Bridging the gap between macro and micro: enhancing students' chemical reasoning: how to use demonstration experiments effectively for the teaching and learning of structure-property reasoning

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Chapter 6:

General Conclusions and Discussions

6.1. Aim and Research Question

To learn to think like a chemist is an important goal of chemistry education. This chemical reasoning among others involves the explanation of the properties of compounds by means of the structure models used to describe the micro level. Students experience difficulties with this so-called structure-property reasoning. These difficulties rise from the macroscopic orientation students have, the invisibility of the micro level, even with a strong microscope and the difficulties students experience when working with the models which are needed to describe the particles and their interactions (de Jong & Taber, 2015; Gabel, 1993; Johnstone, 1991, 2000). Literature shows that explicit teaching of structure-property reasoning and showing of the chemical phenomenon and subsequently explaining the phenomenon with the micro level could improve the acquiring of structure-property reasoning by students (Gabel, 1999; Johnstone, 2000; Kelly & Jones, 2008; Ramsey et al., 2000; Stowe et al., 2019; Talanquer, 2018; Tsaparlis, 2009). Therefore, we expect that education with regards to structure-property reasoning may benefit from the use of appropriate demonstrations.

However, existing literature still offers little direction for this explicit teaching of structure-property reasoning by demonstrations. The teaching approach should not only effectively promote structure-property reasoning in students but should also be perceived as practically useful by teachers. Because research shows that teachers only implement innovations into their daily teaching practice if the teacher considers the innovation as practical (Doyle & Ponder, 1977; Janssen et al., 2015; Janssen et al., 2013). Against this background, the overarching research question of this thesis is: *What are the characteristics of an effective and practical approach that supports chemistry teachers in designing lessons in which a demonstration experiment is used to enhance students' structure-property reasoning?*

Four studies were performed to answer this research question (Figure 6.1). First, it was explored how structure-property reasoning could be explicated in the form of a perspective that can be used to scaffold students' structure-property reasoning by integrating the skill structure-property reasoning and the knowledge in the form of chemical concepts (Chapter 2). When developing a teaching practice to enhance students' structure-property reasoning, an evaluation instrument to establish students' proficiency in structure-property reasoning should be available. This perspective for structure-property reasoning served as base for an evaluation instrument to assess the proficiency of students in structure-property reasoning (Chapter 3). The perspective also served as base for the design of demonstration lesson series together with the POE task (Predict-Observe-Explain) to increase the engagement of students during demonstrations (Chapter 4). In Chapter 5, the practicality of the teaching approach described in Chapter 4 was investigated. In this Chapter, the main results of the four studies of this thesis were summarized followed by a general discussion, limitations with suggestions for further research and theoretical and practical implications.

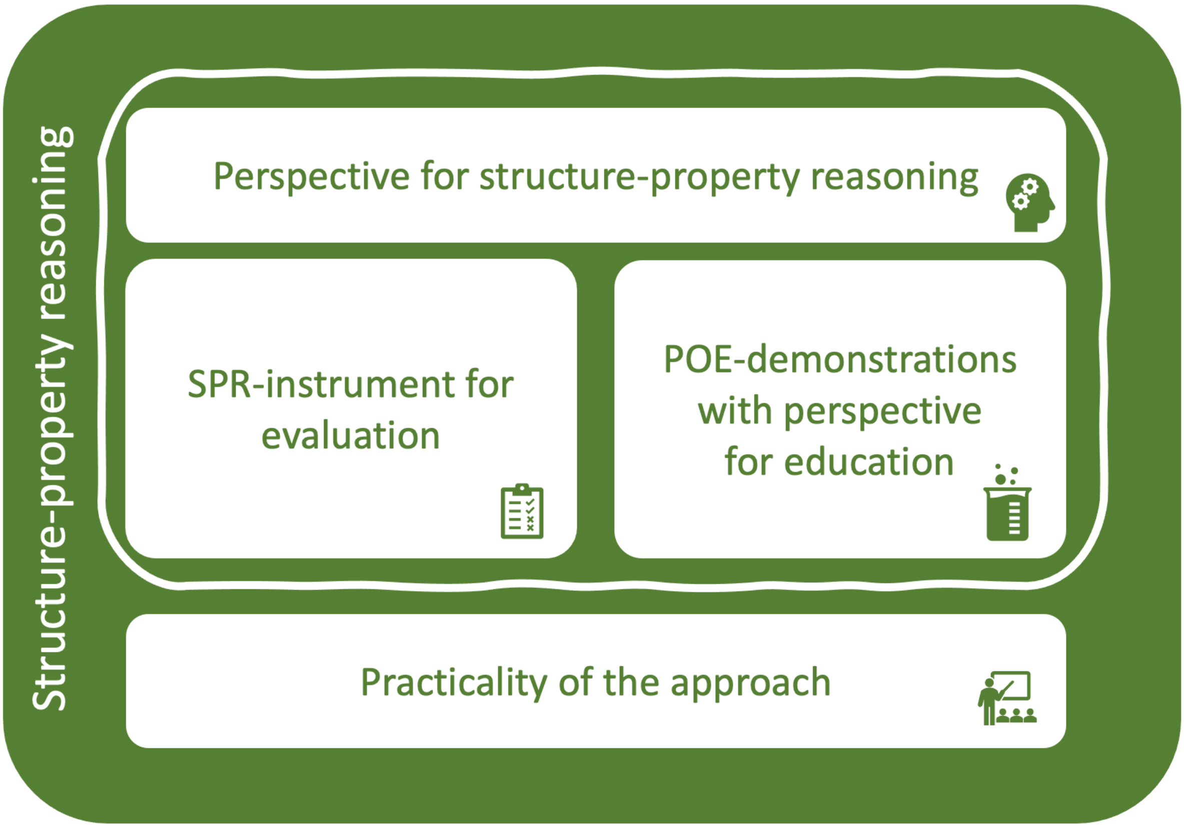

Figure 6.1: *graphical overview of the study described in this thesis.*

6.2. Main Findings

For chemistry students, learning to think like a chemist is an essential part of their education. Historically, Johnstone's triangle was an important stepping stone for explicating chemical reasoning and thereby structure-property reasoning. Furthermore, the triangle showed why structure-property reasoning is so difficult (Johnstone, 1982, 1991). Nevertheless, Johnstone's triangle has one important limitation: there is a division between the skill of chemical reasoning and the use of the chemical concepts. As a result, these models give students little scaffolds for structure-property reasoning.

In the study of Chapter 2, it was proposed that a model for effective structure-property reasoning should include concepts and reasoning skills in coherence, hence a perspective was introduced. In the perspective for structure-property reasoning (Figure 6.2) the core of structure-property reasoning was elaborated in a coherent scheme. Subsequently, this scheme determines which main questions can be asked. These main questions branch into sub-questions with corresponding chemical concepts, both giving direction to structure-property reasoning. In this way, the skill of structure-property reasoning is connected to the chemical concepts. The four presented cases from Chapter 2 showed that the reasoning strategy evolving from the questions of the perspective can be used to solve the cases. The perspective induces an implicit learning progression by the questions constantly branching out. In such, the questions can support reasoning strategies that increase in complexity over time. With each further differentiation of the perspective, the strategy becomes more powerful. An additional benefit is the increase of the horizontal and vertical coherence. Horizontal coherence refers to the alignment of related chemical concepts and skills within a certain grade. Vertical coherence refers to the alignment of related concepts and skills across different grade levels or subject areas. It ensures that the chemical concepts and skills taught in one grade level build upon those taught in previous and subsequent levels (Jin et al., 2019). The four presented cases showed that horizontal coherence is established with the perspective for structure-property reasoning. The cases also provide insights into how vertical coherence could be elaborated into a learning progression.

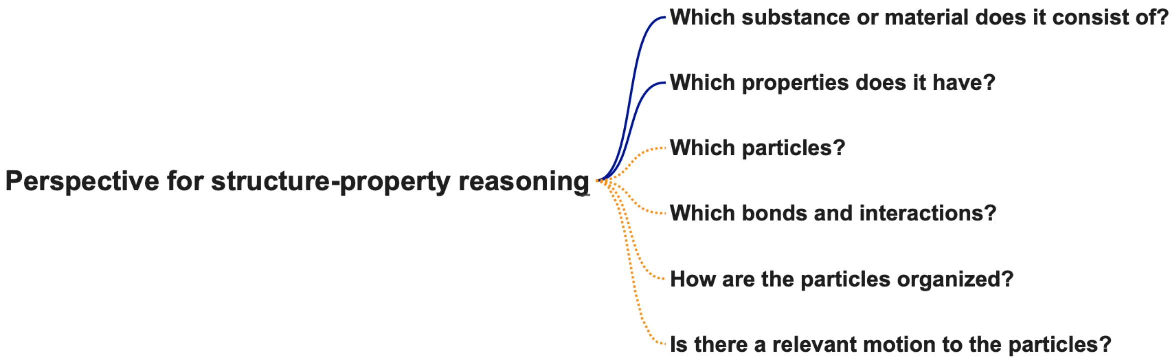

Figure 6.2: *Perspective for structure-property reasoning used in the studies of this thesis, elaborated for the first level.*

Chapter 3 described the development of a tool for chemistry teachers to assess students' proficiency in structure-property reasoning, namely the SPR instrument. Three criteria were listed: a) the instrument should be based on a comprehensive model for structure-property reasoning; b) the instrument should be cost-effective; and c) the instrument should be adaptable to the teachers' own teaching goals. To accomplish these criteria, the instrument combines a sorting task and a mapping task, both framed and unframed. Results show that the SPR instrument appear to discriminate between secondary school students at the pre-university track and first-year chemistry students at university. The perspective for structure-property reasoning served as comprehensive model that covers the aspects of structure-property reasoning needed in the chemistry curriculum for secondary education, thereby complying our first design criterion. The instrument also complied with our second criterion: cost-effectiveness. Preparation and administration of the instrument was not time consuming, and the instrument was suitable for big groups. However, analyzing the test results is still relative time consuming. Finally, the SPR instrument was adaptable to a teacher's own teaching goals, complying the third design criterion.

Chapter 4 described the design of demonstration-based lessons aiming to help students develop structure-property reasoning based on two design principles. The two design principles were: 1) adding a POE task to demonstrations to stimulate students' modeling process and to create opportunities for students to think for themselves, and 2) scaffolding of the POE task with the perspective for structure-property reasoning to explicitly guide the modelling at the micro level for students in the Explain-phase of the POE task. For the design of the lesson series, conventional demonstrations served as a basis and the two design principles were used to redesign these demonstrations. The redesigned demonstrations were part of a lesson series. This lesson series was tested in two cohorts of year 4 pre-university students (age 15-16) to investigate the effects of the two design principles on the level of their structure-property reasoning. The results of the SPR instrument (Chapter 3) indicated that the demonstration lesson series contributed to students' proficiency in structure-property reasoning. The unframed and framed mapping task of the SPR instrument showed that most students acquired and understood the chemical concepts needed for structure–property reasoning after the lesson series. In the posttest, the unframed mapping tasks were notably more comprehensive. Furthermore, the framed and unframed sorting tasks showed that students were better able to apply their acquired knowledge to problems concerning structure–property reasoning in the posttest. Students were also found to use more structure–property reasoning to evaluate and sort the types of problems that they were presented with in the posttest. Qualitative data of students' modelling additionally showed how one student made interesting progress in modelling micro-level chemical structures. Considering design principle one, adding the POE task, our data showed that the POE task engaged students in modeling of the structure level and, therefore, in acquiring structure level understanding. Considering design principle two, scaffolding of the POE task with a domain-specific perspective for structure-property reasoning, the SPR instrument showed that students' perspective for structure-property reasoning was more developed in the posttest. Developing the perspective also increased its value as a scaffold for the students. Therefore, both design principles helped to promote structure–property reasoning among students. The two design principles were used for the redesign of traditional demonstrations, thereby increasing the practicality of the approach for teachers. It allows teachers to use what they are already doing.

In Chapter 5, we investigated the extent to which teachers rated the teaching approach we developed as practically useful. We sought to increase the practicality of the approach by starting from existing demonstrations that can be easily converted to the desired approach. In the study, we asked teachers to compare the practicality of their regular approach with that of our approach. The results showed that teachers found the redesigned demonstration with the two design principles as practical as a traditional demonstration. Teachers named as advantages of the redesign is that students are enabled to think for themselves, and that the perspective could serve as thinking frame. A mentioned disadvantage was the large number of questions in the used perspective for structure-property reasoning.

With the main findings of the sub studies, we can answer the overall research questions: *What are the characteristics of an effective and practical approach that supports chemistry teachers in designing, enacting, and evaluating lessons in which a demonstration experiment is used to enhance students' structure-property reasoning?*

The first characteristic we proposed and tested, is the perspective for structure-property reasoning as model for structure-property reasoning. The perspective (Figure 6.1) consists of questions which can be used to describe the macroscopic properties by means of the micro level. For teachers, the perspective for structure-property reasoning can be used as design principle to design lessons and evaluation tools. As evaluation tool, the perspective is used as base for the design of the instrument to estimate the proficiency of students in structure-property reasoning (see Chapter 3). In Chapter 4 and 5, I used the perspective as design tool for demonstration lessons. Teachers estimated the use of the perspective as design tool as practical (see Chapter 5).

The second characteristic of our approach is the POE demonstration (Chapter 4). The POE demonstration allowed teachers to start at students' macroscopic orientation. The Predict-phase of a POE task enables students to engage in the demonstration. The student-centered Explain-phase enables the students to think for themselves and to model the micro level to explain the shown phenomenon. Therefore, the use of the POE task as described in this research enables teachers in explicit teaching of structure-property reasoning.

To help the students with their explanations and models in the Explain-phase, the perspective for structure-property reasoning is used as scaffold. The questions of perspective are used to describe and question the phenomenon. The associated chemical concepts which are the answers to the relevant and applicable questions will help the students in formulating the right answer and using the right micro model. Therefore, the POE-demonstration with the perspective for structure-property reasoning enables the teacher in explicit teaching of structure-property teaching and therefore the combination of the two characteristics is effective.

The two design principles combined are also estimated as practical by teachers (Chapter 5). From the three criteria of practicality, this can also be explained. The practicality for the teaching approach for structure-property reasoning is increased by the possibility for teachers to redesign their existing approach by only making minor adjustments. First, because the POE task only adds one building block, namely “predict”, to a regular demonstration, the teaching practice is only slightly changed. In addition, the perspective for structure-property reasoning rearranges the existing content building blocks, namely the educated chemical concepts in a more coherent manner. Both enabling the teacher to stay close to teachers’ own teaching practice. in this way both the POE task as the perspective increases the instrumentality. Second, the POE task enables the student think for himself during the demonstration (Chapter 4). That will, in turn, enables the teacher the achieve his teaching goals with the demonstration, making the approach congruent. Last, the approach is cost-effective. Adding a demonstration to the teaching practice instead of practical work performed by the students costs less time and resources.

6.3. Limitations and Suggestions for Future Research

A first limitation of this research is the small sample size of students participating the study in Chapter 3. This was the result of both the selection of the samples bound to the available groups and classes and the use of a qualitative research design. Therefore, the redesigned demonstration lessons were limited to year 4 of the pre-university track. Recommendations for further research is an increase in the sample size and to broaden the sample selection. First, the redesigned demonstrations should be performed by other teachers and thereby including more groups of year 4 students at the pre-university track. Next, the design principles should be used in the redesign of other demonstration in which students acquire and develop structure-property reasoning. This could be students of all levels and years of secondary education.

The cost-effectiveness of the SPR instrument (Chapter 3) should be increased. Now, administering and analyzing the SPR instrument for bigger groups is too time-consuming. We think that the cost-effectiveness could be increased by digitalizing the sorting task. Therefore, a group of students of the bachelor informatics designed an online application for the sorting task of the SPR instrument. In this app the teacher can design a sorting task, framed or unframed, 1d or 2d, determined or undetermined. With a simple code, students can perform the sorting task and the percent pairs is calculated. This app will make it possible to administer sorting tasks to various groups of students as formative assessment or as assignment, but also for investigation purposes. In further research, this app should be investigated to reveal if the cost-effectiveness of the SPR instrument is increased by this app and how it can be used in the abovementioned suggestions for further research.

The demonstration lesson series was designed to enable students to acquire structure-property reasoning (Chapter 4). One lesson series to develop the perspective for structure-property reasoning, associated chemical concepts and proficiency in using the questions is clearly not enough. Repetitive use by students of the perspective and application of the chemical concepts in several assignments and tasks would be needed for students to fully acquire structure-property reasoning. The lesson series described in Chapter 4 could be the start of systematic use of the perspective for explicit teaching of structure-property reasoning. Further research could aim to develop a learning progression for structure-property reasoning, in which the development of students' structure-property reasoning is followed over a longer period.

As the study described in Chapter 4 showed, both design principles helped to promote structure–property reasoning among students. However, these principles will only be used in day-to-day practices and on a wider scale if teachers estimate the principles to be practical. In Chapter 5, the practicality of both design principles was investigated by interviewing 8 teachers. An important limitation of study described in Chapter 5 is the context in which the research was performed. The interviews were conducted at the end of the first Covid-19 lockdown in the Netherlands (June 2020). Nevertheless, the scores and the advantages for the two building blocks were still promising for the practicality of the innovation and thus for a place in the teaching practices of teachers when performing a demonstration.

A limitation of the study described in Chapter 5 is that it concerns teachers' estimated practicality of the demonstration. It is not based on teachers' personal experience with implementing the approach in their own classes. In addition, there might be a natural resilience to change. Therefore, the one-time study of Chapter 5 might show greater differences in practicality when more lessons and demonstrations are designed. A next study could address these limitations. A bridging trajectory in which teachers step by step expand their repertoire with this approach should be developed and conducted. Then, it would be possible to assess how teachers rate the practicality after they have designed, taught, and evaluated this approach themselves.

Last, the applicability of the perspective used in this thesis has been demonstrated through a limited number of examples (Chapter 2). No extensive research has been performed on its general applicability for other topics and materials in K-12 chemistry education. Therefore, it should be noted that perspective for structure-property reasoning is only applicable to a limited part of the chemistry curriculum, i.e. structure-property reasoning. It has not been shown to be applicable to other topics that are important, like sustainability, kinetics, biochemistry and/or chemical industry. The perspective for structure-property helps students in relating the structure models to the macroscopic properties of the compound and scaffolds them structure-property reasoning. Further research should reveal how other topics of the chemistry K-12 education (and beyond) could incorporated to form a comprehensive chemistry perspective.

6.4. Theoretical and Practical Implications

This research explored how to evaluate and educate structure-property reasoning with the help of POE task demonstration and the perspective for structure-property reasoning. This gave rise to useful insights and various theoretical and practical implications. First, the theoretical and practical implications of the perspective itself were discussed, namely the use possibilities of perspectives and how they relate to existing approaches. Next, the use of the POE task and wherein it differs from a traditional demonstration is discussed. Last, the practicality of the approach is discussed.

Acquiring structure-property reasoning and to learn to think like a chemist are important goals of chemistry education. Novice chemistry learners experience difficulties in acquiring this type of chemical thinking due to the multilevel thought as depicted in Johnstone's triangle (Johnstone, 1982, 1991). However, the triangle provides insufficient guidance for chemical thinking. Therefore, one of the implications of this research is that it shows that the perspective for structure-property reasoning can serve as an explication of structure-property reasoning. The study described in Chapter 2 showed three advantages of the perspective of structure-property reasoning, namely coherence between reasoning skill and chemical concepts, horizontal and vertical coherence.

As Johnstone (1993) pointed out, an expert in chemical thinking and thus in structure-property reasoning makes various connection between the macro and micro level. Students experience difficulties with these connections and with easily and smoothly switching between these levels (de Jong & Taber, 2015; Gabel, 1999; Johnstone, 1991; Kozma et al., 1997). The perspective for structure-property reasoning allows visualization of the multilevel thought and thereby making the teaching and the learning of structure-property reasoning explicit. This visualization is accomplished by the questions of the perspective. Therefore, the perspective can be used as scaffold for students. By starting where the student starts, namely the macro level, the perspective allows students to make explicit connections between the macro and the micro level.

The perspective for structure-property reasoning is part of a more over-arching chemistry perspective. This chemistry perspective covers chemistry curriculum standards for K-12 education by organizing chemical topics in relation to the basic scientific ideas underlying chemical thinking. The learning progression for matter and the atomic molecular theory proposed by Smith, Wiser, Anderson and Krajcek (2006) distinguishes three core knowledge domains in chemistry:

- The properties of things depend on the matter they are made of.
- Matter can be transformed by chemical and physical processes.
- Atomic-molecular theory explains the properties and behavior of matter.

The perspective for structure-property reasoning develops the first and third of the abovementioned domains. The addition of the second domain can expand the perspective for structure-property reasoning into an overarching chemical perspective as shown in Figure 6.3.

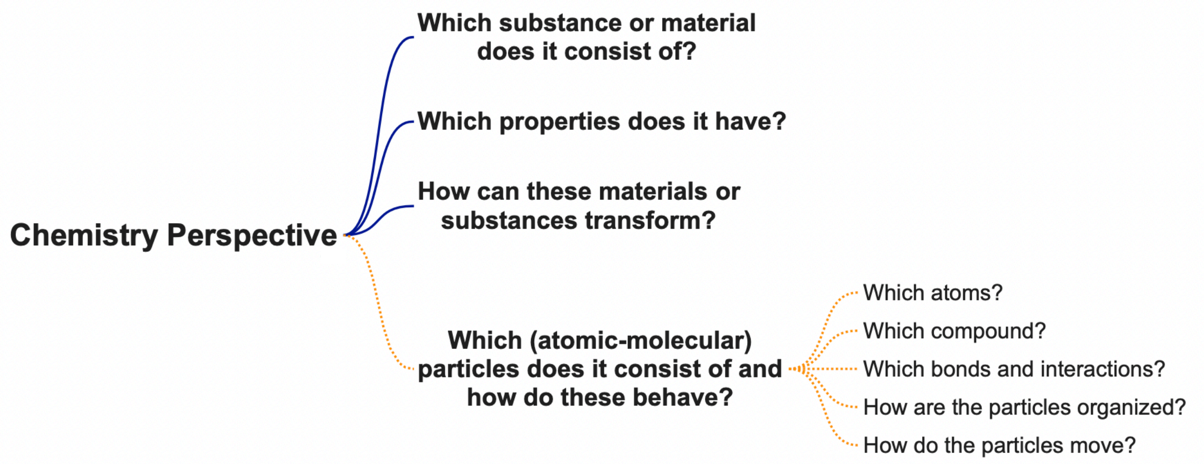

Figure 6.3: Perspective for structure-property reasoning elaborated into the chemical perspective.

The first three questions of the perspective for structure-property reasoning correspond directly with the first two and the last of the four main questions in Figure 6.3. The other three questions of the perspective for structure-property reasoning concerning how the particles behave (which bonds, which organization, and which movement) find their place as sub-questions under main question "Which (atomic-molecular) particles does it consist of and how do these behave?". When these main and sub questions are further elaborated and differentiated, branches are added containing more specific and detailed chemical questions, eventually creating a chemical knowledge hierarchy (Figure

6.4). Note that the above-proposed chemistry perspective integrates the four chemistry perspectives described by Landa et al. (2020).

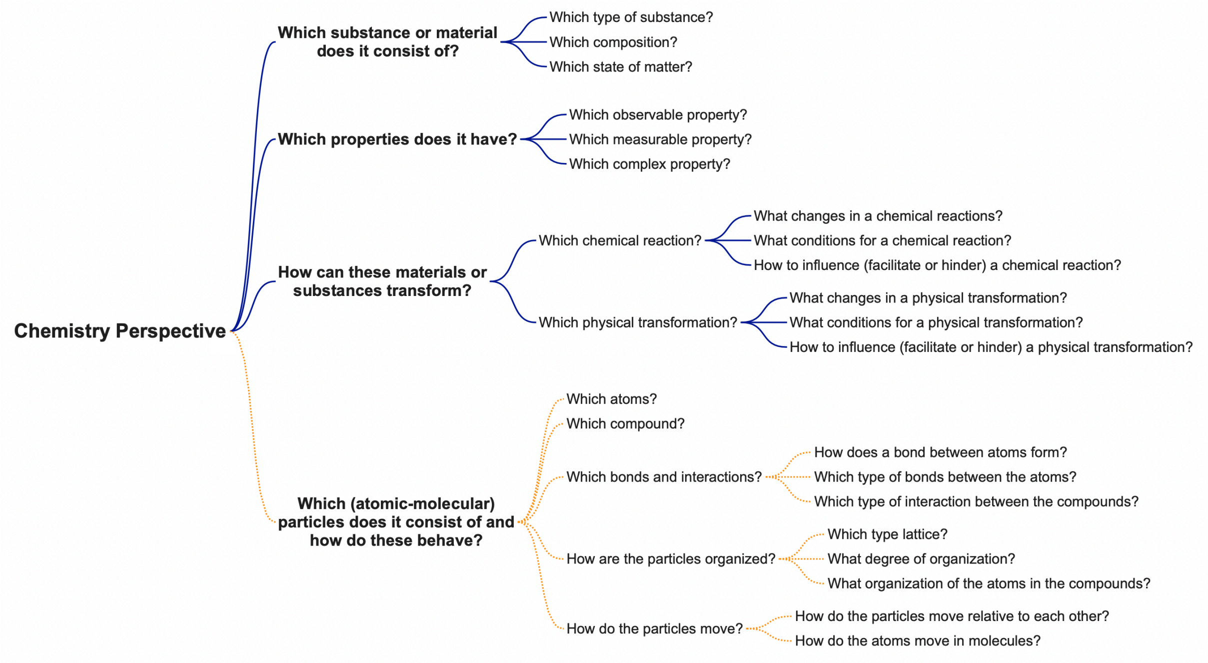

Figure 6.4: *chemistry perspective elaborated to two or three levels.*

Because the perspective is composed of questions and structured in a hierarchy, the perspective is applicable as thinking tool, scaffold and knowledge organizer for students as described in Chapter 4 and 5 and as design tool for designing lessons, lesson series (Chapter 4) and curricula. The perspective can also be used to design formative evaluation tools as described in Chapter 3. In the following paragraphs, these implications will be further elaborated.

For students, the perspective for structure-property reasoning is used as scaffold and as knowledge organization (see Chapter 3 and 4). The main and sub-questions of the perspective support the student in solving chemical problems and in reasoning about structure-property relations. The student starts with some worked examples of the perspective (Figure 6.6). Next, the student elaborated the perspective himself when solving a chemical problem by formulating answers on the relevant questions of the perspective. The teacher scaffolds this process by preselecting the relevant main- and sub-questions and formulating relevant and applicable follow-up questions. When the student progresses in structure-property reasoning, the scaffolding of the teacher can be reduced by backward fading. Eventually, a student will be trained in questioning difficult chemical problems to formulate an answer. In addition, when progressing in structure-property reasoning, more chemical concepts as answers to the questions of the perspective for structure-property reasoning will be acquired. The concepts are organized in the perspective, resulting in a knowledge organization. Such a knowledge organization offers structure and thereby insight into students' progression in the intended learning objectives.

The perspective for structure-property reasoning as depicted in figure 6.1 (and Figure 6.4) give rise to increased vertical coherency. Therefore, the perspective is a starting point for a learning progression of structure-property reasoning. This enables teachers to let students practice step-by-step by using the perspective to (re)design various lessons and (practical) assignments. In that case, the perspective operates as a design tool for teachers at the level of single lessons, due to its hierarchic structure of questions and the resulting horizontal coherence. The learning objectives in the form of chemical concepts can be mapped in the perspective, thereby revealing their interconnection (See Figure 6.6). Because of the questions, the back and forward thinking between the structure models (micro level) and the properties of the compounds and materials (macro level) becomes visible. This gives structure to the lesson design. The questions, and the hierarchy of the perspective for structure-property reasoning could also be used for structured and supportive instructions by teachers.

Due to the resulting vertical coherence, the perspective for structure-property reasoning also functions as tool for curriculum design. The designer starts with mapping of the chemical concepts of one or more years in the perspective. This will create an overview of the curriculum. The coherence between the topics will be revealed and redundant concepts can be removed. Next, the designer can plot various learning pathways by following the branching questions with corresponding concepts. These learning pathways can be used for the design of separate lessons and lesson series.

In existing approaches to the development of curricula, an atomistic approach is often chosen. In an atomistic approach the whole (the curriculum) is broken down in parts (all the knowledge, concepts, and skills). In doing so, knowledge and skills are divided. Therefore, a holistic approach to curriculum design is preferred. The holistic approach makes it possible to focus on details without losing sight of the whole (Reigeluth, 2007). Some holistic approaches to curriculum design make it possible to design and validate learning progressions which focus on a core idea, for example acids and bases, and/or a skill like asking questions (Duschl et al., 2011; Jin et al., 2019). The working method causes a focus on the core idea which diverges further and further, and skills and knowledge are no longer divided. Disadvantage is that the ideas underlying the learning progressions are much smaller in scope (Janssen et al., 2019). By using a domain specific perspective, like the perspective for structure-property reasoning the various core ideas, knowledge, and skills could be integrated in a powerful thinking tool for students (Janssen, in preparation).

For the teaching of structure-property reasoning, a teacher requires insight into students' proficiency in structure-property reasoning (Sevian & Talanquer, 2014) to support them in acquiring these expert-like reasoning skills. Several assessment instruments could help the teachers with this insight (Chandrasegaran et al., 2007; Cooper et al., 2013; Irby et al., 2016; Kohn et al., 2018; Kozma & Russell, 1997; Maeyer & Talanquer, 2010; Nyachwaya et al., 2011; Talanquer, 2008). Nowadays, formative assessment (Sluijsmans et al., 2016; Wiliam, 2020) is of increasingly importance in the daily teaching practice, in teacher education and teacher training. Assessment of students supports learning of students and gives the teacher information about the effectiveness of his teacher practice (Surma et al., 2019; William, 2011). Therefore, another implication of this research is the SPR instrument. This instrument, as described in Chapter 3, could support teachers in assessing the level of proficiency of students' structure-property reasoning. The SPR instrument can be used as tool to get insight into the class as whole, which is interesting for the teacher, and as tool to get insight into the individual students. The latter will support students themselves in self-regulated learning as well the teacher in giving valuable feedback. Because the SPR instrument was based on the perspective for structure-property reasoning, the study described in Chapter 3 showed that domain-specific perspectives could be used to evaluate the learning of students. The use of a perspective in the instrument makes it possible to quickly redesign the instrument to other types of domain-specific reasoning just by using the other domain specific perspectives in the design of the sorting task and the mapping task.

Practical work performed by students is common in the chemistry lesson and many teachers believe that practical work plays an important role in learning chemistry. However, literature shows that the effectivity of practical work performed by students is low (Hodson, 2014). Students are hindered by noise caused by the complexity of performing an experiment yourself. Demonstrations performed by the teacher reduces this noise significantly and the possibility of showing the chemical phenomenon remains. To increase the engagement of students during the demonstration, a POE task can be used (Crouch et al., 2004; Treagust & Tsui, 2014). The POE task will enable the students to think for themselves. Therefore, our research contributes to the theory and the practice of POE tasks used for demonstrations. As the study described in Chapter 4 showed, the POE task enables the teacher in explicit teaching of structure-property reasoning. The addition of the building block 'Predict' to the demonstration teaching sequence enables teachers to engage students more with the chemical phenomenon showed by the demonstration. By asking the students on forehand to their predictions and by letting them explain their observations afterwards students can actively participate in the demonstration. Furthermore, the POE task enables students to think for themselves and practice his structure-property reasoning skills. Teachers interviewed in the study described in Chapter 5 underline this increased engagement.

In literature, the POE task is not new (Crouch et al., 2004; Hilario, 2015; Liew & Treagust, 1998; Treagust & Tsui, 2014; White & Gunstone, 1992; Zakiyah et al., 2019). However, the addition of the perspective for structure-property reasoning to the POE task enables students with their explanations and models in the Explain-phase. Students use the perspective for structure-property reasoning as scaffold in their reasoning about explanations of the chemical phenomena by means of the micro level models.

The research described in this thesis is not only focused on effective teaching practices to teach structure-property reasoning to students. The research is also aimed at making the innovation practical for teachers. Therefore, we used the bridging approach in which innovating is done by recombining building blocks (Dam et al., 2013; Janssen et al., 2013). This usually involves recombining building blocks with teaching-learning activities like instruction, practice and demonstrate. In this study, the recombining of building blocks was done by adding the building block Predict and changing the building block Explain. In addition, the use of perspective for structure-property reasoning in this research is also a form of recombination of building blocks, namely a recombination of content building blocks. This type of recombination can be added to the bridging methodology and expand the possibilities for teachers to expand their teaching repertoires.

Demonstrations could be an important online teaching method. A weakness of online teaching, however, is the lack of interaction with students. Therefore, the addition of a POE task to demonstrations could increase the interactions with students and therefore it could make online demonstration more minds-on. This will broaden teachers online teaching skills. Using the perspective as instruction tool and as scaffold for the students, the interaction during the online teaching could also be increased.

In this study, the two design principles were employed in the (re)design of demonstrations. These design principles are also applicable to the (re)design of practical or written assignments, where students are required to engage in reasoning about structure-property relations, facilitating the further development of structure-property reasoning as the core of chemical reasoning.

A redesigned approach to conductivity of solid salts and salt solutions

The teacher starts the demonstration by briefly explaining what will be measured. The students are asked to write down their predictions of the demonstration experiment and to justify / explain these predictions. They discuss this with their classmates. The teacher then performs the experiment, while the teacher emphasizes the important observations. He asks the students to write down their observations. Afterwards, the students compare their expectations with their observations and try to explain the difference. Next, a class discussion with questions that help students reasoning with structure-property relations follows so that every student has taken notion of the model (micro) behind these macroscopic properties. (Figure 6.5)

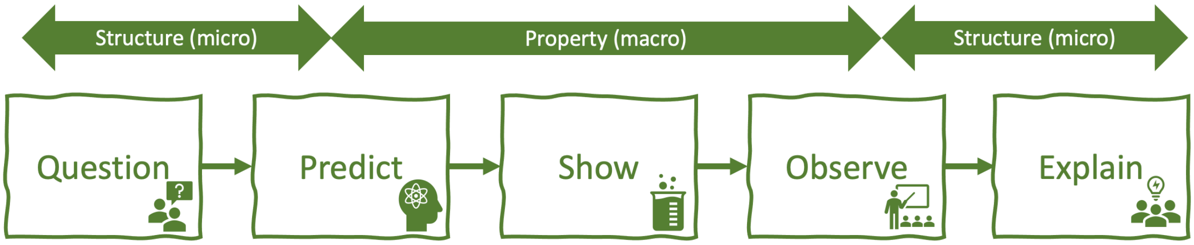

Figure 6.5: Building blocks of a demonstration with a POE task.

Perspective for structure-property reasoning as thinking frame for structure-property questions

To scaffold students' thinking in the explain-phase, the perspective for structure-property reasoning can be used. The students use the questions of the perspective to describe and analyze the demonstrated structure-property relation. This will help the students in formulating the best explanation (see Figure 6.6).

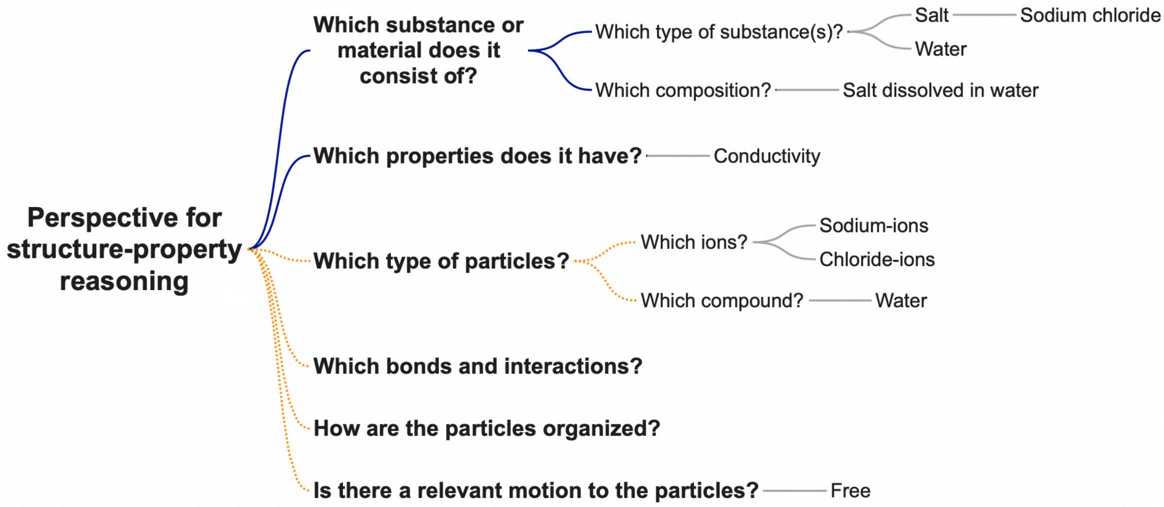

Figure 6.6: perspective for structure-property reasoning after the demonstration experiment 'conductivity'.