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ARTICLE

The Cultural Argument for Understanding Nature of Science

A Chance to Reflect on Similarities and Differences Between Science and Humanities

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Abstract Understanding Nature of Science (NOS) is a central component of scientific literacy, which is agreed upon internationally, and consequently has been a major educational goal for many years all over the globe. In order to justify the promotion of an adequate understanding of NOS, educators have developed several arguments, among them the cultural argument. But what is behind this argument? In order to answer this question, C. P. Snow's vision of two cultures was used as a starting point. In his famous Rede Lecture from 1959, he complained about a wide gap between the arts and humanities on the one hand and sciences on the other hand. While the representatives of the humanities refer to themselves as real intellectuals, the scientists felt rather ignored as a culture, despite the fact that their achievements had been so important for Western society. Thus, Snow argued that as these intellectual cultures were completely different from each other, a mutual understanding was impossible. The first European Regional IHPST Conference took up the cultural view on science again. Thus, the topic of the conference "Science as Culture in the European Context" encouraged us to look at the two cultures and to figure out possibilities to bridge the gap between them in chemistry teacher education. For this reason, we put together three studies—one theoretical and two independent research projects (one dealing with creativity in science, the other with

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scientific laws and theories) which contribute to our main research field (promoting an understanding of NOS)—in order to address the cultural argument for understanding science from an educational point of view. Among the consented tenets of what understanding NOS implies in an educational context, there are aspects which are associated mainly with the humanities, like the tentativeness of knowledge, creativity, and social tradition, whereas others seem to have a domain-specific meaning, like empirical evidence, theories and laws, and the role of technology. Thus, the cultural argument for understanding science invites us not only to consider domain-specific concepts but also to reflect on similarities between science and the humanities by way of examples.

1 Introduction

The educational challenge to teach science not as a body of knowledge but as a cultural activity is in accordance with a claim that Henri Poincaré stated in 1902:

> Science is built up of facts as a house with stones, but a collection of facts is no more a science than a heap of stones is a house. (Poincaré 1905)

A few years later, the Central Association of Science and Mathematics Teachers (1907) advocated the idea of Nature of Science (NOS) as an important goal for science education (Lederman 2007). Since then, there has been much effort, first in Anglo-Saxon countries, then also in our country, to improve an understanding of science that goes beyond the collection of facts. But it turned out that determining what NOS could mean in an educational context was not an easy enterprise (Lederman 1999). Especially, philosophers of science as “those who study purported tenets of science” (Alters 1997) did not agree with basic aspects of NOS. Depending on their methodological and epistemological position (e.g., positivism, falsificationism, structuralism, Feyerabend’s individualism) they arrive at different tenets (cf. Chalmers 1999). Though science educators were aware “that there is considerable disagreement regarding certain issues in the NOS among people interested in the philosophy of science” (Smith et al. 1997), they try to defend them from an educational point of view. Hence, in 2003, several experts from different disciplines tried “to determine empirically the extent of agreement among scientists, science communicators, philosophers and sociologists of science, and science educators about those aspects of nature of science that should be an essential feature of the school science curriculum” (Osborne et al. 2003). The results of the Delphi study overlapped mostly with aspects determined in previous studies (e.g., McComas and Olson 1998; see Table 1).

Though there are still further problems that have been discussed controversially, like “Nature of Science or Nature of Sciences” (Schizas et al. 2016), “The Multicultural Question Revisited” (Stanley and Brickhouse 2000), “The Scientific Method as Myth and Ideal” (Woodcock 2014), the results of the Delphi study serve as a kind of consensus of what NOS could imply at least in an educational context. Among the themes, there are some like analysis and interpretation of data, science and technology, which seem to be specific for science. But there are also themes which are not necessarily expected to be relevant in science as they are mainly associated with the humanities, like tentativeness, creativity, and historical development. Apart from the consensus on NOS, there is another ongoing question: Why should NOS be included in science education? In 1996, Driver et al. made some important arguments (economic, utilitarian, democratic, cultural, moral, learning) for promoting public understanding of NOS which they had found in literature.

Table 1 Comparison of themes emerging from the Delphi study with those from McComas and Olson's (1998) study of national standards (based on Osborne et al. 2003, p. 713)

McComas and Olson	Delphi study
Scientific knowledge is tentative	Science and certainty
Science relies on empirical evidence	Analysis and interpretation of data
Scientists require replicability and truthful reporting	Scientific method and critical testing
Science is an attempt to explain phenomena	Hypothesis and prediction
Scientists are creative	Creativity
	Science and questioning
Science is part of social tradition	Cooperation and collaboration in the development of scientific knowledge
Science has played an important role in technology	Science and technology
Scientific ideas have been affected by their social and historical milieu	Historical development of scientific knowledge
	Diversity of scientific thinking
Changes in science occur gradually	
Science has global implications	
New knowledge must be reported clearly and openly	

Though the cultural argument for promoting NOS understanding is difficult to define, it seems to be important to make students aware that understanding science is not only restricted to domain-specific aspects but also offers the opportunity to reflect on aspects which science has in common with the humanities. The article consists of three interrelated parts: based on a theoretical discussion by author 1 about what is behind the cultural argument, the research project by author 2 on creativity is presented in chapter 3, and the objective of chapter 4 is author 3's research project on the nature of laws and theories. This structure is based on the symposium held at the IHPST conference in Flensburg in 2016.

2 An Attempt to Clarify the Cultural Argument

According to Driver et al., the "cultural argument" implies that "Science is a major cultural achievement; everyone should be enabled to appreciate it" (Driver et al. 1996, p. 11). This argument refers to a more detailed overview of arguments rendered by Thomas and Durant (1987) and might help to clarify what is behind the cultural argument. They listed nine arguments for promoting understanding of NOS, among them the benefits for intellectual life, i.e., "the place of science in our intellectual culture, where by intellectual culture we mean the attributes of an *educated* and *cultivated mind* [emphasis added]" (Thomas and Durant 1987, p. 7). In the following discussion, the attributes of an educated and cultivated mind will be used to come closer to the implication of the cultural argument. Though both attributes are closely interrelated and affect each other mutually, a cultivated mind seems to be the more comprehensive attribute as it includes not only knowledge but furthermore a special attitude towards knowledge which is going to be demonstrated below.

The attributes of an educated mind are closely related to the notion of literacy, which has changed severely in the last decades. Especially the contribution of science to literacy had been ignored and rejected for a very long time and motivated C. P. Snow to address this problem in his famous Rede lecture in 1959. He complained about the ignorance of a company who was considered as a group of highly educated people: "Once or twice I have been provoked and have asked the company how many of them could describe the Second Law of Thermodynamics. The response was cold: it was also negative. Yet I was asking something which is about the scientific equivalent of: *Have you read a work of Shakespeare's*?" (Snow 1993, p. 14 f.). Snow's complaint about an image of literacy which excludes the contribution of science and solely refers to literacy as an "ability to read and a condition of being well-read" (DeBoer 1997, p. 69) has predominated the notion of literacy for a very long time. Within the educational context, the struggle has come to an—at least temporary—end at the turn of the millennium, when key competences of an educational concept were defined by the PISA Consortium. Apart from *reading literacy*, *mathematical literacy*, and *cross-curricular literacy*, *scientific literacy* was defined as one important condition of setting up universal premises that ensure participation in society (Baumert et al. 2001, p.21):

> Scientific literacy is the capacity to use scientific knowledge, to identify questions and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity (OECD 1999).

Since then, this concept of scientific literacy has influenced national education standards in many countries (Waddington et al. 2007) and has been adopted similarly all over the world. One remarkable justification can be found in the Benchmarks for Scientific Literacy published by the American Association for the Advancement of Science, a milestone on the way to a precise concept of scientific literacy. They offered the following reason for understanding NOS:

> When people know how scientists go about their work and reach scientific conclusions, and what the limitations of such conclusions are, they are more likely to react thoughtfully to scientific claims and less likely to reject them out of hand or accept them uncritically. (AAAS 1993, p. 3)

In order to find out what today's preservice teachers think about science's contribution to literacy, an informal survey among 100 future chemistry, science, and nonscience teachers was carried out at our university. Their answers on the question, "Does science in your opinion contribute to literacy? Please justify your opinion" could be roughly summed up in four categories. Apart from a few who denied the contribution, and those who confirmed it without further justification, science as well as nonscience student teachers mentioned two major reasons for the contribution of science to literacy:

The first one was that *scientific knowledge helps to understand and explain everyday life.* For instance, the student teachers believed that "science helps to explain and understand phenomena in everyday life"; "Science is important in medicine and technical processes"; "Science helps us to understand how our body works".[1] These arguments emphasize the necessity of including science content in educational curricula. But apart from that, there were also arguments supporting the view that *science offers a specific way of thinking and reasoning.* For example, they noted that "In science lessons, we learn how to develop hypotheses, how to prove and modify them. Learners develop new cognitive structures and experimental techniques in order to do research. And for me, research is a fundamental part of literacy"; "In science, problems come up that afford abstract and differentiated thinking to initiate problem-solving processes. This helps to dissociate yourself from common cognitive structures in order to find and work on new problem solutions"; "In science lessons, you are taught content and **methods** [stressed by author] which help to cope with the world around you". Although the survey is not representative, the results indicate the student teachers'

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[1] All German quotations in this article were translated by the authors.

conviction that knowledge of science (content) and knowledge about the way how science works (method) are important constituents of an educated mind (cf. Heering 2016).

Compared to the attributes of an educated mind, *the attributes of a cultivated mind* are even more complex and difficult to define. One useful source for a general notion of culture can be derived from UNESCO (1972). According to the World Heritage Convention, the status of cultural heritage is awarded to “architectural works […], which are of outstanding universal value from the point of view of history, art or science.” The notion of culture was also central in C. P. Snow’s Rede Lecture, in which he discussed the split between the arts/humanities and sciences that determines our intellectual and educational life. His lecture addressed the rejected contribution of science to culture and has given rise to a long-lasting controversy that encouraged him to respond to this discussion 4 years later. In “A Second Look” (1963), he also responded to the protest on using the phrase “The two cultures” by differentiating two different meanings of culture.

> The term ‘culture’ in my title has two meanings […]. First, ‘culture’ has the sense of the dictionary definition, ‘intellectual development, development of the mind’. […] The word ‘culture’ has a second and technical meaning, which I pointed out explicitly in the original lecture. It is used by anthropologists to denote a group of persons living in the same environment, linked by common habits, common assumptions, a common way of life. (Snow 1993, p. 62–64)

In order to justify science’s contribution to culture, he pointed out the specific, but until then neglected, traits of science:

> Non-scientists pretend that the traditional culture is the whole of culture, as though the natural order didn’t exist [...] As though the scientific edifice of the physical world was not, in its intellectual depth, complexity and articulation, the most beautiful and wonderful collective work of the mind of man. (Snow 1993, p. 14)

And in the *Second Look* (1963), he argues: “Curiosity about the natural world, the use of symbolic systems of thought, are two of the most precious and most specifically of all human qualities.” (Snow 1993, p. 62).

Although the selected quotations, and with them the definitions of culture, are just examples from different fields, they have one aspect in common: Culture implies an aspect of positive evaluation and appreciation (“outstanding universal value”; “most beautiful and wonderful collective work”; “most precious […] quality”) and thus adds an emotional and affective element to the cultural argument. The emotional element also corresponds to Snow’s emphasis on curiosity, which can be defined as “desire for knowledge or information in response to experiencing or seeking out collative variables, which is accompanied by positive emotions, increased arousal, and explanatory behavior” (Grossnickle 2014, p. 8).

Returning to the notion of intellectual culture, the attributes of an educated mind refer to knowledge (of content and method), whereas the attributes of a cultivated mind refer to appreciation and admiration of this knowledge. An educated mind is able to explain scientific phenomena, whereas a cultivated mind goes beyond this ability and is furthermore curious of the explanations and the way how science works. Therefore, a preliminary answer of what is behind the cultural argument could be that an adequate understanding of NOS can pave the way to an intellectual and emotional access to science.

But there is still the problem of how to deal with *two* cultures. Though the question of how many cultures do exist has been answered controversially from different perspectives (Lepenies 1988; von Engelhardt 2007), Snow’s dichotomy runs the risk of replacing one by the other. And he was aware of this problem himself. Therefore, he pointed to the potential of the clashing of the two cultures, which “ought to produce creative chances” (Snow 1993, p. 16). In order to identify these chances, it seems worthwhile to have a closer look on the aspects of nature of science presented in Table 1.

Some of these aspects are domain-specific, such as “empirical evidence” and “role in technology.” But there are others, like “creativity” and “social tradition,” which overlap with aspects of the humanities. Taking all these aspects into account, an extended answer to the question what is behind the cultural argument could be that an adequate understanding of NOS can make students aware and curious of the common and different traits of the two cultures and appreciate them as complementary views of our world.

Based on this clarification, the research projects described in the next sections address similarities as well as differences between the two cultures. They were carried out in chemistry teacher education and exemplarily offer the opportunity to arrive at an understanding of NOS that brings together traditional and modern concepts of literacy and helps to get rid of the dichotomy between science and the humanities.

3 Creativity: a Common Aspect of the Arts, Humanities, and Sciences

Even though creativity is often used to differentiate between science and the humanities, we consider creativity to be a quality that the two cultures have in common. Creativity is considered as one of the key competencies of modern society (Kind and Kind 2007). Due to global economic restructuring, accompanied by fundamental and rapid changes, life is characterized more and more by complexity and uncertainty (Hodson 2003). Creativity—as the ability to produce something new and relevant (Sternberg and Lubart 1999)—is a necessary condition to meet the requirements of an uncertain future. This is also a challenge for the educational systems. Who if not the schools and universities should prepare students to handle these demands and become possible future innovators?

In chemistry education, the implementation of creativity is also important in terms of representing an adequate image of the discipline. Science is often characterized as solely logical and analytical and creativity is associated with arts, music, literature, architecture, and similar disciplines rather than science (McComas 1998). The following is a typical school student statement: “Chemists think logically but are not necessarily creative. Creative people are good in languages, and chemists are good logically.” (quoted from Becker et al. 2014, p. 358) Such conceptions are mainly based on students’ experiences in their chemistry classes. Consequently, students who prefer open and inventive tasks reject chemistry as a potential career aspiration (Tobias 1990). The problem is that such an image of chemistry strongly contrasts with research on NOS, whereupon “science is an activity that involves creativity and imagination as much as many other human activities” (Osborne et al. 2003, p. 702; cf. Table 1). If chemistry education more strongly addressed creative elements, this would not only promote an adequate image of chemistry and prepare the students for future tasks in this profession but it could also lead to a broader acceptance of the discipline and motivate young people to become chemists (cf. Heering 2016).

Although these are desirable perspectives, creativity has neither been established as a main topic in chemistry education research nor in chemistry education practice (Kind and Kind 2007). This article presents a research project at our university, in which we try to address this deficiency.

3.1 The Notion of Creativity in Chemistry and Chemistry Education

Our definition of creativity is based on an analysis of general, educational, and science-specific literature, as well as on a survey among lecturers of a regional educational institution. It includes all four central components of creativity described by Rhodes (1961) at the beginning of creativity research: the *creative person*, who in a *creative process* creates a *creative product* and, during the process, is embedded in a *creative environment*. For the definition and a visualization of the relationship between the four components, see Fig. 1.

From an educational point of view, some results of psychological research are interesting. Summing them up briefly, creativity is a generic ability, which is hardly systematically trainable and not validly measurable (Simonton 2012; cf. also Bliersbach and Reiners 2017c). Nonetheless, this generic ability can be achieved in every domain, though it depends on distinct knowledge in the respective disciplines (Ericsson 1996). The content knowledge is not only a necessary condition to become creative but also important to evaluate whether creative ideas are appropriate. In evaluating creativity qualitatively, psychologists differentiate between “Big C Creativity” and “little c creativity” (Simonton 2012). The first relates to creative achievements that are of high relevance for the whole society and includes what Kuhn (1962) considered as “revolutionary science.” In contrast, little c creativity refers to creative products that solely influence the immediate environment of the creative person and includes what Kuhn described as “normal science.”

So, what has chemistry to do with creativity? Firstly, there are some examples of handling chemical content in a creative way. One of them is the artist Vivian Torrence, who deals with chemical content artistically. In her paintings, she usually refers to certain chemical phenomena and creates analogies to everyday life situations (Hoffmann and Torrence 1993). Another example, in which chemistry is connected to creativity, this time literary, is “The Periodic Table” by Primo Levi (1984)). In his autobiography, Levi connected different episodes of his life, for example, his experiences at the concentration camp in Auschwitz, with different chemical elements.

But as mentioned before, it is not necessary to leave chemistry to find creativity. Research on the epistemology of science confirms that creativity is a key component in the development of scientific knowledge (Simonton 2004; Menna 2001). The next question then is: Where exactly in chemistry do we depend on creativity? Based on NOS literature (e.g., McComas 1998, Osborne et al. 2003; Lederman 2007), some international documents on educational

“Creativity describes the potential of any human being to make something new and relevant for the environment, by means of metacognitive strategies which are particularly based on breaking out of familiar structures and recombining existing knowledge.”

Person Process Product Environment

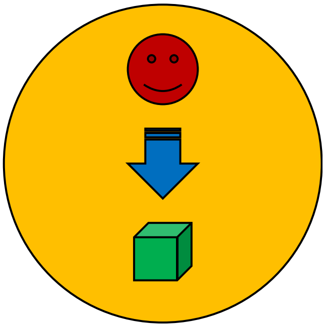


Fig. 1 A definition and the four components of creativity

standards (e.g., National Research Council 2012) and on own considerations, five moments can be emphasized: *generating research questions*, *formulating hypotheses*, *planning and conducting experimental investigations*, *generating theories and models*, and *presenting research results* (Bliersbach and Reiners 2017c). Thus, creativity is required throughout the whole scientific process.

In our research project, the generation of theories and models was our main focus. We think that it presumably represents the most creative act in the scientific enterprise. The history of the Nobel Prize in chemistry reveals that its winners usually come up with new, often revolutionary theories or models, which clarify long-existing problems and/or open new research fields (Bliersbach and Reiners 2017c). Hence, according to our definition, such theories and models represent creative products of very high *relevance for their environment*, which are often strongly characterized by *breaking out of familiar structures*.

Although creativity is rather connected with other school subjects, there are some more or less common approaches including creative elements in chemistry education. On the one hand, problem-centered concepts include some chemistry-specific creative moments that were described above. One famous example is *inquiry-based learning* (Abd-El-Khalick et al. 2004). In its most open form, the students have to come up with their own research questions, hypotheses, and experimental designs and also have to present their findings. Similar common approaches that possibly include chemistry-specific creative moments are *project-based learning* (Polman 2000) and *egg races* (Davies 1990). Whereas the other four moments, especially designing and conducting experiments, are essential parts of these approaches, model building processes are underrepresented in chemistry education.

On the other hand, there are some interdisciplinary approaches including creative activities that are not chemistry-specific. In these approaches, students have to write chemical poems (Watts 2001), paint pictures (Lock 1991), or perform theater or role plays (Ødegaard 2003; Toonders et al. 2016). They can be compared with the abovementioned examples of dealing creatively with chemical content.

3.2 Project Overview

Although creativity is a main component of chemistry research and there are some possibilities to implement creativity into chemistry lessons, it is not an important topic neither in chemistry education research nor in actual school practice. The long-term aim of our research project is to support school students in appreciating creativity as a part of chemistry. To achieve this target, they have to be confronted with creativity in their chemistry classes. Based on the assumption that adequate conceptions of teachers represent a necessary condition on the way to implement NOS into science education appropriately (Lederman 1992), we focused on preservice chemistry teachers. We assumed that they can function as “multipliers” and convey their conceptions to their future students. In order to analyze how these aims can be best achieved, the following two main research questions were formulated:

1. Which preconceptions about the role of creativity in chemistry do prospective chemistry teachers have?
2. How can prospective chemistry teachers be supported in developing appropriate conceptions about the role of creativity in chemistry?

In order to answer the research questions, various qualitative studies were conducted (Bliersbach and Reiners 2015, 2017a, b). Based on the assumption that preservice chemistry teachers possess inadequate conceptions about the role of creativity in chemistry, we first focused on the research question 1. The aim was to get detailed information about the prospective chemistry teachers' views, including possible reasons for and educational consequences of their conceptions. Based on this information, we then focused on the second research question and investigated which approaches could be suitable to address these conceptions (cf. chapter 3.3). All studies took place in regular chemistry didactics courses for preservice chemistry teachers at our institute. The participants were 207 student teachers between 19 and 33 years old (average age is 22) and usually in the second year of their bachelor studies (intended degree: chemistry education at higher secondary level).

3.3 Interventions

In order to be able to answer the second research question, various interventions were developed and evaluated within the chemistry didactics courses. Among other objectives (e.g., scientific literacy, experiments in chemistry education, models in chemistry education, teaching methods), each course contained some sessions about creativity in chemistry. The number and the content of the sessions varied in the different studies. In general, two main approaches were used to convey the role of creativity in chemistry: case studies (teaching *about* creativity) on the one hand and creative activities (teaching *with* creativity) on the other hand. See Table 2 for an overview of some selected studies.

With regard to the case studies, historical as well as contemporary examples were used. The historical case studies (cf. Abd-El-Khalick and Lederman 2000) focused mainly on creative model building processes. We selected cases in which scientists broke with established knowledge and came up with new and revolutionary ideas of distinct relevance for chemistry.

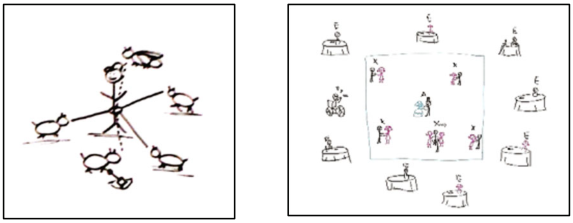
One study covered the development of different theories of combustion in the seventeenth and eighteenth century (Ströker 1982; cf. also Bliersbach and Reiners 2015). The phlogiston theory, introduced by Johann J. Becher (1635–1682) in 1667 and refined by Georg E. Stahl (1660–1734), postulated that combustible bodies contained a fire-like element called phlogiston, which was released during combustion. The theory was acknowledged for over hundred years, until Antoine L. de Lavoisier (1743–1794) came up with his revolutionary oxidation theory. Lavoisier in a certain manner inverted the phlogiston theory and stated that combustion requires a gas (oxygen), which combines with the combustible body during the process. With his theory, which is most widely accepted today, Lavoisier laid the basis for modern chemistry research. Another study addressed Jacobus H. van 't Hoff (1852–1911), the first Nobel Prize winner in chemistry in 1901 (Cohen 1912; Krätz 1974; cf. also Bliersbach and Reiners 2017a). Before van 't Hoff, scientists had not even thought about the structure of molecules. Thus, their description was limited to two dimensions. In 1874, van 't Hoff accounted for the phenomenon of optical activity by assuming that the chemical bonds between carbon atoms and their neighbors were directed towards the corners of a regular tetrahedron. Accordingly, he formulated a revolutionary theory about the spatial arrangement of molecules (Cohen 1912, pp.82–92), which laid the foundation of stereochemistry and stereoisomerism as we know it today. Concerning the contemporary case studies, we dealt among others with Stefan Hell, who together with William E. Moerner and Eric Betzing won the Nobel Prize in chemistry in 2014 “for the development of super-resolved fluorescence microscopy” (Welter 2014). In these three case studies, the students had to deal with primary and secondary literature, or—in the case of Stefan Hell—with interview and video material. In a further contemporary case study, the students had to visit and reflect on lectures of three chemistry researchers of our university.

In contrast to considering creative persons and products from the exterior (teaching *about* creativity), the creative activities (teaching *with* creativity) offered student teachers an environment where they could experience creative processes themselves. One approach was an interdisciplinary one, performed in collaboration with Vanier College in Montreal, Canada. The task for the student teachers was to develop artworks, in which they artificially represented one of Atkins's (2010) "chemistry's core ideas" (for further considerations, cf. Lima 2016). In another approach, we wanted to generate an environment that is more chemistry-specific. As mentioned before, there are not many concepts focusing on autonomous model building processes in science education. Black box activities (Lederman and Abd-El-Khalick 1998) are one of them. Even though they are suitable to convey some important characteristics of scientific models (e.g., that models are not a copy of reality and are based on individual interpretations and preferences), they are less suitable to convey the notion of creativity in model building processes. A possible way to implement autonomous model building processes into chemistry education, which stresses creativity on the one hand, while not being too ambitious on the other hand, is the generation of analogical models. Why analogical models? Firstly, analogies are a crucial compound of scientific models. Every appropriate model includes certain features analogous to the real phenomenon that it represents (Gilbert 2004). Secondly, analogies often play a crucial role in creative model building processes. One common example is August Kekulé (1829–1896), who stated that he had discovered the ring shape of the benzene molecule after having a daydream of a snake seizing its own tail (Rocke 2010). Thirdly, empirical studies concerning the use of self-generated analogies in science education show positive results with regard to students' learning and enjoyment (Haglund 2013). Finally, analogical models can be used in school to introduce relevant scientific models (e.g., the electric circuit, which is compared with a model of a water circuit in physics education (Olson 1958)).

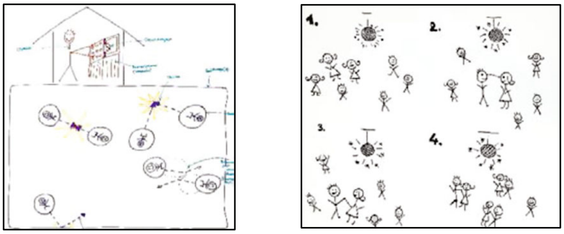
Based on these assumptions, the task for student teachers was to generate one or more analogical models to represent certain educationally relevant chemical models or theories, for example, the valence shell electron pair repulsion (VSEPR) model (Gillespie 2004) or the collision theory (Goldberger and Watson 1964). They were asked to cover as many characteristics of the original model as possible, but were free to use any analogy they wanted. The students could relate to everyday life contexts, other chemical models, or anything else they could think of. The analogical models could be visualized via posters, animations, or role plays. After every group had presented their product, they were compared and evaluated, particularly concerning their content-related appropriateness (cf. chapter 3.1). The intervention ended with a plenary discussion about model building processes in general. Figure 2 presents excerpts of a few examples of the analogical models that were developed.

3.4 Data Collection

In our research project, we tried to investigate which preconceptions about the role of creativity in chemistry student teachers possess (research question 1) and how their conceptions can be influenced by the described interventions (research question 2). In order to get insights into the student teachers' conceptions, qualitative data were collected by means of open-ended questionnaires, semi-structured interviews, portfolios, and participant observation. The different



VSEPR model 1: Dog breeder VSEPR model 2: Wedding ceremony



Collision theory 1: Bumper car Collision theory 2: Discotheque

Fig. 2 Excerpts of some student-generated analogical models

methods were used to triangulate data by validating the obtained results through the combination of data collected from different sources (Mayring 2002).

The items of the questionnaires were adapted to the respective studies with their different investigation questions and interventions. Furthermore, they were also continually modified and optimized, resulting in a two-parted format. The items of the first part of the questionnaires were partially based on the items of the *Views of Nature of Science* questionnaires (Lederman et al. 2002), which implicitly refer to creativity. In these items, the term creativity is not mentioned. The "implicit" items were chosen to allow for free and autonomous answers and to avoid forcing a choice upon the students. In some studies, a second part of the questionnaire was handed out after the first part, with additional questions that more explicitly deal with creativity and its relation to chemistry. In other studies, only items of the first part of the questionnaire were used, to ensure that unprejudiced answers were given in the posttests (see below). Figure 3 shows an overview of some selected items that were used in the various studies. All questionnaires that we used were previously tested with students and science education researchers to ensure their validity and reliability.

The semi-structured interviews were based on the same items and used to further validate the responses to the questionnaires. Furthermore, they facilitated the generation of individual, in-depth profiles of some student teachers. Compared to the questionnaire, the students had more time to describe their viewpoints and conceptions. The portfolios that the student-teachers had to write during the courses were also used to support the results of the questionnaires. They are particularly suitable for analyzing the development of the student teachers' perceptions (Klenowski 2002). The participant observation was used as an additional means of triangulation (Mayring 2002). In our studies, it served to directly capture the students' communications—especially the discussions during and at the end of the respective interventions.

With regard to research question 1, we documented the conceptions of all course participants at the beginning of the respective courses. In the advanced studies (focus on research question 2, cf. Table 2), this data collection also served as a pretest. In these studies, the participants'

Table 2 Overview of selected studies and interventions concerning research question 2

Main approach	Concrete intervention	Sessions	Participants	Data collection
Case studies(teaching *about* creativity)	Theories of combustion in the seventeenth and eighteenth century: from phlogiston to oxidation theory	6	24	Open-ended questionnaires Participant observation Portfolios
	Jacobus H. van 't Hoff and his models about the spatial arrangement of molecules	2	21	Open-ended questionnaires Participant observation Follow-up interviews
	Visiting and reflecting lectures of chemistry researchers at the University of Cologne	6	15	Open-ended questionnaires Participant observation Portfolios
Creative activities (teaching *with* creativity)	Interdisciplinary approach: developing artworks representing Atkins's "chemistry's core ideas"	4	23	Open-ended questionnaires Participant observation Portfolios
	Production of analogical models to represent chemical models and/or theories	2	37	Open-ended questionnaires Participant observation Follow-up interviews

conceptions were also collected after the respective interventions (posttest), in order to be able to evaluate the impact of the different interventions on student teachers' views and competencies. In the pretest, as well as in the posttest, all students responded to the respective questionnaires, while some of them were additionally interviewed. In some studies, we also conducted some follow-up questionnaires and interviews to evaluate the sustainability of the students' perceptions about half a year after the interventions. Portfolios and participant observation were used as additional information and—as mentioned above—particularly served to analyze the development of the preservice teachers' conceptions. In the various studies, (Table 2 only gives an overview of selected studies concerning research question 2), 391 open-ended questionnaires (207 pretests, 163 posttests and 21 follow-up-tests), 30 interviews (13 pre, 11 post, 6 follow-up), and 60 portfolios were collected. For a more detailed description of some individual studies, see Bliersbach and Reiners (2015, 2017a, b).

3.5 Data Analysis

The analysis of the collected data followed two different approaches. To gain an unprejudiced insight into the students' preconceptions (research question 1), grounded theory, an inductive systematic methodology involving the construction of theory through the analysis of data, was used (Glaser and Strauss 1967). To evaluate the interventions concerning their impact on the student teachers' views (research question 2), the collected data were analyzed following the rules of qualitative content analysis (Mayring 2002). In this case, the categories were built mainly deductively, based on theoretical considerations outlined in the beginning of this article. In order to evaluate the learning progression of every student, their conceptions before and after the respective interventions were compared. To be able to analyze whether there were differences in the impact of the various interventions, the collected results of the respective courses were compared. It was assumed that the results of the posttests were only based on the respective interventions the students participated in, in particular since there are no other courses at our university dealing with nature of science. Nevertheless, this assumption was tested with the aid of a control group in the context of one of the earlier studies. It could be confirmed that students, who did not participate in an intervention, did not change their perceptions according to the questionnaires. Therefore, the subsequent studies were conducted without control groups. All data were analyzed by two of the authors and another science education researcher to ensure reliability in the coding.

3.6 Findings

As it is difficult to summarize the results of all (qualitative) studies quantitatively without going beyond the scope of this article—in particular with regard to the different means of data collection and analysis—quantitative data is presented only for some selected studies.

In relation to research question 1, typical misconceptions were found. Table 3 gives a summary of the results of the studies, in which the first part of the questionnaire presented in Fig. 3 was used.

Table 3 Summary of the results concerning research question 1: "implicit" questionnaires (155 participants, one category for each participant)

Main category	Frequency	Typical student statements
Explicit confirmation of the role of creativity in chemistry	22	*Chemists sometimes have to use their creativity to come up with new knowledge.* (item 1b)
		Similarity: *Perhaps creativity is also needed in chemistry.* (item 2)
Implicit confirmation of the role of creativity	29	*In gaining new knowledge, old knowledge is combined.* (item 1a)
(Synonyms, paraphrases and important components of creativity)		*You have to work on new and unknown problems.* (item 1b)
		Sometimes, you need to break with an existing theory. (item 1b)
		Like artists, a chemist needs to use his imagination. (item 2)
No reference to creativity or implicit/explicit denial of the role of creativity in chemistry	104	*Chemistry is objective.* (item 1a)
		Chemists have to work logically. (item 1b)
		In arts, the own creativity can be unfolded, open space is provided, where you can create for your own. In chemistry, you have to act according to and argue with the scientific laws. (item 2)

Part 1 (“implicit”, partially based on items of VNOS)

1. What, in your view, is chemistry?
    a) Which properties and/or attributes characterize chemistry in your opinion?
    b) Which skills and/or abilities do chemists need to be successful researchers?
2. What are the similarities and what are the differences between chemistry and artistic disciplines (e. g. art, music and architecture)?

Part 2 (“explicit”, handed out after part 1 was finished)

3. How would you define or describe the term “creativity”?
4. Has chemistry anything to do with creativity? Please give reasons for your opinion.

Fig. 3 Overview of selected items used in the open-ended questionnaires

Only 22 of 155 student teachers mentioned creativity explicitly as an feature of chemistry. Implicit mentions of creativity (via synonyms, paraphrases and important components of creativity) were barely used either. Most students did not refer to creativity or even denied a certain role in chemistry.

In the second part of the respective questionnaires (which was handed out only in some of the studies), when the student teachers were explicitly asked about the role of creativity in chemistry, considerably more students (95 of 106 participants) affirmed a certain meaning. But, in many of these cases, their further argumentation remained somewhat vague. Fifty-two of the 95 students related to the research or problem-solving process as a whole. Eighteen students justified their statements with general aspects of creativity—for example, “combining existing knowledge” or “breaking with familiar structures”—that would be important in chemistry. Only 25 students mentioned concrete research activities involving creativity. In these cases, creativity was often related to experiments (cf. Table 5, in which some selected student statements are collected). Especially in the pretest interviews, it became apparent that many of the student teachers had not even thought about the role of creativity in chemistry (cf. Table 5).

After the interventions (research question 2), the students’ answers changed. In the studies in which only the (implicit) items of the first part of the questionnaire were used, more student teachers mentioned creativity explicitly or implicitly. See Table 4 for the results of two selected studies, in which the items presented in Fig. 3 were used.

In the case of the studies, in which also items of the second (explicit) part of the questionnaire were used, the meaning of creativity in chemistry was already widely affirmed in the pretests (see above). Here, the students’ answers became more elaborate and contained more concrete examples of research activities involving creativity, although—comparing the different interventions—in different forms and to different extent.

Summarizing the results of all studies conducted concerning research question 2, the following can be said: Concerning the different historical and contemporary case studies (teaching *about* creativity), the examples of Stefan Hell and especially Jacobus van ’t Hoff

Table 4 Summary of selected results concerning research question 2 (implicit questionnaires; one category for each participant; *EC* explicit confirmation of the role of creativity in chemistry, *IC* implicit confirmation of the role of creativity, *NR* no reference or denial of the role of creativity in chemistry, cf. Table 3)

Intervention	Frequency (pretest)			Frequency (posttest)		
	EC	IC	NR	EC	IC	NR
Jacobus H. van ’t Hoff and his models about the spatial arrangement of molecules (21 participants)	2	3	16	8	9	4
Production of analogical models to represent chemical models and/or theories (37 participants)	6	5	27	11	13	14

were the most appropriate means to convey the meaning of creativity in chemistry (cf. Table 5). In the case of the combustion theories of the seventeenth and eighteenth century and in the course of the attendance at science lectures, the progress was less obvious. Besides, there were some motivational (combustion theories) and time-related problems (attendance at lectures).

Concerning the creative activities (teaching *with* creativity), only the building of analogical models really led to more informed views of the student teachers. In being asked to come up with a model for themselves, they recognized that they were depending also on creative ideas (cf. Table 5). Also from a motivational point of view, the activity was well accepted. The students liked the fact that the course offered them the opportunity to act in an open environment. Besides, many of the preservice teachers stated that they could imagine incorporating the activity into their future chemistry classes. The interdisciplinary approach (arts and chemistry) indeed was also a “nice variety” for some of the students. The problem was that they did not see a concrete relationship with actual chemistry research. Thus, their conceptions did not change significantly.

The follow-up tests showed that—no matter which course the students participated in—their conceptions remained relatively robust (cf. Table 5).

3.7 Conclusions

A comparison between the data obtained in the different studies indicates that contemporary and historical case studies as well as the building of analogical models can contribute to more informed views of preservice teachers about creativity in chemistry. Many of the students, who did not mention or even denied creativity as a part of chemistry before the interventions, changed their minds after the respective course elements. Students, who affirmed that creativity is important in chemistry (presumably, because they thought that otherwise, they would not have been asked), but who could not really provide evidence for their assessment, were enabled to justify their view as a consequence of the interventions. With the aid of concrete requests concerning the course content and its influence on the students’ perceptions in the semi-structured interviews, it could also be assumed that these changed perceptions were based on the respective interventions. Other approaches were not as effective: The case study about combustion theories in the seventeenth and eighteenth century and the attendance at science lectures rather conveyed other NOS aspects. The interdisciplinary approach, even though it

Table 5 Selected student teacher statements in the questionnaires and interviews (pre, post, and follow-up tests)

Item (data collection method, stage of study)	Typical student statements
What, in your view, is chemistry?	cf. Table 3
a) Which properties and/or attributes characterize chemistry in your opinion?	
b) Which skills and/or abilities do chemists need to be successful researchers?	
What are the similarities and what are the differences between chemistry and artistic disciplines (e.g., art, music, and architecture)?	
(questionnaire, part 1, pretest)	
Has chemistry anything to do with creativity? Please give reasons for your opinion. (questionnaire, part 2, pretest)	*Yes, in research processes.* *I think so. For example when solving problems.* *Yes. When doing experiments.*
Has chemistry anything to do with creativity? (interview, pretest)	*Hm… creativity and chemistry? To be honest, I never thought about a possible relationship.*
Which skills and/or abilities do chemists need to be successful researchers?	*A certain amount of creativity, logical thinking, interest, interdisciplinary thinking, content knowledge.*
(questionnaire, part 1, posttest, intervention: Jacobus H. van ’t Hoff)	*Creativity, faculty of abstraction, richness of ideas, content knowledge.*
What are the similarities and what are the differences between chemistry and artistic disciplines (e.g., art, music, and architecture)?	*What arts and chemistry have in common is that creativity is needed, if you compose a piece of music or you create a model.*
(questionnaire, part 1, posttest, intervention: building of analogical models)	*Similarities: creativity is needed. (...)*
In the course, did you learn something new about chemistry? (interview, follow-up test, intervention: Jacobus H. van ’t Hoff)	*I liked the example of van ’t Hoff.* (…) *Before the course, I would not have connected creativity with chemistry.*
In the course, did you learn something new about chemistry? (interview, follow-up test, intervention: building of analogical models)	*Especially as we made the analogical model for ourselves, it became obvious that it is not easy* (…), *you need creativity to find something that represents the model adequately.*

provides other benefits, was not suitable for conveying the importance of creativity in chemistry either, since it does not include chemistry-specific creative moments.

All in all, the use of (well chosen) historical and contemporary case studies that offer explicit examples of creative persons and their creative products is a great possibility for enabling student teachers to recognize *that* creativity is important in chemistry. The production of analogical models offers the opportunity for generating a creative environment. Accordingly, this approach, where students actively go through chemistry-specific model building processes for themselves, is appropriate for realizing *how* creativity works in chemistry. To exploit its full potential, the latter, rather implicit approach, should be combined with explicit instructions (as in the case studies). In order to develop comprehensive conceptions about creativity in chemistry, a combined approach of both course elements seems to be the most suitable.

These conclusions were already put into practice. For the final study of the research project, a combined course unit about creativity in chemistry and chemistry education was compiled and evaluated. It consists of a general introduction to the topic, the case studies of van ’t Hoff and Hell and the building of analogical models. Since the course also deals with further possibilities for implementing creativity into chemistry education (cf. 3.1) and offers the opportunity to plan corresponding teaching units, there is a strong connection to educational practice. As a concrete outcome of the research project, we implemented this course unit into chemistry education curricula at our university as well as into our training programs for in-service chemistry teachers. We hope that this will contribute to an increased implementation of creativity into chemistry education practice.

4 The Peculiar Nature of Laws and Theories in Sciences

This project focused on the domain-specific notion of theories and laws that is peculiar to science. Hence, it served to illustrate the differences between science and humanities. Chemistry students are often confronted with different technical terms that include the words *theory* or *law* (Table 6). These words are supposed to encompass epistemological functions that are often vague to students and even to preservice teachers (Abd-El-Khalick et al. 1998; Lederman et al. 2002). The uncertainty about the meanings of scientific laws and theories makes people prone to myths and misconceptions. Those myths may even manifest themselves in political debates, where the term *theory* is often being used in a derogatory, nonscientific sense, as in “only a theory” (Ben-Ari 2005). This kind of abuse of scientific terminology illustrates the relevance of the topic; hence, it is often included in national educational standards as part of the NOS topic (McComas and Olson 1998; Waddington et al. 2007). Furthermore, knowledge about fundamental epistemological concepts of science is a contribution to scientific literacy.

The nature of scientific laws and theories is a well-researched topic in philosophy, while there is little research on the field in science education. It is often included as one of many aspects inside the NOS complex (Lederman 1992; Lederman et al. 2002), while little research has specifically targeted this aspect of NOS. Examples include McComas (2003), who focused on biology teaching, and Tobin (2013), who focused on chemistry education. An interesting approach by Allchin (2007) has suggested to teach science without any laws. In order to cope with the common misconceptions, however, our study aimed at a better understanding by explicitly targeting the concept of scientific laws (and theories). We used historical case studies to convey an informed image of scientific laws and theories. Our goal was for preservice teachers to acquire a better understanding of this topic in order to be able to teach it to students. Since the exact definitions of laws and theories are open to philosophical debate, our aim was to provide simplified definitions that can be used on a school level.

Table 6 A selection of scientific theories and laws related to chemistry

Laws	Theories
Avogadro's law	Atomic theory
Boyle's law	Crystal field theory
Bragg's law	Kinetic theory of gases
Gay-Lussac's law	Ligand field theory
Ideal gas law	Molecular orbital theory
Law of conservation of mass	Phlogiston theory
Law of constant composition	Radical theory
Law of mass action	Structural theory
Laws of thermodynamics	Valence bond theory
Periodic law	VSEPR theory

4.1 The Nature of Scientific Laws and Theories

The nature of scientific laws can be discussed on various levels of philosophical complexity, and philosophical viewpoints might differ in certain details (Weinert 1995; Swartz 1995; Armstrong 1983). At the school level and for chemistry teacher education, a simple definition is sufficient to convey the general idea. According to such a definition, originating from science education, scientific laws "are descriptive statements of relationships among observable phenomena" (Lederman et al. 2002, p. 500). Similarly, the definition of a scientific law in a chemistry textbook is that of "a concise verbal statement or mathematical equation that summarizes a broad variety of observations and experiences" (Brown et al. 2005). In a nutshell, laws are of descriptive nature, dealing with regularities in empirical data, but without the potential to explain the data. For example, *Proust's law* (or the *law of definite proportions*) describes how the mass ratio is equal for a given chemical compound, but does not provide an explanation of the reasons behind that.

Scientific theories, on the other hand, are a different kind of scientific knowledge. Theories are used to explain and predict scientific facts and observations (Winther 2015). In a historical perspective, "[t]he discovery of laws of nature is only the first stage in scientific interpretation. The second stage is the incorporation of these laws into theories. According to [John] Herschel, theories arise either upon further inductive generalization, or by creation of bold hypotheses that establish an interrelation of previously unconnected laws" (Losee 2001). Popper (1934/1976) described a scientific theory as "the net which we throw out in order to catch the world—to rationalize, explain, and dominate it". This research project uses a more precise definition, also based on NOS research:

> Scientific theories are well-established, highly substantiated, internally consistent systems of explanations. Theories serve to explain large sets of seemingly unrelated observations in more than one field of investigation. [...] Theories have a major role in generating research problems and guiding future investigations. Scientific theories are often based on a set of assumptions or axioms and posit the existence of nonobservable entities. Thus, theories cannot be directly tested. Only indirect evidence can be used to support theories and establish their validity. (Lederman et al. 2002, p. 500)

As an example, the ideal gas law can be used to *describe* how pressure, volume, temperature, and the amount of substance relate in a gas. The kinetic theory of gases provides an *explanation* for this behavior, drawing from models involving submicroscopical particles. Conclusively, scientific laws and theories are two separate categories of knowledge. Both are substantiated based on empirical evidence and are equally valuable to science. There is no direct, hierarchical relationship between theories and laws, as both serve different functions. Thus, a theory cannot be "transformed" into a law or vice versa (see Fig. 4). It should be noted that theory as a term is also used in the humanities, such as in feminist theory, critical theory, or linguistic theories. While also serving to provide a framework for research, they differ from scientific theories as they are lacking an experimental basis. This paper, however, is focused on the domain-specific nature of theories and laws in science.

4.2 Myths About Scientific Laws and Theories

There are three prevalent misconceptions about laws and theories among both students and the public. First of all, there is the idea that scientific laws are an absolute kind of knowledge and equivalent to "the truth" (Horner and Rubba 1978; McComas 1998). However, scientific laws are as tentative as other types of scientific knowledge. They are not "absolute" knowledge and not simply statements that are universally "true" (Cartwright 1983; Giere 1988; Allchin 2007). As an example, the discovery of nonstoichiometric compounds showed that not all chemical compounds behave according to Proust's law. Iron(II) oxide, for instance, typically has a composition ranging between $Fe_{0.84}O$ and $Fe_{0.95}O$, not one fixed ratio. Scientific laws are results of idealizations of nature. The term *ideal gas law* even suggests this itself, since there is no such thing as an ideal gas in real life.

Related is the myth of a hierarchical relationship between laws, theories, and hypotheses (Horner and Rubba 1979; McComas 1998; Maeng and Bell 2013). This myth pictures scientific research as a linear process starting with a hypothesis, gathering evidence leading to a theory, which is then proven, becoming a scientific law. Aside from the impossibility of "proof" in science, laws are not "mature" theories, as they serve completely different functions.

The false conception of hierarchical relationship is related to the notion of scientific theories as particularly uncertain knowledge. It is common to hear people dismiss scientific knowledge as "just a theory" (Ben-Ari 2005), implying that scientific theories on evolution or climate change are poorly substantiated and lacking sufficient "proof." This manifestation of common misconceptions demonstrates the actual relevance of teaching the nature of scientific laws and theories to students. Scientific theories are in fact the mightiest tools of science, offering explanations and predictions of phenomena. They are constructs based on indirect evidence, with no possibility of direct testing. It is however possible to deduce hypotheses from a theory, which can be tested empirically. Thus, scientific theories are well-supported by empirical evidence and not particularly less substantiated than scientific laws.

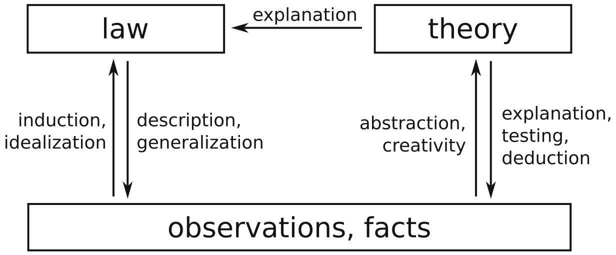


Fig. 4 A simple scheme showing theories and laws as non-hierarchical entities and how they are obtained from observation and facts. Note that while creativity is present in all aspects of science, its role is peculiar in developing theories (cf. chapter 3)

The origin of these three misconceptions has not yet been researched. It seems plausible that the usage of *theory* and *law* in colloquial speech is highly influential. In colloquial speech, *theory* is often used as a derogatory term for mere speculation, while a *law* carries a normative connotation. Allchin (2007) has discussed this problem with regard to scientific laws, concluding that "[w]e need to ensure that our thinking about science is not biased by meanings in cultural contexts". The absolute idea of laws corresponds to the historical origins of the notion of "scientific laws" in theology (Zilsel 1942). The idea of laws as principles inherent to the universe is conveyed in the distinction between *natural law* and *scientific law*, with the latter corresponding to our definition used for modern science (Weinert 1995).

4.3 Project Overview

The main objective of this research project was to incorporate the nature of scientific laws and theories into a university course for preservice teachers. The rationale was that an adequate understanding of these concepts is an important precondition for teaching NOS-related content to students. Previous NOS research has shown that most students and preservice teachers are not able to give adequate definitions of laws and theories, with many maintaining a hierarchical concept (Abd-El-Khalick et al. 1998; Lederman et al. 2002).

The research question is whether case studies are suitable means to improve student teachers' conceptions of scientific laws and theories, since history of science is often suggested as an adequate context for teaching NOS (Matthews 1994; Irwin 2000; Heilbron 2002). As a part of chemistry education courses, these conceptions were assessed and two different approaches with varying degrees of contextualization were tried (see Fig. 5). The highly contextualized approach encompassed historical case studies in chemistry in order to achieve a better understanding of laws and theories. The results were assessed using open-ended questionnaires asking for participants' definitions of laws and theories and their relationship and diary-like portfolios in which the students document their learning progress accompanying the courses.

The pilot study was part of an introductory course in the winter term 2014/2015 involving 49 participants (only counting students who filled in both the pretest and the posttest). Most of the student teachers were in their third semester with little previous knowledge of NOS. The course featured general topics related to science education, such as the role of experiments in chemistry classes, national educational standards and curricula, safety regulations, and the role of models in science. The nature of scientific laws and theories was addressed during three sessions covering an introduction to the nature of scientific models (Kircher 1976), the evolution

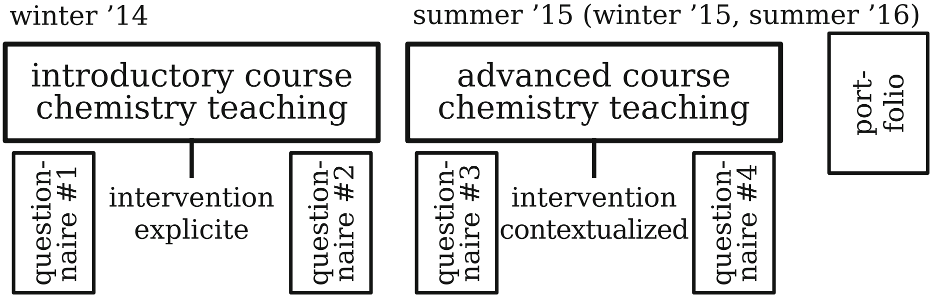


Fig. 5 Overview of the pro+ject

of atomic theory over history (Dalton, Thomson, Rutherford, and Bohr), and the epistemological foundations of scientific experiments (Chalmers 1999). This pilot study was limited to "explicit and reflective decontextualized NOS instruction" (Clough 2006), with one portfolio and two questionnaires per student documenting the pre- and post-conceptions along the course.

After the pilot study, there was another course in the summer term 2015 involving 18 participants, featuring a highly contextualized approach based on historical case studies. During six sessions in the advanced chemistry education course, the students were introduced to NOS and given historical source material on chemical discoveries. These included chemical contents relevant to school curricula, such as

- Gas laws (Boyle, Gay-Lussac)
- The law of mass conservation (Lavoisier, Lomonossov)
- Organic structural theory (Kekulé, van 't Hoff)
- Inorganic structural theory (Werner)

The source texts were selected to illustrate several NOS aspects, such as tentativeness and the inferential and the social nature of science. As an example, the emergence of organic structural theory was met with some hostile reactions by elderly chemists, such as Hermann Kolbe, who defended their old-fashioned "empirical" chemistry against the "esoterical" (inferred) claims made by August Kekulé or Adolf von Baeyer. The student teachers analyzed and discussed the inferential nature of scientific theories through Kekulé's original articles from 1866 and 1872. Additionally, the student teachers were periodically asked to draw a scheme of how they think terms like "hypothesis," "theory," "law," "observation," or "facts" are related. In the end, the schemes were discussed together and a non-hierarchical view was established. This context-embedded study used the same kinds of portfolios and questionnaires as described before.

4.4 Methods

All participating student teachers responded to two questionnaires (pretest and post-test) on the nature of science, with special focus on the nature of scientific laws and theories. The following questions were considered for analysis:

- What, in your view, is a scientific theory? Illustrate your answer with examples, preferably from chemistry.
- What, in your view, is a scientific law? Illustrate your answer with examples, preferably from chemistry.
- What is the difference between theories and laws? Is there a relationship between these two terms? If so, what kind of relationship? Please explain.

The questionnaire was based on the VNOS-B questionnaire (Lederman et al. 2002), breaking one question about theories and laws down into three separate items. It was then piloted with student teachers to eliminate ambiguities. Since there are no other chemistry courses at our university dealing with philosophy of science, it appears unlikely that other factors apart from our treatment may have influenced the outcomes.

Analysis of all data was carried out through qualitative content analysis (Mayring 2002, 2008) with a deductive category system based on definitions and misconceptions of scientific laws and theories, as described in the previous sections. The categories were connected to a scoring scheme with informed aspects yielding positive points and misconceptions giving negative points, adding up to a total score. Their definitions are based on the descriptions given in Sections 4.1 and 4.2.

The categories encompassed important aspects of scientific laws and theories, including

- The function of scientific laws (score +3)
- The function of scientific theories (score +3)
- The empirical nature of scientific laws (score +1)
- The empirical foundations of scientific theories (score +1)
- The mathematical form of scientific laws (score +1)
- The inferential origin of scientific theories (score +1)
- Different theories may be used for solving the same question (score +1)
- The absolute nature of scientific laws (score −1)
- The scientific theories as mere speculation (score −1)
- The hierarchical relationship between laws and theories (score −1)

The following statement provides an example of how the scoring rubric was used: “A law is the determination of relations between at least two physical quantities. Their correlation can be observed and described by a law.” This statement scored +3 points for stating the descriptive nature of scientific laws, as well as +1 point for mentioning observation as a foundation. As it can be inferred, total scores could range between −3 and +11 points. These scores were used as an indication for the students’ progress along the courses. The portfolios were consulted as an additional source, especially for ambiguous cases.

4.5 Findings

The findings of the pilot study show that the common misconceptions were also prevalent among all participants:

> “Laws grow out of theories; theories are proven until they become law.”
>
> “A theory was designed and postulated by a scientist, while a law is mathematically proven. Theories may change or improve or be untrue, but a law may not be changed by any person.”
>
> “A theory is a tested hypothesis. A law is a theory that has turned out to be proven by many experiments over a longer period of time.”

While students may recognize the tentative nature of scientific theories, this was mostly due to a hierarchical understanding of theories and laws, considering theories as mere guesses. The view of scientific laws as absolute, “proven” knowledge was even more common, with none of the students mentioning the tentativeness of laws. Overall, there was not one single informed view (i.e., one leading to a positive score according to our rubric) of laws and theories among all of the 49 students. Strikingly, even after the explicit instructions, only one student showed significant improvement with six students mentioning at least isolated aspects of an informed view. This led to the conclusion that the decontextualized approach can be deemed unsuitable for teaching the nature of laws and theories.

However, the highly contextualized approach proved considerably more successful. With the same misconceptions prevalent in the beginning, the analysis of case studies resulted in more informed statements, such as:

> Theories are mental constructions that explain observations at least in part. They have to be inferred indirectly and include a creative process. A law is a generalization of statements that was directly deduced. It is of descriptive character (e.g. gas law). While laws work as a generalization of observations and allow predictions, the theory provides the corresponding explanation. Several theories may exist for the same phenomenon.
>
> A theory explains a phenomenon, e.g. collision theory explaining the behavior of molecules in space. A law describes an observation, e.g. the gas law that describes the behavior of ideal gases during changes of state. The difference is that one explains a phenomenon while the other describes it. Both may relate to the same phenomenon.

In total, 11 out of 18 participants showed an increased score. Likewise, a better understanding was noticeable in the portfolios, as one student wrote: "While a theory seeks to explain observations (or a law), a law only describes the observations and may make predictions due to regularities. Laws are also falsifiable, which is exemplified by the law of conservation of mass in the context of mass defect." Another student wrote: "Laws are limited to observations, while theories add the explanations of those laws." Yet another student stated: "Hence, laws describe phenomena, while the theory is the explanation behind them. … However, theories can never be proven." Many participants added to their portfolios that they were presented new perspectives on science. The overall feedback was positive.

4.6 Conclusions

The results reconfirm that a highly contextualized approach is an effective means of NOS instruction (Clough 2006). This is further supported by the fact that our study failed to yield improvements using the decontextualized approach. Hence, the advanced chemistry-teaching course featuring historical case studies continues at our university and further studies are conducted to investigate its success. It would be desirable to further investigate the origins of the misconceptions of scientific laws and theories. In order to counter these naive NOS views, it may prove helpful to sharply distinguish between the colloquial meanings of *law* and *theory*, and their scientific meanings. The long-term goal is to transform how the topic is taught in chemistry classes. Possible approaches are to improve learning material and school textbooks, as well as implementing (aspects of) NOS into university courses in the long term.

5 Discussion

Two independent research projects that dealt with NOS were used to support the idea that the cultural argument of understanding NOS which is clarified in the theoretical part offers an opportunity to provide evidence that creativity, laws, and theories belong to the humanities as well as to science. Though creativity is mainly associated with the humanities, it plays a central role in science as well. Laws and theories are set up in the humanities and in science, but in science they have a domain-specific function and meaning. Regardless of the controversy about the NOS tenets and based on the consensus figured out for the educational level by the study of Osborne et al. (2003), the two projects seem to be suitable for disproving Snow's assumption that the two cultures are completely different and prevent a mutual understanding of their representatives. In the first project, historical and contemporary case studies (teaching about creativity) as well as creative activities (teaching with creativity) turned out as appropriate means to make students aware that creativity is not only important in the humanities but also in scientific disciplines like chemistry. In the second project, historical case studies on school-relevant theories and laws were used to get rid of the myths on theories and laws in science. It turned out that a highly contextualized approach is an effective means to point out that theories and laws are two separate categories of scientific knowledge which are not related hierarchically and which are, in contrast to the humanities, based on empirical evidence. Thus, both cultures must be taken into account to point out common and domain-specific traits and to arrive at a complementary perspective in understanding NOS.

Although at a first glance, the notion of "Nature of Science" leads one to think that there are *exclusive* domain-specific tenets a closer look at particular tenets refutes this assumption. For instance, theories play an important role in science as well as in the humanities. In both cases, they serve for interpretation and their mental construction requires a lot of creativity, but in the humanities, theories are lacking an experimental basis. Especially, the cultural argument for understanding NOS encourages us to go beyond systematic differences and to adopt a systemic view, from which differences as well as similarities between science and humanities become evident. Thus, from an educational point of view, the integration of sequences like those described in the two projects in science teacher education seems to pave the way to a systemic understanding of NOS. Or to follow Georg Christoph Lichtenberg's famous aphorism, "He who understands nothing but chemistry does not truly understand chemistry either."

But paving the way indicates that there is still something left to be done to arrive at an adequate understanding of NOS in teacher education as well as in school. For instance, in accordance with many studies on NOS in the past, more time will be needed to foster students' views on the addressed aspects of NOS and to integrate such courses into teacher education in the long run. Furthermore, there are other tenets of NOS that seem to be suitable to point our similarities (e.g., tentativeness, social tradition) as well as differences (e.g., empirical evidence, role of technology). Apart from the cultural argument which was used in our studies to arrive at a systemic point of view, other arguments such as the democratic or the moral argument might also offer the opportunity to reflect on commonalities as well as differences between science and humanities. It would also be interesting to look at other scientific disciplines like biology or physics to find out students' views and to develop and test equivalent case studies. It might turn out that in other scientific disciplines, students are more likely to associate the notion of creativity with science or that their conceptions of theories and laws differ from the one in chemistry. And finally, the question how future teachers can be supported to put these ideas into practice has been left out of account in our studies, which predominantly aimed at the necessary condition, but not at the sufficient condition to support teachers to put NOS into practice.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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