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Reflections on Challenges and Rewards in Teaching Chemistry

Juraj Lipscher*

Abstract: The author gives his personal and subjective view of the manifold challenges in teaching chemistry and argues that, in most cases, the challenges lie in the difficulty of balancing two opposing concerns and thus can be formulated as dilemmas. He discusses, among others, the role of general education, language skills, finding the correct level of simplification, and specific problems of teaching the language of chemistry. Furthermore, he points out possibilities to overcome the pitfalls inherent in teaching chemistry and describes examples of the challenges and their solutions. Awareness of individual challenges is the prerequisite for finding solutions and improving one's teaching.

Keywords: Challenges · Chemistry · Education · Gymnasium · High school · Teaching

Juraj Lipscher was born in 1948 in Prague, former Czechoslovakia. He studied physical chemistry at the University of Zurich, graduating with a PhD in 1982 under the supervision of H. Fischer. After achieving the Diploma for teaching at higher secondary schools (*Höheres Lehramt*) from the University of Zurich, he taught chemistry at the Kantonsschule Baden from 1982 to 2014. During his professional career as a chemistry teacher, he was also responsible for the exams in chemistry at the Swiss Federal secondary school exams (*Schweizerische Maturaprüfungen*) (1993–2022), he was a member of the Swiss Chemistry Commission (*Deutschschweizerische Chemiekommission*) (1997–2014) and was active in the education of future teachers at the ETH Zurich (*Praktikumslehrer*) (1999–2014). He was awarded the Balmer Prize of the Swiss Chemical Society in 2010 for innovations in the teaching of chemistry. Lipscher was a research fellow at the MINT Learning Center of the ETH Zurich from 2013 to 2021 (Institute of Cognitive Studies, Prof. Dr. Elsbeth Stern).

1. Introduction

The following paragraphs delineate my personal subjective views distilled from my experience and reflections made during my professional existence as a chemistry teacher. I have been retired for 9 years now, after 32 years of soldiering in the classroom of a Swiss high school, and the temporal distance allows me an exterior and impartial view. But one must also be wary of romanticizing the good old days and glossing over genuine challenges. Moreover, the elders have an unpleasant inclination of wanting to patronize and advise the younger practitioners who do not yet have the benefit of hindsight.

One question emerged in the course of writing this article: were the challenges encountered in my career isolated thorns in the flesh of an educator or could there be a common denominator to them? I will argue in the following paragraphs that many a challenge in the chemistry classroom can be traced back to an effort to balance two opposing concerns and thus might be formulated as a dilemma.

Correspondence: Dr. J. Lipscher, juraj@lipscher.ch, Aarestrasse 29 A, CH-5102 Rupperswil, Switzerland

2. General Challenges

Seeking to isolate the unique challenges pertaining to teaching chemistry, one inadvertently slides into the realm of challenges inherent to all educational activities.

2.1 *Allgemeinbildung*

One of the basic tenets of Swiss high schools (*Gymnasium*) is to provide the students with a basic education in a dozen individual subjects, ideally resulting in a balanced body of knowledge. This knowledge body should not only prepare the students for their university studies but also constitute the building blocks of their *Allgemeinbildung* (general knowledge), a term resisting a proper translation into English. Teachers are required to educate the students in the skills and specific areas of knowledge pertaining to their subject on the one hand and to embrace aspects broadening the general education on the other hand. The challenge of addressing areas of cultural, philosophical, and societal interest in subjects such as chemistry lies in the necessity of a solid theoretical foundation for a qualified analysis of these problems. The advantage of such an approach lies in putting the subject-specific pieces of knowledge in a broader context and anchoring them in students' prior knowledge. Here, I do not only mean the mere application of chemistry to practical or environmental concerns.[1] It is also the broader meaning and implications of the specific chemical knowledge that we ought to point out to the students.

The emergence of ideas about the inner workings of the atom can be put into the context of Modernism, the societal, technological, and cultural changes at the end of the 19th and the beginning of the 20th century.[2] We can discuss the philosophical implications of quantum theory in addition to learning about the structure of the electron shell and explaining the chemical bond.[3] Discussing the role of enthalpy and entropy in chemical reactions can contribute to understanding the ramifications of the present-day energy crisis.[4]

Why Ask Why?

The building blocks of practically all the protein molecules found in living organisms are twenty specific amino acids which then combine in a certain sequence to build a protein molecule. This is an important fact we teach in the section on biomolecules. But why is the immense variety of biological protein molecules built from this universal stock of exactly twenty specific amino acids? Why these specific amino acids and no others? And why exactly twenty and why not less or more? And why do the alphabets of all word-based languages consist of a similar number of letters, namely around twenty-five? The answers to these questions are not altogether clear[5] but asking them can lead to a discussion of the origin of life on Earth and might titillate the imagination, and yes, even increase the motivation of the students.

Utilitarianism

Students might confront the teachers with questions on the order of 'What is the use of X for me?', where X stands for any sliver of subject-specific knowledge. The answers should not be limited to explaining why X might indeed become useful to the student. The Swiss Gymnasiums are not vocational schools preparing students for a specific profession, but as I mentioned above, provide the students with general education, and prepare them for their university studies. Teachers should thus be wary of utilitarian tendencies among the students and take the time to ensure that the purpose of education as represented by the Swiss Gymnasiums remains clear to them. On the other hand, we should not construe this statement as a justification for overburdening the students with senseless details which are indeed of no use to them.

We should provide students with relevant subject-specific knowledge and skills but not lose sight of the general implications and context of the specific knowledge.

2.2 *General Language Skills*

Our students should be able to improve their capability of coherent and differentiated verbal and written expression and all subjects including chemistry ought to contribute to the development of their language skills. Conversely, adequate language skills facilitate students' learning.[6] We should expect an educated young person, as an example, to describe a tiny difference as *infinitesimal* and a great and notable change as a *quantum leap* instead of exclusively relying on the words *small* and *large*.

Throwing around Latin proverbs and the names of Greek gods is certainly overrated as a sign of erudition. Nevertheless, a small excursion into the origin of the names of chemical elements can help our students to orient themselves in the historical and mythological allusions they might encounter in literature. This is not only true for the element titanium named after the pre-Olympian gods because of its mechanical strength. The similarity of the elements tantalum and niobium can be put into the context of the tragic fates of both Tantalus and his daughter Niobe, pointing out the origin and rationale of the proverbial 'Torment of Tantalus' and the etymology of the English verb to tantalize.[7] Or, in a different context, the names of the two elements polonium and francium can be related to the two countries which played a role in the life of the discoverer of polonium and double Nobel prize laureate Marie Curie-Skłodowska.[8]

We should provide students with relevant subject-specific knowledge and skills but not lose sight of improving their ability to express their ideas in correct, coherent, and adequate language.

2.3 *Heterogeneity of the Student Body*

The heterogeneity of the student body poses a well-known challenge in teaching any subject in a classroom setting. The students come to us equipped with differing levels of prior knowledge and intellectual capabilities, which determine their possibility to absorb the subject matter. But our students differ in their interests as well, and we can assume that the interests of the students determine their willingness to absorb the subject matter. As a rule, we are teaching future chemists, biochemists, medical doctors, environmental scientists, future economists, linguists, and attorneys at law, and ought to adapt our teaching to the needs of all of them. This may appear nigh impossible to achieve and is indeed one of the causes of considerable hardship for high school teachers.

We should provide students with relevant subject-specific knowledge and skills but not lose sight of the differences in the personalities and future vocational trajectories of our students.

2.4 *Epistemology*

Epistemology is a big word and introducing its tenets in teaching high school chemistry might seem and is indeed unnecessary and even preposterous. But reflecting on the ways how mankind acquires knowledge in the context of a specific topic might enhance the understanding of this topic and even provide additional motivation for the students.

Our students can easily grasp the concept of the predictive power of a scientific theory. A scientific theory has high predictive power when it is not only able to describe and explain existing phenomena but can also predict phenomena hitherto unknown. An instructive example would be the discovery of the periodic table. Mendeleev not only discovered the periodicity in the properties of the elements but also recognized the predictive power of this principle. This enabled him to predict the existence of yet-to-be-discovered elements. Additionally, discussing his unsuccessful predictions caused by his inability to find the correct placement of the transition elements can be just as educational.[9]

Another example suitable for discussions in more advanced courses (*Schwerpunktfach*) would be the difference in the predictive power of the Bohr model and the Orbital model of the electron shell. Niels Bohr based his theory on two postulates and was able to describe some aspects of the behavior of electrons in atoms, *e.g.,* the lines in the emission spectra of atoms. However, his theory did not provide a causal explanation for these phenomena. The subsequent discovery of the wave nature of the electron and the realization that electrons enclosed in the atom can be described as standing waves led to the causal explanation of the discrete energy levels of electrons in atoms, the development of the Orbital model of the electron shell and the prediction of a whole plethora of new phenomena.[10]

We should provide students with relevant subject-specific knowledge and skills but not lose sight of the path which led to this knowledge.

3. Specific Challenges in Teaching Chemistry

3.1 *Structure-Property Relationships*

We can posit that these relationships are the mainstay of chemistry education at all levels. Our students should become aware of the fact that phenomena encountered in nature, or their everyday life (macroscopic world) can be explained by examining the structure of the particles involved (microscopic world). The unceasing oscillation between the observable macroscopic world and the unseen world of submicroscopic particles is the hallmark of accomplished chemistry teaching. Examples are too numerous to count, but how about explaining the peculiar properties of water, the secondary structure of protein molecules, the structure of DNA molecules, or the stickiness of ice cream by understanding the hydrogen bonds? And how about explaining the vast differences in the properties of carbon dioxide and quartz, seeing that their formulas are so similar?[11] And, in more advanced courses (*Schwerpunktfach*), how about explaining the color of painters' pigments such as azurite (basic copper carbonate), Thénard's blue (cobalt aluminate), or Prussian blue (iron(III) hexacyanoferrate(II)) by understanding the Ligand-field theory or the basics of Charge transfer complexes?[12]

One of the challenges in this area is the clear distinction between the microscopic and macroscopic worlds. It is exceedingly incorrect to mix the two and utter statements such as 'water consists of two hydrogen atoms and one oxygen atom', or 'sulfur molecules are yellow'.

We should awaken the curiosity in our students about the reasons for natural phenomena and strengthen their belief that chemistry can help them to understand the world around them.

3.2 *Scope of Abstraction*

The high school chemistry curriculum spans an enormous range of abstraction levels from the electrons as standing waves and abstract chemical formulas to tangible and directly observable phenomena such as soap bubbles or the dissolution of common salt in water. In this respect, chemistry is a unique subject.

We should consider this span of abstraction when deciding on sequencing the curriculum. The author would not recommend introducing chemical formulas and reaction equations too early, *i.e.*, before the students have grasped the basics of the atomic structure and gained at least a basic understanding of the chemical bond. These concepts give them the foundations from which they can mount the next plateau of abstraction. The challenge lies in our awareness of the numerous abstraction steps inherent to even the simplest chemical formula. We should avoid overwhelming the students with abstract concepts too early, as it might be one of the main reasons for the lack of popularity of chemistry as a subject.

We should provide students with relevant subject-specific knowledge and skills but not lose sight of the degree of abstraction inherent in the concepts we are teaching them.

3.3 *Language of Chemistry*

The formalized language is one of the main characteristics of chemistry as a subject facilitating the formulation of ideas and solving chemical problems. It is not the language of chemistry itself posing problems for chemists; it is the teaching of this language to novices that is fraught with challenges.[13]

The first challenge mentioned in the previous section concerns the abstract nature of chemical formulas and equations. The next challenge is caused by the 'educational' inadequacies of the language of chemistry. In other words, the students' difficulties in grasping certain basic concepts are inherent in the language of chemistry itself. How can we expect a new student to look at the two formulas NaCl and HCl and conceive of the fundamental differences between the two substances these formulas represent, when the formulas look so similar? And how can we expect them to grasp that there are no individual particles (such as molecules) in a crystal of sodium chloride when presented by the formula NaCl? As the chemical community is unwilling to introduce formulas for salts that would reflect their microscopic structure, *e.g.* $\{NaCl\}_\infty$, we must be wary of the possibility of misconceptions formed by our students caused by the above-mentioned inadequacy in the language of chemistry. We ought to be aware of this unfortunate state of affairs and actively help the students to avoid these stumbling blocks. A. Zwyssig investigated the extent of such misconceptions both in high school and university students in collaboration with the author of this article.[14] Also see his article in this issue.[15]

The latest developments in artificial intelligence will certainly bring about new challenges and new possibilities in the realm of education. The chemistry capabilities of the large language models, such as GPT-4, are reaching levels that we soon will be unable to ignore.[16]

We should provide students with a solid knowledge of the formal language of chemistry but be aware of its inherent pitfalls and possibilities for misconceptions.

3.4 *Simplification*

One of the obvious challenges in teaching chemistry in high schools is deciding on the correct level of simplification. And what could be a better example of this challenge than the choice of the model of the atom? Some of us choose the Bohr model relying on its relative simplicity and its ability to explain the beautiful and 'exocharmic' experiments[17] with colored flames, atomic spectra, and, to a limited degree, the periodic table. This choice has two distinctive disadvantages. On the one hand, exactly defined electron orbits contradict a fundamental law of nature, namely the uncertainty principle. On the other hand, the Bohr model relies on postulates and cannot be derived from other more fundamental natural principles and does not provide a causal explanation for the behavior of electrons in atoms, as I have argued in the above paragraph on epistemology. The obvious alternative to this approach would be the introduction of the mathematical description of the electrons in atoms by the Schrödinger equation, which is, by all measures, a hopeless proposition in the context of a high school chemistry curriculum. So, how could we negotiate the narrow waters between the Scylla of an incorrect model with low predictive power and the Charybdis of the intractable (at our level) mathematical treatment of the electron shell of an atom? There is no correct answer to this dilemma, and that is the truth we ought to be aware of while contemplating viable solutions. The author has developed and successfully taught a qualitative and simplified teaching unit employing the necessary quantum mechanical principles while circumventing the use of the mathematical apparatus.[18]

We should take the cognitive capabilities of our students into account while being wary of not oversimplifying at the cost of correctness.

3.5 *Quantitative Versus Qualitative Approach*

Let us imagine a discussion of the greenhouse effect and global warming in a classroom setting. One student points to the burning of fossil fuels as the principal cause of global warming due to the increased concentration of carbon dioxide in the atmosphere. The next student argues that the natural degradation of biomass produces significantly larger amounts of carbon dioxide, and the anthropogenic amounts are negligible. It is evident that both students must employ quantitative arguments to continue the discussion and finally decide on their difference of opinions. This example is representative of a multitude of problems encountered in the chemistry classroom and we are obliged to include chemical calculations in our curriculum and raise the awareness of our students for the necessity of a quantitative approach to chemical problems.

On the other hand, it is also true that the students can become too involved in the calculations to the detriment of their actual understanding of the problem. We should teach our students to calculate the reaction enthalpies, but it is also not without merit to show them how to estimate these values by considering the polarity and multiplicity of the bonds in the substances participating in the reaction. Why not write the equation for the decomposition of nitroglycerine or a similar substance (without mentioning its name or properties) on the blackboard and let the students ponder the question if such a reaction might be exothermic or endothermic?

We should teach our students the skills for a quantitative approach to chemical problems but not lose sight of the conceptual understanding of the underlying principles.

3.6 *Exception to the Rules*

I would argue that we encounter exceptions to the rules too early in the chemistry curriculum, and I wonder if this is the case in other science subjects such as physics or biology. Our students learn as novices that a covalent bond is formed by two atoms with singly occupied atomic orbitals, only to be confronted by the radical structure of the molecules of the two environmentally important nitrogen oxides NO and NO_2. They learn the rules governing the construction of Lewis formulas of molecules and have difficulties understanding the existence of molecules such as carbon monoxide. The main challenge in this case is not the difficulty in rationalizing the existence of the triple bond in the carbon monoxide molecule, but, much worse, our inability to provide the students with *a priori* rules for predicting the existence of this molecule. They are led to accept the existence of the carbon monoxide molecule as a given fact and then learn to *a posteriori* rationalize its molecular structure.

We should find the middle ground between providing the students with an illusion of ironclad rules in chemistry and demotivating them with the notion of chemistry's disordered and illogical nature.

4. Conclusions

We must become aware of the described challenges as the first step to improving our teaching. However, the never-ending quest for ways to master these challenges harbors possibly the largest satisfaction our profession provides. We can invest all our abilities and our creativity into solving these challenges and observe the improvement in our students' understanding. Moreover, we might even engage our students in a meta-discussion of such challenges to illustrate the character and the nature of our science.

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