalize, that is to transfer characteristics from the known to the unknown subject. Gigerenzer *et al.*[2] describe in their book 'Simple Heuristics Make Us Smart' that it can be beneficial to infer something using simple heuristics. If, for example, asked which city has a higher population, Schlossrued or Zürich, many would correctly assume it to be Zürich since they have heard about the city before, whereas they have not heard about Schlossrued with a low population. Using simple heuristics is also efficient. It can be time and energy-consuming to look for and consider all cues given and rationalize every decision-making at all times. In most real-life settings most of the information is not even accessible and time is of the essence. In another paper Todd and Gigerenzer[3] argue that the process of looking for more and more information to decide when to stop the decision-making process (*i.e.*, optimization under constraints) might even be more energy-consuming and is likely not an efficient way for fast and frugal human reasoning. To sum up, since simple heuristics are often useful, students tend to overgeneralize and it should not come as a surprise that students overgeneralize from situations they have encountered before, for instance by transferring the idea of molecules to ionic compounds.

Why Generalization Is Desired but Overgeneralization Is Not

While students' ability to deduce general principles from more specific examples should be promoted, overgeneralization tendencies should not. Chemistry is an experimental science and its origin stems from the interest in the properties and reactivity of different substances. The seemingly indefinite possibilities of how to combine atoms of different elements inevitably lead to a huge variety of reactivities and properties of substances. This variety may not only be overwhelming and challenging for students to organize coherently but has long posed – and arguably still poses – a challenge for scientists in the field of chemistry. Experts have hence always strived to generalize and deduce general patterns and principles to

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tame this wilderness of properties: The introduction of one of the most important tools of chemistry itself, the periodic table, is only one of these examples. Dmitri Mendeleev and Julius Lothar Meyer strived to find similarities in properties and reactivity and arranged the elements accordingly. The more general view on elements and their properties even allowed for the prediction of elements and their properties that had not been discovered at the time. This example illustrates the usefulness of generalization in chemistry. Since chemistry educators constantly strive to induce students' ability to generalize phenomena and observations, it should not come as a surprise that students are not automatically aware of where the line of wanted and unwanted transfer from the known to the unfamiliar or unknown lies. If left unchecked, students tend to overgeneralize, and this can lead to a faulty understanding of core principles in chemistry. For instance, students with a molecular understanding of sodium chloride crystals will not fully understand the composition of an ionic compound. They might wrongfully transfer characteristics from molecular substances to ionic compounds: For example, they might infer neutral charges of ions, the pairing-up of ions, or the presence of intermolecular forces in an ionic compound. These misconceptions may hinder further learning and conceptual understanding of more complex topics in chemistry.

We Cannot See the Atomic and Molecular World

Students' overgeneralization tendencies are also observed in other disciplines, but chemistry might be especially susceptible since the atomic and molecular world cannot be observed by the human eye. For novices, with limited knowledge of the properties of substances, it is very tempting to overgeneralize in the light of superficial similar properties. They are likely to make quick assumptions based on a familiar substance in their daily life, such as ice. This could lead them to mistakenly apply its properties to a substance they know less about, like sodium chloride (NaCl), which has a similar crystalline structure but is held together by ionic bonding. Molecules of limited size and atoms are so small that students need to imagine the composition of substances. Chemists and chemistry educators came up with different methods of how to best represent such atomic or molecular structures (*e.g.*, with physical models or illustrations). However, to many students, these models remain an abstract representation (*i.e.*, letters and lines), which are more prone to misconceptions than well-understood concepts.[4] Imagining the molecular world and the composition of substances does not come easily to all students, hence it is necessary to spend a great deal of time fostering students' mental representation of such entities. For example, water (H_2O) is comprised of many water molecules, and each of those consists of one oxygen atom and two hydrogen atoms with an angled arrangement (v-shape). Following the successful assimilation of such representations pertaining to molecular entities, students are subsequently required to exhibit cognitive vigilance, refraining from hasty inferences and unwarranted imposition of molecular frameworks upon all substances. Upon being introduced to ionic compounds (*e.g.*, sodium chloride), it becomes imperative for students to construct a novel representation of the different bonding situation, whilst circumventing the undue transference of pre-existing knowledge of the representation of molecular substances. To put it simply: to know about *molecules (alone) is not enough*. However, as long as we are not able to convey comprehensible models, students are left alone in how to organize their knowledge and representation of the chemical and microscopic world. Such uncertainties could play a vital role and act as gateways for misconceptions, as can for example be observed when learning about chemical bonding.

Students' Tendency to Overgeneralize Covalent Bonding

While chemistry experts know the differences between the three types of chemical bonding, novices struggle to keep them apart and often overgeneralize the covalent bonding type. Additionally, it remains a challenge for many students to correctly distinguish intermolecular forces from chemical bonds as well as interpret the relative strength of intermolecular interactions and chemical bonds. The prevalence of such challenges in learning about chemical bonding is supported by the findings of my dissertation[5] as well as previous research conducted in other countries and different school systems.[6] In my dissertation, I investigated Swiss Gymnasium students' understanding of chemical bonding before and directly after they were taught the topic and shortly before the start of their studies of a science subject at ETH Zürich. The results showed that students tended to overgeneralize the covalent bonding type even before they were taught about chemical bonding. Misconceptions resulting from overgeneralization were still present in students' views after they were taught about chemical bonding. The persistent nature of such misconceptions was made more salient by the fact that they were still detected before the start of their university studies. Before attending lectures, approximately 40% of natural science first-year students (N = 1946, 2021–2022, ETH Zürich) held major misconceptions and showed difficulties keeping the different bonding types apart.[5] Because chemical bonding is one of the core topics of the chemistry curriculum at the Gymnasium it was to some extent surprising to see that chemical bonding was not understood to a larger extent, even though in Switzerland typically more than 25 lessons are spent to cover the topic.

The common approach to teaching about chemical bonding in Gymnasium is to teach each bonding type one after the other in a *sequential* manner with a short comparison at the end of the sequence. A possible rationale for this method is the attempt to separate the different types of chemical bonding more clearly. This approach follows the logic that if taught separately, it will help students keep these similar concepts separate in their mental representation. The numerous discussions with chemistry teachers led me to the assumption that it was already common knowledge that students had difficulties with holding the different bonding types apart. They assured me that students were told multiple times that sodium chloride is not a molecule. Hence repeatedly telling students not to overgeneralize, for example, "sodium chloride is not a molecule but an ionic compound", does not suffice to change all students' views of ionic bonding sustainably. Additionally, the common sequential instruction of the bonding types might not foster awareness of the differences between the bonding types strongly enough. This raises the question: What could be done to overcome students' overgeneralization tendencies and foster a sustainable conceptual understanding of chemical bonding and related concepts?

How to Overcome Students' Overgeneralization Tendencies

While there are investigations into students' misconceptions of chemical bonding, empirically evaluated methods or attempts to overcome the challenges involved in learning about chemical bonding are rare. In their review article, Hunter *et al.*[7] describe only a few such investigations conducted until 2020. Unfortunately, none of the investigations cover all types of chemical bonding, and many are explorative or lack empirical evaluation. I will therefore discuss a promising approach from mathematic education research. Similarly to the discussed problems in learning about bonding, students had difficulties in mathematics distinguishing different principles in algebra. There students often confuse the algebraic principles for addition and multiplication of variables (*e.g.*, $a + a + a = 3a$ versus $a \cdot a \cdot a = a^3$). Those sets of principles are typically introduced in sequential order as is the case for the introduction of the different types of chemical bonding. Ziegler and Stern[1a] were able to show that students' understanding profited strongly when those two principles were introduced *simultaneously* and *compared and contrasted*. Students were working on self-learning materials and were randomly assigned into two groups: half of the students were introduced to the principles in sequential order, *i.e.* first addition and then multiplication principles. The other half was assigned self-learning materials with a simultaneous introduction to addition and multiplication principles. Students generally had a harder time working on different types of principles at the same time. However, in the long term they outperformed students from the sequential group and made fewer mistakes. The results were similar in a follow-up study with the same conditions but with direct instruction.[1b] These studies show that the contra-intuitive idea of simultaneously introducing two complex concepts (*i.e.* increasing the cognitive load more) can be beneficial for students in the long term. Bjork[8] argues against removing too many obstacles and challenges during learning despite the apparent struggle of some students. What Bjork describes as *desirable difficulty* (*i.e.,* the additional challenge due to the simultaneous exposure to different concepts at the same time) might be key to the long-term benefits of this method.

Teaching Materials Based on Comparing and Contrasting

These studies built the foundation for a *comparing and contrasting* approach to teaching about chemical bonding. In cooperation with the MINT Learning Center of the ETH Zürich (Dr. Juraj Lipscher and Dr. Ralph Schumacher), we designed teaching materials that introduce the three different bonding types simultaneously. Based on the concept of electronegativity and the classification of elements into metals and non-metals, three main groups of substances with three different types of bonding situations can be presented:

1. Non-metal and non-metal – covalent bonding
2. Metal and metal – metallic bonding
3. Metal and non-metal – ionic bonding

Since the simultaneous introduction of three concepts at once may lead to cognitive overload,[9] students are supported in their mental organization of chemical bonding: An overview illustration, containing the most important features of how to distinguish the different bonding types, is handed out to students. The illustration is used as a roadmap and consulted and revisited multiple times when going through the teaching materials. The roadmap can be retrieved from my dissertation[5] or a book chapter on cognitive activation by comparing and contrasting[10] I contributed to.

After the introductory lessons, the three bonding types are covered in more detail: ionic bonding first, then metallic and covalent bonding last, to break the dominant representation of the covalent bond in many students' minds. There is another important main difference to conventional teaching materials: As soon and as often as possible, the bonding situations are *compared and contrasted* with each other to highlight the differences between bonding types. A reoccurring experiment with a focus on the electrical conductivity of water, sodium chloride, and aluminum has the aim of making the differences between the different bonding situations more salient on a macroscopically observable level (see Table 1).

Common misconceptions found during the investigations of natural science freshmen's understanding of chemical bonding were also taken into account when designing the materials. The interested reader can find a detailed description of the development and the main ideas and rationale behind the design of the teaching unit (comprising around 23 lessons) in my dissertation or by contacting the author of this article.[5]

Effectiveness of the Comparing and Contrasting Approach

In my dissertation, I described an intervention study at the gymnasium level (N = 326, mean age 16 years, grade 10).[5] In this study, conventional teaching materials were compared to the comparing and contrasting materials and investigated for their effectiveness. The findings reproduce similar results to the previously described studies by Ziegler and Stern:[1] The simultaneous introduction of concepts promoted conceptual understanding more strongly than sequential instruction of the concepts. Students outperformed the control group (sequential instruction) directly after and as well as three months after the topic of chemical bonding was taught in class. This shows that *comparing and contrasting* can effectively be used in the context of chemistry education. The simultaneous introduction of the three bonding types is cognitively more demanding for students. However, students profit from this *desired difficulty* and acquire a more persistent conceptual understanding of chemical bonding with fewer misconceptions in the long term.

Conclusions

While experts distinguish between different bonding situations with ease, doing so remains a challenge to many students, even after being instructed on the topic for more than 25 lessons. The nature of chemistry as a subject with its categorization and generalizations of similar groups of substances, builds an optimal growing ground for overgeneralizations and misconceptions, for instance by using superficial properties as grounds for inferences on unknown substances. Such misconceptions may hinder further learning in chemistry and actively hinder students from deepening their understanding of certain phenomena connected to their environment and chemical phenomena (*e.g.,* explanation of relative melting temperatures of molecular and ionic substances). Research in learning and instruction suggests the use of comparing and contrasting activities if students tend to confuse similar concepts. The presented comparing and contrasting materials on chemical bonding take up this idea with a simultaneous introduction of the three bonding types. Successful teaching about chemical bonding may be achieved in a variety of ways, with associated advantages and disadvantages. I would not go so far as to state that this comparing and contrasting approach is the only way to successfully teach about chemical bonding. However, the empirically proven effectiveness of the mentioned comparing and contrasting materials may serve as a motivator to have a deepened look at the carefully designed teaching materials. In the past, the understanding of chemistry has profited from the adaption of ideas of how to think about chemical phenomena and new methods have

Table 1. Conductivity experiment with water, sodium chloride, and aluminium

Substance	*pure water (liquid)*	*sodium chloride (solid crystal)*	*sodium chloride in water (solution)*	*aluminium (solid)*
Electrical conductivity	none[a]	none	yes	yes

[a] Electrical conductivity due to autoprotolysis is discussed when discussing acids and bases.

been introduced to further investigate the wonders and unknowns of chemistry. Rethinking the way we teach about certain topics in chemistry might similarly enrich students' understanding of the chemical world in general and help convey the idea that knowing about molecules is in fact not enough.

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