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

Otter, M. den

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

Marie-Jetta den Otter

ICLON, Leiden University Graduate School of teaching

The reseach reported in this dissertsation was carried out within the Dudoc-Bèta program with financial support of the Dutch Minitery of Education, Culture and Science.

Title: 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.

Titel: De kloof tussen macro en micro overbruggen: het verbeteren van het chemisch redeneren van leerlingen. Hoe demonstratie-experimenten effectief te gebruiken voor het onderwijzen en leren van micro-macrodenken.

ICLON PhD Dissertation Series

Print: Mostert en Van Onderen! Leiden
Cover design: Marieke Wedemeijer-Hosman en Julian Kruidhof
Lay-out: Marie-Jetta den Otter
ISBN/EAN: 978-94-90383-46-6

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

Proefschrift

ter verkrijging van

de graad van doctor aan de Universiteit Leiden,

op gezag van rector magnificus prof.dr.ir. H. Bijl,

volgens besluit van het college voor promoties

te verdedigen op woensdag 6 december 2023

klokke 11:15 uur

door

Marie-Jetta den Otter

geboren te Groningen

in 1977

Promotores:

Prof.dr.ir. F.J.J.M. Janssen

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Dr.ir. A.J. Kuijpers

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Chapter 1:

General Introduction

1.1 Introduction

“Mrs., what am I actually doing now?”, Claire (year 5, age 16) exclaims during an experiment where she prepared salt precipitations. Performing the research proceeded fine, by the way, but she could not explain for herself what those actions had to do with her research question and the associated chemical concepts. James in year 6 (age 17) asked just before his exam “But what are these molecules really?” and later he mentioned: “I wish I could think like you do....”.

In my experience as chemistry teacher abovementioned exemplary student remarks show that it is hard for students in general to achieve a primary goal of our chemistry education: to learn students “to think like a chemist”. Students experience learning chemistry as difficult. For an expert in chemistry, thinking about chemical problems and topics seems quite simple, but for a novice this is quite elusive.

The challenge inherent in chemistry stems from the requirement of engaging in multilevel thought for chemical reasoning. (Johnstone, 1982, 1991). In the realm of macroscopic observations, we perceive the properties exhibited by compounds and duly take note of their transformations. In chemistry, this is called the macro level. If we want to explain and describe these properties and changes, we need to go down into a world invisible for the naked eye, or even with the best microscope. We need to zoom in to the level of the particles, the so-called (sub)micro level. Last, when thinking and talking about both the macroscopic world and the invisible world full of chemical models, we need a language, which is called the symbolic level. Johnstone (1982, 1991) depicted the three levels as a triangle to visualize this multilevel thought. The corners represent the three levels, macro, micro and symbolic (Figure 1.1). Although present in the work of other researchers, the question remains whether this symbolic level can be regarded as a discrete level. The symbolic level helps chemists in representing and communicating about the chemical concepts, both at the micro as the macro level (Taber, 2013). Therefore, in the Dutch chemistry curriculum, we use the term micro-macro thinking, which is restricted to these two levels when referring to chemical reasoning with multilevel thought (Meijer, 2011).

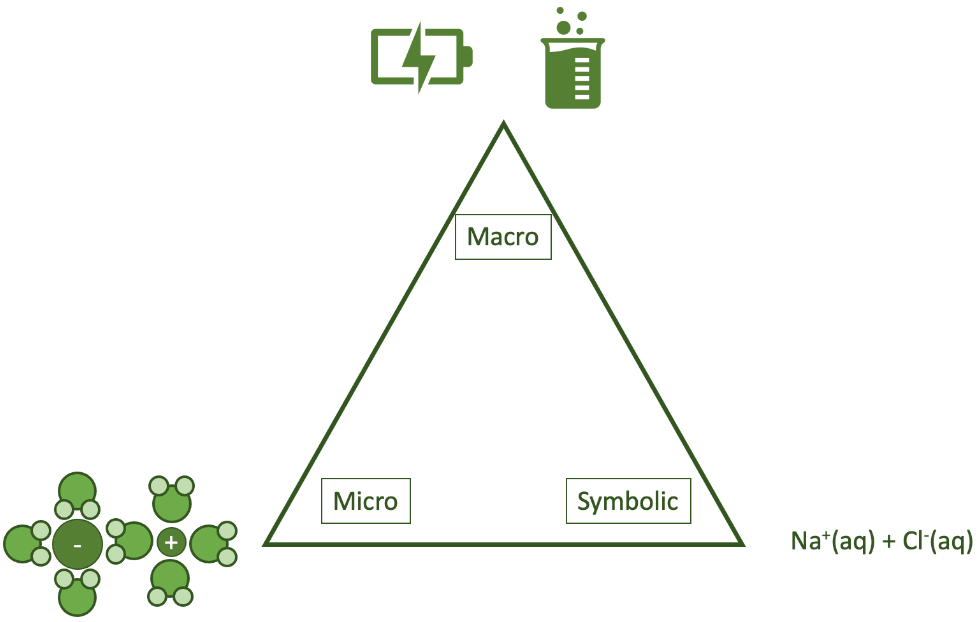


Figure 1.1: *Johnstone’s triangle depicting the multilevel thought of chemistry* (Johnstone, 1991).

Many problems in chemistry are based on the so-called structure-property relations, the relation between the macroscopic properties of a compound and the submicroscopic models like atoms, molecules, and ions. The reasoning about these relations is referred to as structure-property reasoning (Cooper et al., 2013; Talanquer, 2018). The term structure-property reasoning is used in the Anglo-Saxon curricula and chemistry education research (Cooper, 2020; National Research Council, 2013; Stowe et al., 2019; Talanquer, 2018). Structure-property reasoning is also incorporated in the Dutch exam requirement, for example under Subdomain A12: Reasoning in terms of structure properties (*Syllabus Centraal Examen, Scheikunde Vwo*, 2016). Therefore, I will use the term structure-property reasoning in this thesis.

Experts do not experience difficulties with structure-property reasoning, because they easily and unconsciously move back and forth between these levels. Novices in chemistry find it challenging working at the micro level and macro level simultaneously. Their working memory will be overloaded (Johnstone, 1991). Therefore, this multilevel thought needed for structure-property reasoning is very difficult for students.

In the classroom, teachers will experience students' difficulties with reasoning about structure-property relations (Meijer, 2011). First, due to the invisibility of the micro level, chemists use different models to communicate about this level (Cheng & Gilbert, 2017; Chittleborough & Treagust, 2007; Gabel, 1999). Evidently, chemistry teachers want their students to get acquainted with these models. For this reason, chemistry curricula include models of the particulate nature of matter (Harrison & Treagust, 2003). However, students struggle with the needed structure models. They often translate these models one-to-one with reality. Furthermore, students do not know what the boundaries of models are (Adbo & Taber, 2009; de Jong & Taber, 2015). Second, most students have a macroscopic orientation caused by their former experiences (Gabel, 1999; Johnstone, 2000). Third, students have different misconceptions about the particle model and thus the micro level. The main misconception with the particle nature of matter is that students see particles as small portions of the whole substance, with all the properties of this substance (Ben-Zvi et al., 1986; de Jong & Taber, 2015; Talanquer, 2018). Last, teaching is not always matched with students' existing conceptual framework (de Jong & Taber, 2015). Above problems could give rise to misconceptions about the micro level and hinder the acquiring of structure-property reasoning.

Both the importance and general approach to structure-property reasoning are widely endorsed. However, there is little discussion about how to best support students in developing this type of reasoning (Talanquer, 2018). Showing the chemical phenomenon, which students could relate to, to emphasize the three levels and integrate these three levels could make the instruction more effective (Gabel, 1993; Kelly et al., 2010; Kozma et al., 1997). In sum, structure-property reasoning should be taught explicitly (Gilbert & Treagust, 2009; Meijer, 2011) to enable students to learn to switch between the macro and the micro level. Furthermore, teaching should be centered on the core idea of this type of reasoning (Stowe et al., 2019; Talanquer, 2018).

However, previous research shows that teachers do not have sufficient experience in the explicit teaching of structure-property reasoning (Dolfing et al., 2011). Moreover, literature offers little clues to teachers need for this explicit teaching (Talanquer, 2018). Teachers would be helped with an approach and tools for the explicit teaching of structure-property reasoning.

Literature shows that a laboratory activity like a demonstration or practical assignment offers opportunities to promote students' structure-property reasoning (Becker et al., 2015; Gabel, 1993, 1999; Kelly & Jones, 2007; Kozma et al., 1997; Ramsey et al., 2000; Treagust & Tsui, 2014; Tsaparlis, 2009). In these experiments, chemical phenomenon (the macro level) is shown that can be explained with the behavior of and interactions between particles (the micro level). In this way, the teacher starts where students start, namely at the macro level (Johnstone, 2000). Moreover, a laboratory activity provides the opportunity for the teacher to connect to students' macroscopic orientation (Gabel, 1999).

Doing a demonstration experiment in the class instead of a practical assignment has an important benefit for students because a demonstration could reduce the level of noise of a practical assignment (Gunstone & Champagne, 1990; Hodson, 2014; Hofstein, 2017; Pols, 2023). Students make errors in observing and measuring - leading to unreliable results, lose interest or fail to finish the data collection in time. These will lead to the wrong data and/or wrong conclusions that restricts the learning of structure-property reasoning. This problem can be prevented by reducing the noise for example by simplifying the activity. However, this is not possible for every chemical phenomenon with associated model on micro level you want a student to experience. In this case a demonstration experiment is a good solution (Hodson, 2014).

Although demonstrations can be preferred over practical activities, the potential of demonstration experiments for the teaching of structure-property reasoning is often not realized. In many demonstrations the teacher shows, points out observations, and explains and the students passively observes (Figure 1.2). Students' attention is mainly with the external characteristics of the experiment. They fail to explain what they observe by means of the micro level and students have very few possibilities to test their ideas and ask their teacher questions (Treagust & Tsui, 2014). Moreover, if there is a group discussion in response to an experiment, the students mainly discuss about symbolic representations - for example the balancing of a chemical reactions. The crucial connections between the micro and the macro levels are not made by students themselves (Becker et al., 2015). Consequently, they have trouble with developing the right conceptual understanding.

Demonstration experiments, when accompanied by explicit support for structure-property reasoning, have the potential to be effective in enhancing students' structure-property reasoning. However, for these approaches to be successful, it is crucial that teachers actively implement them in the classroom. Innovative teaching practices can further augment the effectiveness of demonstration experiments. Specifically, teachers need to explicitly teach structure-property reasoning during demonstrations. Despite the potential benefits of innovations, teachers often experience a gap between what is considered effective and what is practically applicable in the classroom (Doyle, 2006; Doyle & Ponder, 1977; Janssen et al., 2013; Shavelson et al., 2008).

Practicality theory (Doyle & Ponder, 1977) posits that an innovation, a proposal of change, will only be implemented by teachers when they consider the innovation as practical. Furthermore, teachers will adapt or reconfigured an innovation to increase the practicality. Doyle & Ponder (1977) developed the three dimensions of practicality. The first dimension is instrumentality, which means that the innovation has clear and recognizable procedures. The second dimension is congruence, which means that the innovation is congruent with teachers' goals. The third dimension is cost-effectiveness, which means that the innovation costs less time, energy, and materials then the normal teaching practice. When an innovation is considered instrumental, congruent with teachers' goals, and when it has low costs, the innovation will be considered as practical by teachers.

The dimensions of practicality were further elaborated by Janssen and colleagues into a theory and a methodology to make innovations practical without losing the core of the proposed innovation (Janssen et al., 2014, 2015).

The traditional approach to conductivity of solid salts and salt solutions

The goal of this demonstration is developing the awareness that salt consists of ions (structure/micro level). In the demonstration the teacher shows that a molecular compound such as (pure) water does not conduct electricity using a conductivity meter (property/macro level). Measuring the conductivity of a solid salt shows that it does not conduct either. Then the teacher makes a salt solution of the showed solid salt and water and shows the conductivity of this salt solution. Following the demonstration in teacher-directed explanation, the teacher shows that a molecular compound consists of uncharged particles, named molecules and a salt consists of charged particles, named ions (structure/micro level). Only when the salt is dissolved or molten these charged particles can move freely and there will be conductivity of electricity. (Figure 1.2)

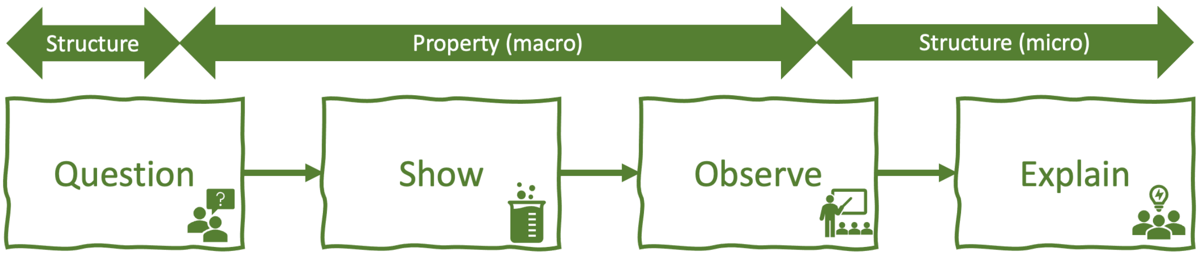


Figure 1.2: Building blocks of a demonstration experiment.

1.2 Research Goals and Overview of the Study

Based on the previous considerations regarding structure-property reasoning and the teaching and learning thereof as well as considerations regarding design of effective chemical demonstrations, we expect that education with regards to structure-property reasoning may benefit from the use of appropriate demonstrations. These demonstrations of the chemical phenomenon should give the students the opportunity to think for themselves. Furthermore, students should be supported in acquiring structure-property reasoning by making the teaching of structure-property reasoning explicit to let students make the crucial connections between the micro and macro level. An essential prerequisite for such an intervention is that teachers perceive the teaching practice as practical. (Janssen et al., 2015; Janssen et al., 2013). Against this background the central research question for this research project is: 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? To answer this research question four studies were conducted. These are described in the next four chapters.

First, explicit teaching of structure-property reasoning presupposes a model by which macro and micro levels are explicitly connected. Chapter 2 describes such a model for structure-property reasoning building on Johnstone's triangle and followers. This model is based on scientific perspectivism (Landa et al., 2020) making it possible to explicitly connect chemical concepts with the big idea of structure-property reasoning. We call this model a perspective for structure-property reasoning. This perspective is designed to support students in structure-property reasoning. Using four chemical cases of increasing complexity, we show how the perspective can be progressively built upon and provide direction in structure-property reasoning.

Because we want to assess the extent to which the desired approach promotes students' structure-property reasoning, we have developed an assessment instrument for this purpose, described in Chapter 3. With this instrument the proficient in structure-property reasoning of secondary school students could be assessed. Proficiency in structure-property reasoning is necessary for a good understanding of many chemical topics. This instrument should meet four criteria: 1) the instrument has to be based on a comprehensive model for structure-property reasoning, 2) the instrument has to be practical for teachers (Janssen et al., 2013), 3) the instrument has to be applicable to large groups, and 4) teachers has to be able to use the instrument repeatedly and adapt the tool to the grade, level, and content they teach. The SPR instrument was administered to two target groups – secondary school students at the pre-university track and first-year university chemistry students – to determine whether it could discriminate between those groups.

In the study presented in Chapter 4, a demonstration-based lesson series aimed at acquiring structure-property reasoning was designed and tested. Two design principles underlie this lesson series: 1) students are encouraged to think for themselves through a predict-observe-explain task; 2) their structure-property reasoning is supported with the perspective for structure-property reasoning. To promote possible practicality, the lesson series was not developed from scratch, but existing demonstration experiments were adapted. Next, the demonstration-based lesson series was tested for the progression of students' structure-property reasoning with the SPR instrument and qualitative data from a case study of one student.

In Chapter 5, teachers' estimated practicality of the teaching approach for teaching structure-property reasoning developed in Chapter 4 was investigated. Eight teachers were interviewed to estimate the practicality (de Graaf et al., 2018) of redesigned demonstration lesson about chemical equilibrium. The teachers were presented the redesign and then asked to score the perceived desirability of the redesign and perceived probability they would use the design in their own teaching practice. To explore their motivational beliefs, the teachers were asked to name advantages and disadvantages of the design. These motivational beliefs give insight into the extent to which a teacher considers the toolbox practical for their own teaching practice.

Chapter 6 discusses the main findings of this thesis. Furthermore, I address the contributions of this research to theory and practice, the practical implications, as well as the limitations and suggestions for further research.

Chapter 2:

A Structure-Property Perspective to Explicate and Scaffold Thinking like a Chemist

Abstract

Chemical reasoning, and in particular structure-property reasoning, is an important goal of chemistry education. Johnstone's triangle (1982) is often used to explicate this type of reasoning. This triangle describes the multilevel thought chemical reasoning requires and shows why students find chemistry so difficult. However, this model gives little guidance for teachers and students on how to teach and learn structure-property reasoning. In this theoretical chapter, we propose an alternative model for structure-property reasoning which has three advantages compared with previous models: namely, more coherence between chemical concepts and the skill of reasoning, more horizontal coherence (coherence between the concepts within a certain grade), and more vertical coherence (coherence throughout the different grades). In four cases selected from the Dutch secondary school chemistry curriculum, the model was used to show how it can guide teachers and students in teaching and learning structure-property reasoning, and to demonstrate its above-named advantages. The presented model has various educational applications as a scaffold for students' reasoning, and as an instruction, design, and curriculum tool for teachers.

This paper based on this chapter has been accepted in Research for Science Education.

2.1 Introduction

Learning to think like a chemist is an important goal of current chemistry education (Landa et al., 2020; Sevian & Talanquer, 2014; Talanquer & Pollard, 2010). At the core of such thinking is structure-property reasoning (Meijer, 2011; Talanquer, 2018), which is included in the standards for chemistry education in many countries (Achieve, 2010; National Research Council, 2013). Structure-property reasoning relies on the fundamental insight that the chemical and physical properties of substances are explained by the nature and structure of the submicroscopic particles of which they are made (Smith et al., 2006; Talanquer, 2018). In chemical practices, structure-property reasoning is not only important for explaining and predicting the properties of existing substances and materials, but also for designing new substances or materials with tailored properties.

Chemistry philosophers have been concerned with the essence of this type of reasoning, and they have developed several models for structure-property reasoning. One of the most prominent models in chemistry education research that addresses the difficulty of structure-property reasoning was proposed by Johnstone (1982). In his research, he examined why chemistry is experienced as difficult by learners. This led to his model, depicted in the shape of a triangle, for explicating the multilevel thought needed for chemical thinking (Reid, 2021).

Johnstone's triangle proposes that a chemical phenomenon can be represented at two levels: namely, at the level of the observable, tangible, and measurable properties of substances and at the level of particulate structure. Johnstone explicated these levels as macro (the observable) and micro (the particulate) levels. In the Netherlands, structure-property reasoning is known as micro-macro thinking, which refers to thinking between Johnstone's two levels. In addition to the micro and the macro levels, Johnstone stated that chemical thinking, and thereby structure-property reasoning also, requires dealing with a symbolic level, such as atomic symbols and equations. Johnstone depicted this multilevel thought as consisting of three levels in a triangle (Figure 2.1), whereby every corner represents a level (Johnstone, 1982, 1991).

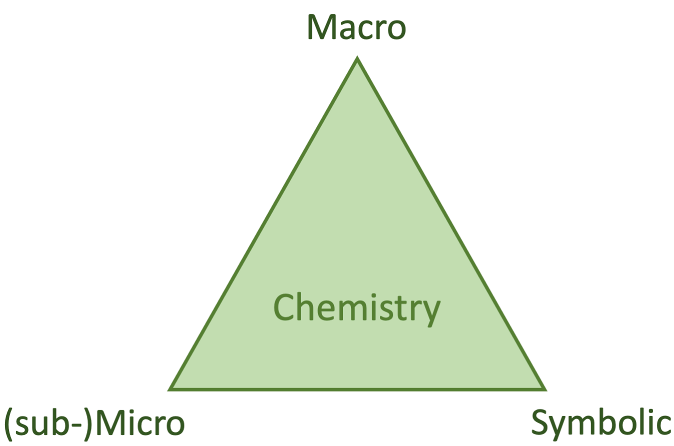


Figure 2.1: *Johnstone's triangle* (Johnstone, 1991; Reid, 2021)

In this theoretical chapter, we first briefly review and explore how Johnstone's triangle evolved into new and adapted models for chemical reasoning and structure-property reasoning. Next, we argue that despite their many advantages, Johnstone's triangle and the adapted models that followed have an important limitation: namely, failure to integrate the chemical concepts needed for structure-property reasoning. As a result, these models give students little direction in their reasoning. We believe that inclusion of the chemical concepts will contribute to educational implementation of the model and, thereby, to improving students' structure-property reasoning. We therefore propose an alternative model for structure-property reasoning that, on the one hand, builds on the existing models but, on the other hand, integrates the concepts needed for structure-property reasoning. The model we propose has a theoretical basis in scientific perspectivism (Giere, 2010; Wimsatt, 2007), making it possible to explicitly connect chemical concepts with structure-property reasoning.

In the proposed model, the core ideas of chemistry and K-12 concepts that are organized along the lines of chemical expertise have a central role. We show how to perform structure-property reasoning using the model for the following chemical topics, in order of increasing difficulty: separation methods, silica gel, cis-trans isomerism, and spider silk. Using these four cases we aim to show that structure-property reasoning can be constructed through the stepwise addition of chemical concepts. These four chemical cases also show how this model enables explicit teaching of structure-property reasoning in chemistry education. The model may also resolve some of the recurring problems of chemistry curricula: namely, the lack of vertical and horizontal coherence and the lack of connection between the skill of reasoning and the necessary chemical concepts for reasoning. Finally, the implications and opportunities of scientific perspectivism in chemistry education are discussed.

2.2 Johnstone's Triangle for Multilevel Thought

Alex Johnstone (1930-2017) started his career as a chemistry teacher in Scotland. In the 1960s, he and his colleagues developed a new approach for the Scottish school chemistry curriculum. In his research, he addressed the question of why chemistry is so difficult to learn (Reid, 2021). Johnstone (1982, 1991) stated that the difficulty lies in the multilevel thought required for learning chemistry, which incorporates three levels: the macroscopic level, the submicroscopic level, and the symbolic level. Johnstone depicted this as an equilateral triangle to symbolize the equal importance of each level (Figure 2.1). The edges of the triangle can be seen as possible connections between the levels.

Structure-property reasoning mainly relies on this multilevel thought (Cooper et al., 2013; Talanquer, 2018). Experts in chemistry unconsciously switch between these three levels when reasoning about a problem with structure-property relations. Johnstone formulated this even stronger by stating that experts in chemistry moves inside the triangle thereby continue mixing the three levels when reasoning about chemistry(Reid, 2021). However, for novices in chemistry, this multilevel thought causes an information overload of the working memory. Multilevel thought needs to be acquired by students when learning chemistry; thus, it should be given a prominent place in chemistry teaching. Furthermore, students need to be scaffolded when learning and practicing this multilevel thought (Gabel, 1999; Johnstone, 1991).

Johnstone brought to the attention of chemistry education researchers that the macroscopic level of compounds, with their observable and measurable properties, and the submicroscopic level of particles and their interactions require separate levels of thinking. These levels are difficult for novice learners to combine, and they need explicit teaching strategies (Gabel, 1999; Kozma et al., 1997). Acquiring structure-property reasoning is valuable for students, and Johnstone's triangle is a powerful and yet very simple depiction of the multilevel thought in chemistry.

Johnstone's triangle has been discussed, adapted, and elaborated since 1991. Several researchers have discussed various aspects of the triangle (De Jong et al., 2013; Gabel, 1999; Kozma et al., 1997; Mahaffy, 2004, 2006; Meijer, 2011; Meijer et al., 2013; Sjöström, 2013; Taber, 2013; Talanquer, 2011; Thomas, 2017). In the following section, we describe the adaptations and elaborations of Johnstone's triangle in chronological order. Since we are primarily interested in explication of structure-property reasoning, we mainly explore models building on Johnstone's triangle in which structure-property reasoning is further elaborated.

Dori and her colleagues used Johnstone's triangle as a model to analyze chemical representations. They expanded the triangle with a process level (Dori & Hameiri, 2003), which refers to the chemical reaction used in the chemical representation. Later, other researchers expanded the four levels of understanding (macro, micro, symbolic, and process) of Dori and Hameiri (2003) with a quantum level. This level includes the electronic structures of atoms and molecules such as energy levels and orbitals (Dangur et al., 2014).

Talanquer (2011) later expanded Johnstone's triangle by adding several levels or scales between the subatomic and macroscopic levels, such as molecular and mesoscopic, changing the triangle into a triangular beam. The corners of the triangle – in Talanquer's model called 'types' – were differently defined: macro changed into experiences, micro changed into models, and symbolic changed into visualizations. According to Talanquer, chemistry knowledge could be viewed from these three types like the three corners of Johnstone's triangle. Within these types, one could distinguish 'dimensions' such as energy or time in the type models, and 'approaches' such as mathematical or conceptual in the type visualizations. Every type has its own approaches and dimensions.

In the same year, Meijer (2011) added meso levels to Johnstone's triangle; these were used to explain properties at different structure levels. This adaption is especially applicable to substances containing macromolecules, such as plastic or bread where the macro structure emerges from the interactions of the macromolecules (Meijer et al., 2013). Ben-Zvi and colleagues (1990) also distinguished in the micro-level several sublevels, i.e., the atomic-molecular level and the multiatomic level, referring to a large assembly of molecules. Similarly, Talanquer (2018) divided the continuum between submicro and macro into levels with different length scales.

Taber (2013) also revisited Johnstone's triangle. First, he separated the experiential level, which describes the chemical phenomena. These phenomena can be described using two other levels: macroscopic concepts and (sub)microscopic concepts. Furthermore, Taber stated that the symbolic level cannot be separated as a discrete level of chemical knowledge. The symbolic level serves as the language in which chemists communicate about the macroscopic and the (sub)microscopic concepts. It is the technical vocabulary and other symbolic representations through which we communicate.

A few years later, Thomas (2017) took up Taber's (2013) suggestion to use the symbolic level as language to represent and communicate about macroscopic and submicroscopic concepts. Based on his study, Thomas (2017) proposed, among other things, guiding questions for students at each level, such as "What can I observe?" for the macroscopic level and "What is happening to the particles in the matter I am thinking about?" for the submicroscopic level.

De Jong et al. (2013) renamed the corners, calling them domains. In addition, they added a process domain, whereby the Johnstone triangle became a tetrahedron. The process domain deals with the chemical reactions, i.e., the breaking and forming of bonds, etc. A chemical equation is written in symbols, but it depicts a transformation of matter. Students must relate the symbols in the equation to the process. This translation of the chemical equation requires understanding of various chemical concepts (Ben-Zvi et al., 1986). This fourth level of understanding, the process level, represents the dynamic nature of chemical reactions.

2.3 The Perspective as a Model for Structure-Property Reasoning

The literature shows that explicitly connecting the macro level with the micro level will strengthen students' structure-property reasoning (Gabel, 1999; Kozma et al., 1997; Meijer, 2011). However, Johnstone's triangle offers hardly any leads for this explicit connection, providing little guidance for teaching and learning structure-property reasoning. What appears to be missing, or has not been made explicit yet, is how structure-property reasoning relates to chemical concepts (knowledge) and topics as described in national curricula and chemistry textbooks. This might be one of the reasons that students' acquisition of structure-property reasoning remains very difficult despite progressive scientific insight into students' learning mechanisms.

Effective structure-property reasoning involves thinking like an expert. Expert thinking involves explicating the micro level and macro level and elaborating on these levels using the key chemical concepts, leading to coherence between the chemical concepts and the skill of structure-property reasoning. In addition, expertise studies have shown that knowledge organization is essential. Expert-like reasoning requires an organization of knowledge in which concepts are not only interconnected but also organized hierarchically (Jensen, 1998). Current curricula and teaching practices often do not contribute to the development of the required knowledge organization. On the contrary, the present way of teaching may lead to fragmentation of chemical concepts (knowledge), causing a lack of horizontal coherence (coherence between the chemical concepts). In addition, a coherent structure of chemical concepts and structure-property reasoning over the years of schooling is also lacking, causing a lack of vertical coherence. Both may cause a lack of direction for students in structure-property reasoning.

We propose a perspective (Giere, 2010; Wimsatt, 2007) as a framework to connect Johnstone's triangle with chemical concepts to facilitate explication of structure-property reasoning by showing how the reasoning skills and chemical concepts are connected. Furthermore, we believe that a perspective will increase vertical and horizontal coherence.

A perspective represents a knowledge hierarchy, which implies that it starts with general scientific ideas, which are progressively elaborated on and differentiated. The advantage of such a perspective is that chemical concepts are coherently organized. Furthermore, the knowledge in a perspective is formulated as questions to make students familiar with domain-specific ways of reasoning, the underlying assumptions, and the construction and evaluation of answers.

Perspectives for various chemical concepts have been described elsewhere (Janssen et al., 2019, 2020; Landa et al., 2020). Four chemistry perspectives were developed in Landa's research. These four perspectives were synthesized from the analysis of chemistry domains and associated core reasoning schemes (Goedhart, 2007; Sevian & Talanquer, 2014).

To cover the chemistry curriculum standards for structure-property reasoning and to identify its associated core reasoning schema, we first identified the central ideas of structure-property reasoning about matter and particles using K-12 science standards (Harlen et al., 2015; McComas, 2014; National Research Council, 2013; Smith et al., 2006). The K-12 science standards for matter and the atomic molecular theory proposed by Smith, Wiser, Anderson, and Krajcek (2006) distinguish three core knowledge domains in chemistry: namely, the properties of things depend on the matter they are made of, matter can be transformed, and atomic-molecular theory explains the properties and behavior of matter. This will lead to a central core reasoning scheme for structure-property reasoning:

*"The **properties** of **substances** can be explained by the nature of the **particles** of which they consist, the **bonds and forces** between them, and the **movement** and **organization** of those particles."*

Based on this core reasoning scheme, it is a small step to formulate six basic questions which can be asked about the world from a perspective for structure-property reasoning (den Otter et al., 2021, 2022; Janssen et al., 2020; Landa et al., 2020). The six questions, based on the words in bold from the core reasoning scheme, are shown in Figure 2.2. The macro corner of Johnstone's triangle will be illustrated by a pair of questions concerning the substance and its properties (blue solid lines in Figure 2.2). These inquiries pertain to the property component of structure-property reasoning. The micro corner of Johnstone's triangle will be depicted by four questions regarding the particles, interactions, organizations, and motions (orange dotted lines in Figure 2.2). These questions address the structural aspect of structure-property reasoning. The symbolic corner is integrated into all questions, as this level is utilized to convey information about both macro/property and micro/structure. The questions of the perspective enable the user to move consciously between the macro and the micro level thereby increasing the awareness of the multilevel thought.

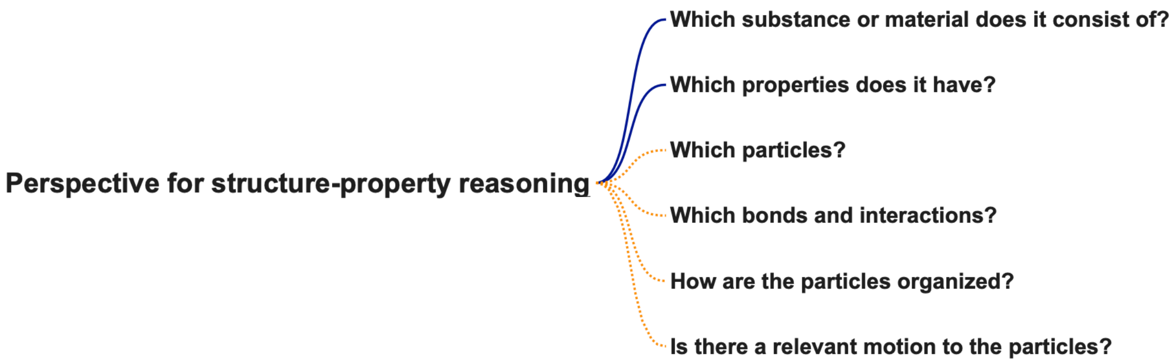


Figure 2.2: *The six main questions of the perspective for structure-property reasoning: dark blue lines for the macro-level questions, dotted orange lines for the micro-level questions.*

Additionally, we elaborated on and differentiated the six basic questions using branches containing more specific and detailed questions, eventually creating a chemical knowledge hierarchy for structure-property reasoning (Figure 2.3).

Our model targets K-12 students learning structure-property reasoning. Therefore, the perspective focuses on reasoning about matter: its properties and explaining these properties using the micro-level models. However, the perspective can be extended more deeply toward chemical and physical processes (De Jong et al., 2013; Dori & Hameiri, 2003), the meso level (Ben-Zvi et al., 1990; Meijer, 2011; Meijer et al., 2013), and the quantum level (Dangur et al., 2014).

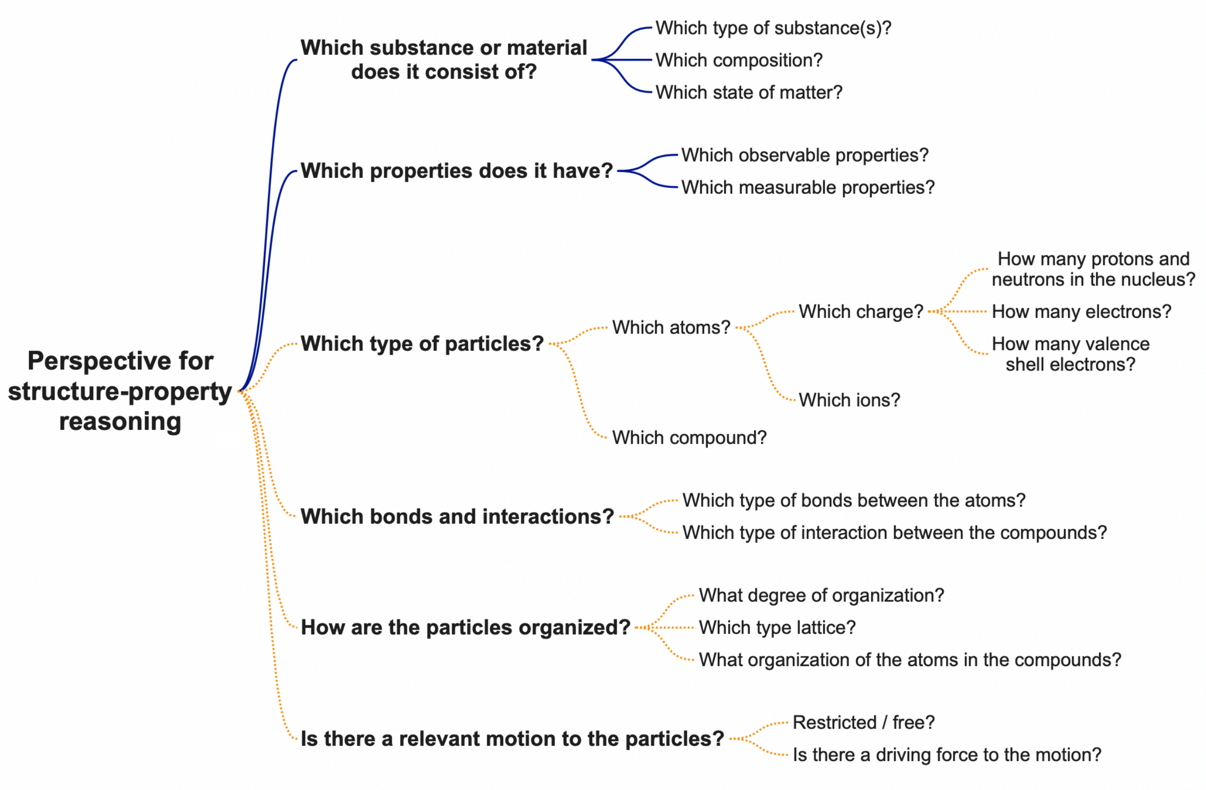


Figure 2.3: *The perspective for structure-property reasoning elaborated with several levels of questions: dark blue lines for the macro-level questions, dotted orange lines for the micro-level questions.*

2.4 The Structure-Property Perspective in Action

In the following section, the four chemistry topics used as cases are elaborated on using the main questions from the perspective for structure-property reasoning. These topics were selected as cases because each represents a different structure-property relation. These topics were selected from the chemistry textbooks used in classrooms in the Netherlands and are therefore part of the chemistry curriculum. The topics are addressed in this order in the Dutch chemistry classroom, starting in Y3 (age 14-15) with the separation methods till Y6 where the emergent properties of a material are addressed. The successive cases were used to illustrate an increased level of complexity for what is expected for the students regarding their development in chemical concepts needed for structure-property reasoning. We use these cases below to show how the perspective has three advantages over other models for structure-property reasoning. First, the perspective for structure-property reasoning enables more integration of the chemical concepts with the skill of reasoning. Second, the perspective enables more coherence between the chemical concepts (horizontal coherence). Third, the low coherence and inadequate build-up of concepts and complexity over the years of school is improved (vertical coherence).

2.4.1 Case 1: Separation Methods

The first case we present is the design of a separation method for a mixture of sand, salt, and water-soluble red dye. In the Netherlands, this topic is usually taught at the start of year 3 of secondary education (age 14-15). The pre-knowledge of these students encompasses a general particle model applicable to describing mixtures or pure substances and the solid, liquid, and gaseous states. The learning objectives of this topic are threefold: 1) the student can apply separation methods, e.g., filtration and distillation, 2) the student understands the differences in properties that a separation method relies on, and 3) the student is able to connect the type of substance with its properties. The understanding in the second objective could be tested by having students design separation methods for simple mixtures of two compounds and for more complex mixtures, for example, mixtures with three compounds. The execution of the designed method measures the first learning goal.

When using the perspective in this case, the macroscopic questions are used first to describe and analyze the problem. In this case, a mixture of sand, salt, and a water-soluble red dye ("Which materials or substances does it consist of?") must be separated into its components. To achieve this goal, properties which can be used to differentiate between the components must be found so that the right separation method can be chosen ("Which properties does it have?").

The choice of a separation method is based on differences in the properties of the various components of the mixture. Therefore, the questions "Which materials or substances does it consist of?" and "Which properties does it have?" are the most relevant to this case as the answers will give enough information to separate the mixture. Posing questions for every substance about different properties such as solubility, grain size at the macro level, adhesion, and boiling point gives a direction for the choice and the sequence of separation methods. This is elaborated on in Figure 2.4, which shows which chemical concepts are associated with the questions of the perspective for this case. The perspective shows the relation between type of substance and its properties is (horizontal coherence) when discussion the choice for the right separation methods.

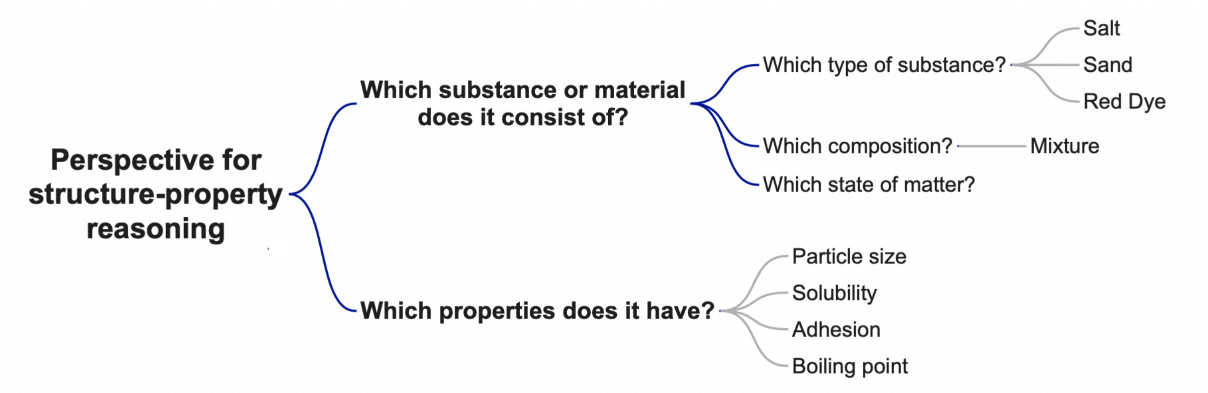


Figure 2.4: *Elaborated perspective for structure-property reasoning for the case of separation methods.*

2.4.2 Case 2: Silica Gel

The second case focuses on the chemistry behind silica gel. Silica gel is commonly used for moisture absorption in packaging to keep products or equipment dry (e.g., footwear in shoe boxes and medicines in capsules). The main question for students is, "What can be the reason for its strong ability to absorb water?" Learning objectives associated with this case are to identify the various types of bonding in molecular compounds and the organization of molecular compounds and, in addition, to discuss these bonds and lattices to explain macroscopic properties. Dutch students are generally introduced to covalent bonds and molecular bonds in year 3 of secondary education (age 14-15). The concepts are elaborated upon in year 4 (age 15-16) using concepts such as hydrogen bonds and bond polarity. They are required to apply their understanding of the concepts to various problems where properties such as capacity to absorb water and boiling point need to be explained using micro-level models.

To explore and describe the problem, students may start with the two main questions of the perspective, describing the macroscopic situation. In this case, a purely solid substance, silica gel ("Which materials or substances does it consist of?"), is used to absorb water from the air. Therefore, the capacity to absorb water is the intended property ("Which properties does it have?"). To explain the water absorbency of silica gel at the micro level, the three main questions, "Which particles?", "Which bonds and interactions?", and "How are the particles organized?" are relevant.

In Figure 2.5, the chemistry perspective is elaborated on using the associated chemical concepts for this case. The three sub-questions of the micro-level explanation branch out to explain the property water absorbency. The question, "Which atoms?" gives us silicon, oxygen, and hydrogen. Next, the question on the organization of the atoms and molecules provides two sub-questions of importance to this problem: namely, "Which type of lattice?" (a polymer network) and "What is the organization of the atoms in the compounds?" (the functional group which plays a role is the alcohol group (OH group)). Subsequently, the question "Which bonds and interactions?" branches out into two sub-questions: "Which type of bonds between the atoms?" (covalent bond between the atoms silicon and oxygen, and oxygen and hydrogen in the polymer) and "Which type of interactions between the compounds?" (hydrogen bonds and Van der Waals bonds between the water molecules and the polymer molecules).

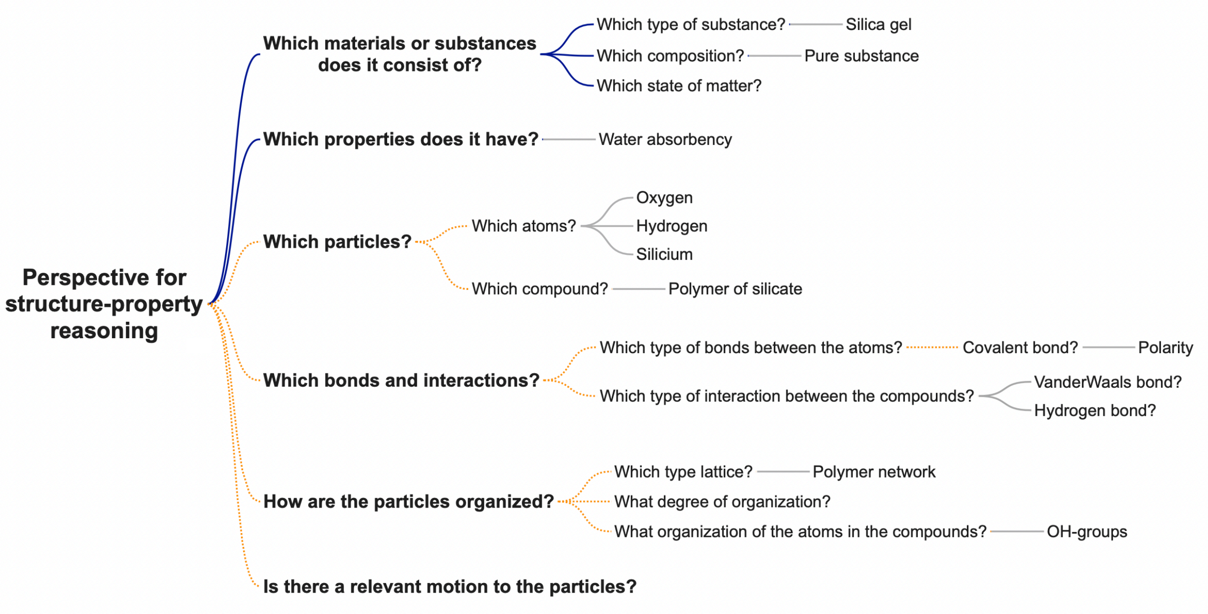


Figure 2.5: *Elaborated perspective for structure-property reasoning for the case of silica gel.*

The questions of the perspective give rise to an answer to the central question of this case: "What can be the reason for the strong ability of silica gel to absorb water?". To answer this question, students need questions and concepts from both the macro level and the micro level. The questions, "Which materials or substances does it consist of?" and "Which properties does it have?" direct students to the macro level and, therefore, the observable. The questions, "Which particles?", "Which bonds and interactions?" and "How are the particles organized?" direct students to the micro level. Therefore, students are enabled to practice structure-property reasoning. After working on the case, students will have acquired new concepts, which can be added to their knowledge and used to solve more difficult problems. Furthermore, the horizontal coherence between the concepts about properties (water absorbance) and the concepts about structure (covalent and hydrogen bonds) becomes clear.

2.4.3 Case 3: Cis-trans Isomerism and Its Influence on Boiling Point

The third case deals with the difference in boiling point between two geometric isomers. Although cis-1,2-difluorethylene and trans-1,2-difluorethylene have the same molecular weight and almost the same spatial arrangement, the boiling points of these isomers are slightly different. Dutch students in year 5 (age 16-17) are typically taught about isomerism and how to use isomerism to explain properties of substances. Prior knowledge of the structural formulas of compounds, Lewis structures, and organic chemistry is needed to learn about this topic. In this case, the learning objective is to apply the knowledge acquired about cis-trans isomerism and its effect on intermolecular interactions to explain properties like differences in boiling point.

To explain the difference in boiling point between cis-1,2-difluorethylene and trans-1,2-difluorethylene, we use the first two questions of the perspective for structure-property reasoning to describe the macroscopic situation: 1,2-Difluorethylene (“Which substance or material does it consist of?”) consists of two isomers which differ slightly in boiling point (“Which properties does it have?”).

To explain this difference, the perspective for structure-property reasoning should be elaborated on for the questions about the micro level (dotted orange lines in Figure 2.6). Therefore, 1,2-difluorethylene consists of three types of atoms: namely, carbon, hydrogen and fluorine (“Which particles?”). Due to their differences in electronegativity, carbon is slightly positively charged and fluorine is slightly negatively charged. This influences the covalent bonds between carbon and fluorine. This bond is polar due to the dipole moment caused by the difference in electronegativity.

The perspective for structure-property reasoning is elaborated to a greater degree in Figure 2.6 than in Figure 2.5. The knowledge acquired when working on the previous case about silica gel serves as starting point for this case. New knowledge, in this case concepts like stereo isomerism is added and the horizontal coherence between the concepts about organization and the concepts about bonds and interactions becomes clear. Furthermore, the same questions about bonds and organizations are used in both cases, showing vertical coherence (the coherence of the concepts over the different grades). In addition, these questions about bonds and organizations are branched out and reformulated more specifically for the case of cis-trans-isomerism, and irrelevant questions are not answered or are even left out. This may scaffold the students in developing their structure-property reasoning by helping them to ask appropriate questions.

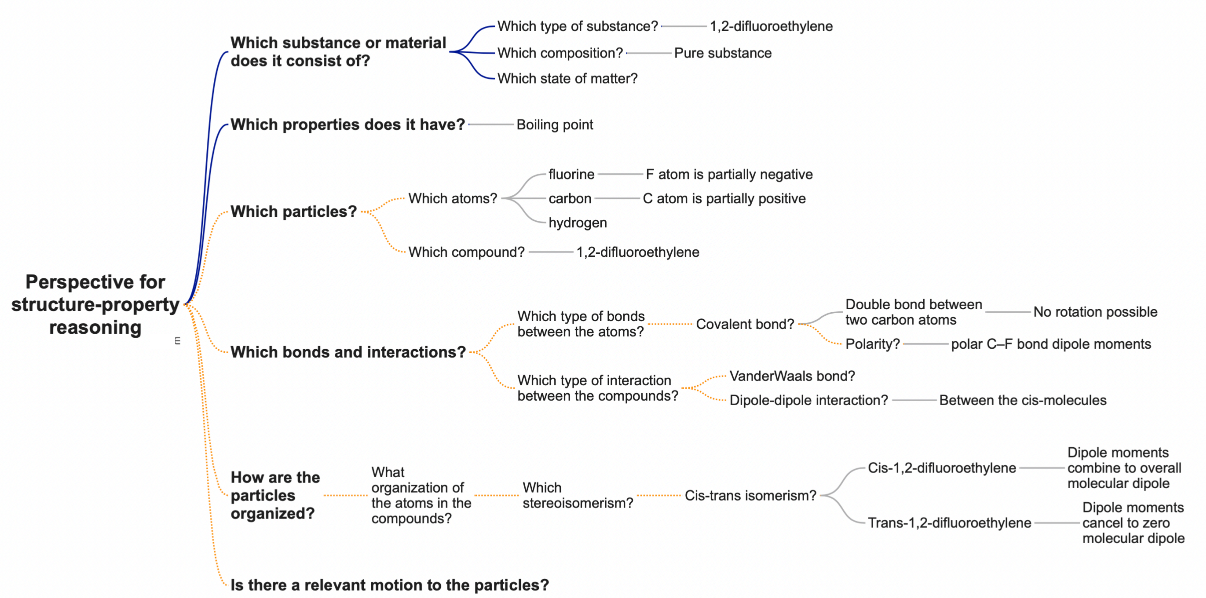


***Figure 2.6**: Elaborated perspective for structure-property reasoning for the case of cis-trans isomerism.*

2.4.4 Case 4: Spider Silk

The fourth case involves the most complexity. Spider silk is a protein fiber made by spiders. This material is extremely tough due to its strength and ductility; the question is how this toughness can be explained by the interactions and organization of spider silk's macromolecules. In years 5 and 6 (age 16-18), Dutch secondary school students are typically taught about macromolecules in synthetic and organic materials such as plastics, cotton, and proteins. The prior knowledge needed for this topic relates to various types of bonds, interactions, and organizations of particles, and the composition, organization, and interactions of macromolecules. The learning objective in this case is to use the knowledge acquired about the micro level of macromolecules and the roles of the bonds, interactions, and organizations of these macromolecules to explain properties of the materials.

The main question in this case is how to explain the extreme toughness of spider silk. First, we describe the macroscopic level of the case. Spider silk ("Which substance or material does it consist of?") consists of proteins. The extreme toughness of spider silk arises from the combination of two properties: namely, strength and ductility ("Which properties does it have?").

Figure 2.7 shows the elaborated perspective for this problem. To explain the properties strength and ductility, the micro level comes into focus. This second main question branches out into three sub-questions. First, the sub-question "Which particles?" shows that a protein is a copolymer of various amino acids. Next, "How are the atoms and molecules organized?" can be explored. The primary organization ("Which degree of organization exists within the polymer chain?") of the protein fiber is an amino acid sequence. Secondary structures, namely, alpha helices and beta sheets, are created owing to this sequence. To explain the formation of these secondary structures, the question "Which interactions occur between the atoms?" is needed. These alpha helices and beta sheets are formed through the creation of hydrogen bonds between the hydrogen, oxygen, and nitrogen atoms of amino acids in the same chain ("Which interactions occur within the alpha helix and the beta sheet?"). Because of the interactions between the beta sheets ("Which interactions occur between beta sheets?"), a tertiary crystalline structure is formed ("Which degree of organization exists between the beta sheets?"), switching back to the sub-question, "Which degree of organization exists?". The organization of the alpha helices is more amorphous ("Which degree of organization exists between the alpha helices?"). The more crystalline domain in the macromolecules explains the strength of the fiber; the more amorphous domains explain the ductility.

As shown in the four cases presented above, the perspective for structure-property reasoning helps students by constructing the chemical knowledge needed for structure-property reasoning in the curriculum. As the student progresses, the main questions branch out into various sub-questions and the knowledge (i.e., questions and answers) expands. This and the number of details of the sub-questions and the used chemical concepts reflect an increased level of complexity. This can be seen in the elaborated chemistry perspectives in the case of silica gel (Figure 5) and the case of spider silk (Figure 7). The knowledge and the questions learned in the case of silica gel serve (discussed in Y5, age 16-17) as a starting point for the case of spider silk (discussed in Y6, age 17-18), which illustrates the vertical coherence. The previously acquired chemical concepts of hydrogen bond and Van der Waals bond are essential for explaining the properties of spider silk.

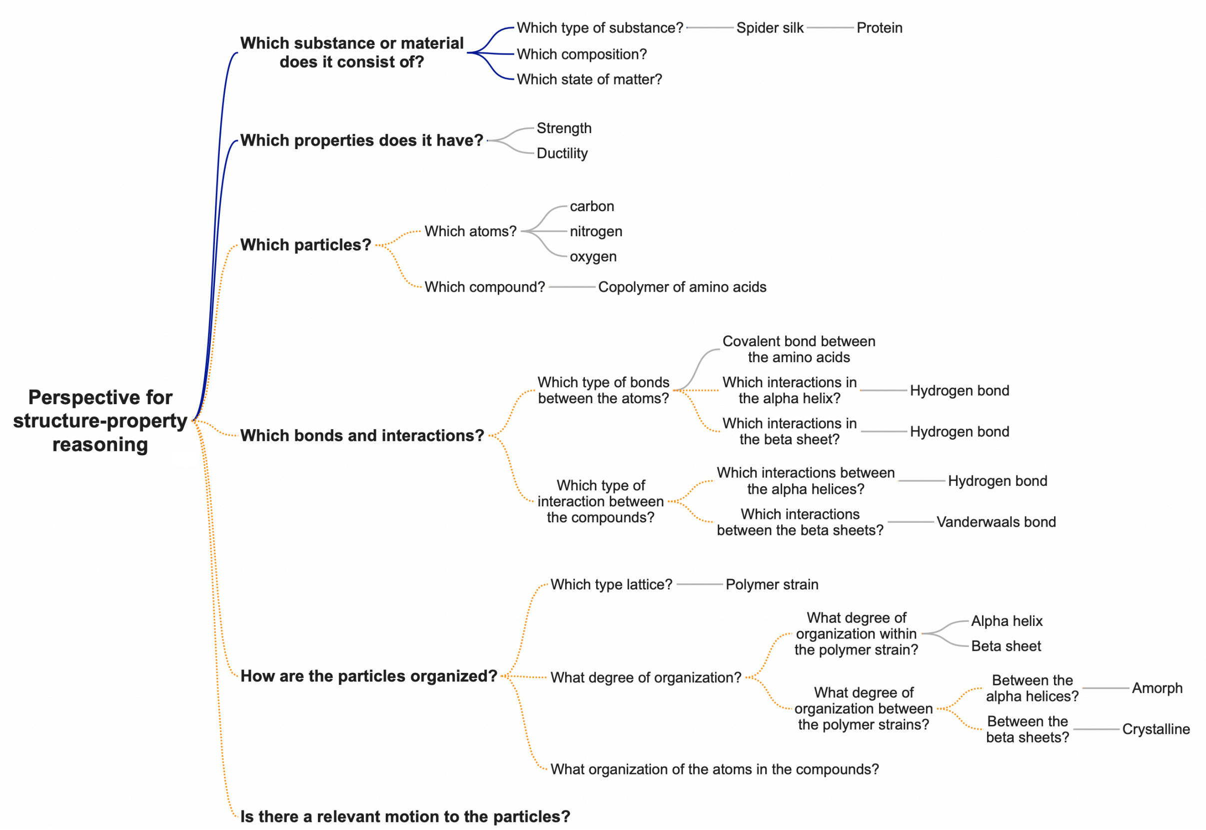


Figure 2.7: *Elaborated perspective for structure-property reasoning for the case of spider silk.*

2.5 Conclusions and Discussion

Learning to think like a chemist is an essential part of chemistry students' education. The Johnstone's triangle (Johnstone, 1982, 1991) is an important step towards explicating micro-macro thinking and, thereby, structure-property reasoning. Many researchers have adapted and elaborated on this model. Nevertheless, we propose that this model has an important shortcoming for structure-property reasoning; a lack of integration between structure-property reasoning and the necessary chemical concepts.

To overcome this shortcoming, we propose the perspective for structure-property reasoning. This perspective integrates structure-property reasoning with the chemical concepts by using questions (Figure 2.2 – 2.7). This gives three advantages compared with other models used for structure-property reasoning: 1) more coherence between chemical concepts and the skill of structure-property reasoning; 2) more coherence between concepts (horizontal coherence); 3) more coherence and a build-up of concepts and complexity over the years of learning how to engage in structure-property reasoning. The perspective presented in this chapter and illustrated in the four cases described above provides these advantages as follows.

First, we believe that the perspective for structure-property reasoning integrates knowledge in the form of chemical concepts and reasoning skills. By using the questions of the perspective and answering these questions in the form of chemical concepts, the coherence between concepts and skill can be increased. In this way, students are given more opportunities to practice thinking like a chemist. Furthermore, they can become acquainted with chemistry as a perspective, a disciplined way of questioning and thinking about certain aspects of the world.

Second, horizontal coherence (coherence between chemical concepts) is strengthened using the perspective for structure-property reasoning. Students can use the perspective as a scaffold and knowledge organizer, because its main questions and sub-questions are connected to the relevant chemical concepts. From this organization, it became clear what the coherence between the chemical concepts is. Therefore, the perspective can contribute to the development of students' chemical reasoning. Further research may tell us how the perspective contributes to the learning of chemical reasoning.

Third, as shown in the four cases, a perspective allows the design of a learning progression in structure-property reasoning, strengthening vertical coherence. Novice learners can start with the six main questions and discover answers which can be generalized to chemical concepts. As students make progress in the acquisition of structure-property reasoning, the main questions branch out into several sub-questions. Consequently, more chemical concepts are discovered. These chemical concepts are in turn necessary for more complex structure-property reasoning about more complex structure-property relations.

Such a learning progression differs from existing learning progressions for structure-property reasoning: for example, the one proposed by Talanquer (2017). He distinguished six dominant stances in the progression of students' thinking about intrinsic properties of materials throughout their schooling. Depending on the conditions, different stances of Talanquer's learning progression may be adopted by the same learner. Talanquer's progression of students' thinking defines an analytical framework to examine and evaluate students' structure-property reasoning, but does not provide instructional strategies.

The selected cases are part of the current Dutch chemistry curriculum. For these cases, the elaboration with the perspective for structure-property has not yet been implemented broadly in the chemistry classroom. However, in a previous study, the perspective for structure-property reasoning was used as design principle for the redesign of demonstrations to strengthen students' structure-property reasoning (den Otter et al., 2021). The perspective can be used in teacher-centered instruction, inquiry-based learning, project-based education, and student-centered learning. It can serve as a scaffold for students to formulate questions and as guidance in developing self-efficacy. Further research is needed on the use of the perspective for structure-property reasoning in the broadest sense for both teachers and students. In addition, further research could be directed at the implementation and practice of the perspective, from the viewpoint of both teachers and students. We think that teachers probably need some time to get used to working with the perspective, i.e., learning to think in terms of connections and using questions. Therefore, further research is needed to help teachers discover the full potential of working with the perspective.

The perspective for structure-property reasoning presented in this chapter is one of twenty perspectives developed to cover the curriculum from primary education to secondary education, and further. Four or five main questions have been formulated for every perspective. These perspectives, with their main questions, can be used to consider problems and topics from several angles. The uses of the perspective for structure-property reasoning, together with the other 19 perspective, for broadening and deepening the learning of students should be explored in further research.

Chapter 3:

How to Assess Students' Structure-Property Reasoning?

Abstract

This chapter describes the design of an instrument to assess secondary school students' proficiency in structure-property reasoning. Criteria for the instrument required that it should be based on a comprehensive model for structure-property reasoning, assess both reproductive and productive use of structure-property reasoning, be cost-effective, and be easy for teachers to adapt to their situation. An unframed and framed sorting task and an unframed and framed mapping task were included in the instrument. It was used to determine the proficiency in structure-property reasoning of two populations: 60 Dutch secondary school students on the pre-university track and 108 Dutch first-year university chemistry students. Results were analyzed using established statistical techniques and they confirmed that the SPR instrument clearly discriminates between pre-university and first-year chemistry students. The chapter concludes by outlining the possibilities offered by the instrument and suggestions for further research.

This chapter was based on:

den Otter, M.-J., Juurlink, L. B. F., & Janssen, F. J. J. M. (2022). How to Assess Students' Structure–Property Reasoning? *Journal of Chemical Education*. 99(10), 3396–3405.

3.1 Introduction

Learning to think like a chemist is considered an important goal of chemistry education (Sevian & Talanquer, 2014). A major part of chemical reasoning concerns structure-property reasoning (Meijer, 2011; Talanquer, 2018). Therefore, this type of reasoning is included in standards for chemistry education in many countries (Achieve, 2010; National Research Council, 2013).

Experts in chemistry use abstract models to explain and predict the properties of substances (Gilbert & Treagust, 2009; Harrison & Treagust, 2003). These models are based on invisible particles, e.g., atoms and molecules, and the interactions between such particles. These two levels of representation – the models of the particles and the properties of substances - have been referred to as the micro and macro levels (Johnstone, 1991). Experts seamlessly switch between macroscopic properties of substances and their particulate structure. Whereas some properties, e.g., melting point or conductivity, are easily connected to the microscopic models of molecules or ions, other properties require a different scale (Meijer, 2011). For example, the ability of super absorbers to incorporate large quantities of water into their structure is explained using conglomerates of polymeric particles. It is this type of reasoning that is generally referred to as structure-property reasoning (Meijer, 2011; Talanquer, 2018).

Proficiency in structure-property reasoning is necessary for a good understanding of many chemical topics. For example, when working with problems concerning acids and bases or organic chemistry, students repetitively switch between the structure level and the property level. Lack of knowledge of the structure level or inability to apply the structure level leads to incorrect answers. The difficulties that students experience with structure-property reasoning have been widely discussed in literature. Reasons for these difficulties range from the macroscopic propensity that students have due to previous experiences (Gabel, 1999; Johnstone, 1991; Talanquer, 2018) to the lack of connection between the structure models and their own prior knowledge (Gabel, 1999). Furthermore, students find it very difficult to work with models - they struggle to learn how to recognize their limitations or how to apply them properly (de Jong & Taber, 2015).

Teachers require insight into students' proficiency in this specific skill to teach structure-property reasoning effectively (Sevian & Talanquer, 2014). Such insight enables teachers to adapt their teaching to enhance this way of reasoning. We aimed to design an instrument that teachers could use to assess the proficiency in structure-property reasoning of students in secondary education. The criteria for such an instrument are the following. First, the instrument must be based on a comprehensive model for structure-property reasoning. By 'comprehensive' we meant that all facets of structure-property reasoning are made explicit and that the concepts associated with these facets cover a generic chemistry curriculum for secondary education. Previously, only specific aspects of structure-property reasoning have been emphasized (de Jong & Taber, 2015; Talanquer & Pollard, 2010). In this chapter, the focus was on the facets and the concepts needed for teaching years 11, 12 and 13 of the Dutch curriculum (*Syllabus Centraal Examen, Scheikunde Vwo*, 2016). Second, as structure-property reasoning can be mastered on two levels: reproductive and productive use, the instrument must assess structure-property reasoning at these two levels (Tienken et al., 2009). Third, the instrument had to be cost-effective, which means that the costs in terms of time, energy, materials e.g., should be as low as possible. Teachers have little time at their disposal(Janssen et al., 2013), therefore, preparation and administering the instrument must be done within a limited time. The instrument also must be applicable to large groups – such as the whole class. Finally, teachers must be able to use the instrument repeatedly and adapt the tool to the grade, level, and content they teach to assess student development over multiple years.

After the design and development, the instrument was administered to two target groups – secondary school students on the pre-university track and first-year university chemistry students – to determine whether it discriminates between these groups. Based on the results, we describe how the assessment instrument fulfilled the criteria and what improvements are necessary.

3.2 Criteria for Structure-Property Reasoning Assessment Instrument

To fulfill the first criterion of the assessment instrument, i.e., that it is based on a comprehensive model for structure-property reasoning, the perspective for structure-property reasoning was used (Figure 1) (Janssen et al., 2020; Landa et al., 2020). The following sections explain what a perspective is, how a perspective could facilitate structure-property reasoning, and how the perspective for structural-property reasoning was developed and validated.

Complex domain specific reasoning requires hierarchical problem solving (Nokes et al., 2010; Ohlsson, 2011; Wimsatt, 2007). In hierarchical problem solving a concrete complex problem is first recognized as a problem of certain kind. This problem type can be often divided in multiple abstract subproblems, each connected to multiple solution types. An abstract solution can be constructed by selection and recombination and this abstract solution can be applied to the original concrete problem by refinement.

To demonstrate how structure-property reasoning works as hierarchical problem solving and how the perspective for structure-property reasoning can be used in this process, an example about the strength and elasticity of a spider's thread will be given. The questions of the perspective for structure-property reasoning (Figure 3.1) can be used to question and explain the structure-property relation between the elasticity and strength of a spider thread. When reasoning a chemist may start with questions concerning the type of substance or material and the relevant properties. The chemist subsequently continues with questions concerning the type of particles, and their interactions (bonds and forces), organization, and movement. The answers combine and enable a chemist to formulate a possible answer. For example, the spider's thread consists of a co-polymer (Which particles?). In this polymer beta-sheets arise which are bounded tightly with hydrogen bonds (Which bonds and forces exist between the particles?) and so on. The questions of the perspective help in structuring different aspects to the problem. The concepts represent the different answer options, and one develops a model by connecting several concepts.

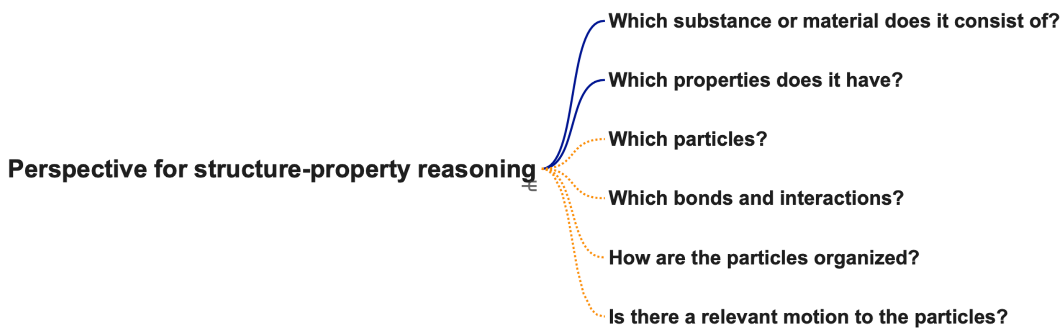


***Figure 3.1**: Illustration of the perspective for structure-property reasoning used as a comprehensive model for structure-property reasoning. The first two questions (dark blue lines) address the macro aspect and the last four questions (dotted orange lines) address the micro aspect.*

In the example above, a domain-specific perspective, i.e., the perspective for structure-property reasoning (Figure 3.1), facilitated hierarchical problem solving. At its core, a perspective is an abstract schema that captures the core reasoning pattern in a domain and structures domain knowledge accordingly (Giere, 2010; Janssen et al., 2020; Thagard, 2012; Wimsatt, 2007). In an earlier study, Landa et al. (2020) identified the perspective for structure-property reasoning as an important perspective that constitute an important part of the Dutch secondary school chemistry curriculum and formulate the following core reasoning schema for this perspective:

*"The **properties** of **substances** can be explained by the nature of the **particles** of which it consists, the **bonds and forces** between them, and the **movement** and **organization** of those particles."*

The bolded words in this core reasoning are variables that can take different values. For instance, the word 'particles' could refer to an atom, an ion of a molecule. A core reasoning schema serves as a template that concisely states how the multitude of concepts in a knowledge field meaningfully interact. To facilitate hierarchical problem solving required for domain specific reasoning the abstract schema underlying a scientific perspective is reformulated in hierarchically connected set of question and related concepts. Earlier studies suggest that perspectives could be used to scaffold and structure students' domain specific reasoning (Janssen et al., 2020; Landa et al., 2020).

The perspective for structure-property reasoning, as one of the four theoretical chemical perspectives was identified and validated in an earlier study in three steps (Landa et al., 2020). First, a group of six chemistry experts were invited to reason about phenomena that we derived from the Dutch secondary-school (pre-university) chemistry curriculum syllabus to identify which distinct theoretical perspectives experts in fact applied in these concrete examples. Four chemical perspectives, namely perspective for structure-property reasoning (particle perspective), kinetic perspective, thermodynamic perspective, and valence-shell perspective, were identified by the authors and validated by the experts. The following experts were involved in this study: a full professor who specializes in chemical drug design, two higher education teachers and researchers (with PhD in chemistry) and two secondary-school chemistry teachers (with a PhD in chemistry). Next, the theoretical perspectives were refined by elaborating them as core reasonings and accompanying hierarchical question agendas. These were, again, validated by the experts and by mapping to the perspectives what various influential documents have identified as the big ideas in chemistry (Atkins, 2010; Claesgens et al., 2009; College Board, 2022; Gillespie, 1997) to verify whether the chemical perspectives "covered" all the big ideas. Finally, the relevance of the four chemical perspectives for secondary-school chemistry education was validated by observing five secondary-school chemistry teachers. It was established to which extent the four perspectives in their reasoning about why-questions were applied (Landa et al., 2020).

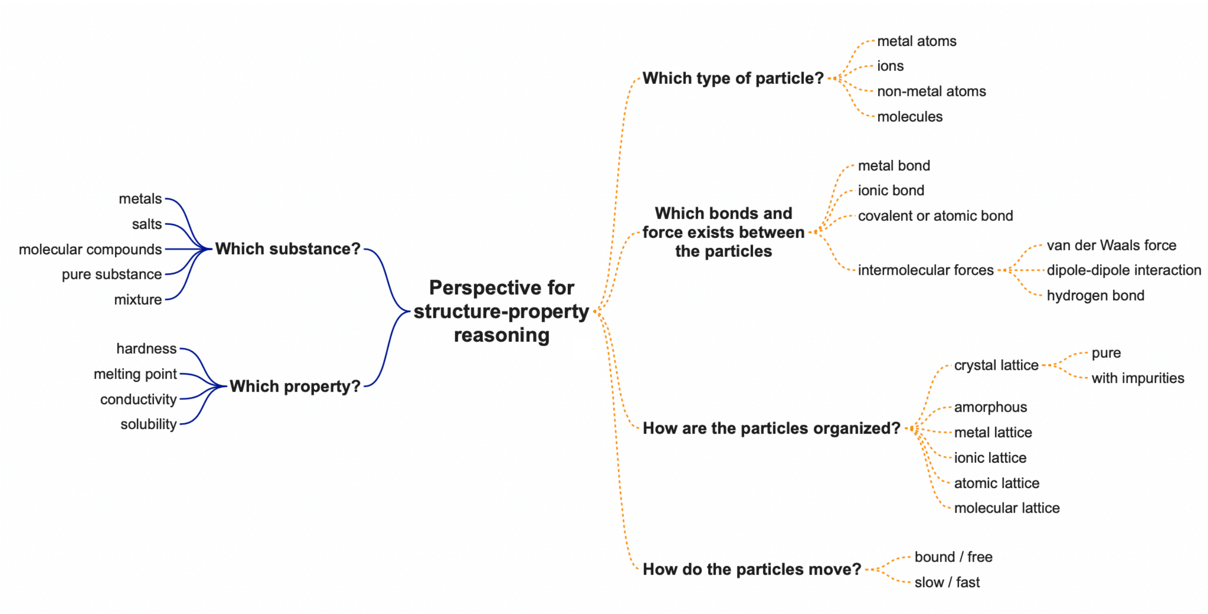


***Figure 3.2**: Model for structure-property reasoning with the corresponding answers to the questions in the branches. Blue lines refer to the macro level, orange dotted lines refer to the micro level.*

The second design criterion required that the instrument assess structure-property reasoning at two levels, namely reproductive and productive use. Reproductive use means that students can reproduce and understand the questions and chemical concepts including their mutual relations in the perspective for structure-property reasoning (Figure 3.1 and 3.2). Productive use means that students can use the questions and chemical concepts of the perspective for structure-property reasoning in problem situations in which they must use structure-property reasoning for analyzing, explaining, predicting, creating and/or evaluating (Tienken et al., 2009).

The third criterion for the instrument related to cost-effectiveness. Teachers have limited time and resources for preparing, teaching, and evaluating. Furthermore, they must work with relatively large groups of students at the same time. Many innovations resulting from educational research require significant preparation and execution time or are difficult to implement in large groups. Lack of cost-effectiveness often results in instruments not being used by teachers (Janssen et al., 2013). This implies that an instrument should require as little time as possible for preparation and implementation. Furthermore, the instrument should be suitable for large groups.

The final criterion concerned the adaptability of the instrument. A ready-to-use instrument may save time. However, the scope of such an instrument may not match the teacher's requirements, for example because of variations in curriculum or the employed textbook. In many cases, a ready-to-use instrument does not suit the teacher's class or needs exactly. The new instrument needed, therefore, to be very easily adapted by teachers to the year group and level they are teaching and/or to the curriculum or topics. The difficulty level and the choice of words needed to be adaptable as well as the subject the class is currently working on. Finally, it had to be possible to use the instrument repeatedly.

3.3 How to Assess Structure-Property Reasoning?

We devised a new instrument to assess structure-property reasoning with components of two existing instruments, namely concept mapping techniques and sorting tasks. These techniques could be cost-effective and easy to adapt by users. Furthermore, they could be based on the perspective for structure-property reasoning. For these reasons, these two techniques were combined to fulfil the design criteria.

To estimate if a student understands and can reproduce answers to questions related to structure-property reasoning, a mapping task based on the concept mapping technique was designed. Concept mapping tasks can be used to measure the structure of a student's declarative knowledge (knowledge organization) in a certain domain (Novak & Gowin, 1984; Ruiz-Primo & Shavelson, 1996). The more common way of concept mapping was adapted to a mapping task in which the chemical concepts needed for structure-property reasoning had to be connected to the questions of the perspective (Figure 3.1) to produce a variation on Figure 3.2.

Based on the technique for producing a concept map (Lambiotte et al., 1989; Novak & Gowin, 1984), two versions of the mapping task were designed, namely a more difficult unframed and an easier framed version. In the unframed mapping task, students were not offered the concepts in advance, but they had to complete the questions from Figure 3.1 themselves with the appropriate chemical concepts. In this way, an indication about students' ability in reproducing and remembering the chemical concepts concerning structure-property reasoning could be obtained. In the framed mapping task, the students were offered the concepts they needed to place under the appropriate question of Figure 3.1 to estimate the understanding of the chemical concepts needed for structure-property reasoning.

Sorting tasks are designed to estimate the levels of cognitive processes applying, analyzing, and evaluating. Students are presented with a set of cards that each contain a problem, a statement, or a relation. Students sort the given cards into categories based on underlying commonality. Experts tend to sort the problems based on underlying conceptual features or 'deep' features. Novices tend to sort the problems based on superficial features related to the presentation of the problem or the 'surface' features (Chi et al., 1981). Card-sorting tasks have been used in physics (Taconis, 1995), biology (Bissonnette et al., 2017; Smith et al., 2013) and chemistry (Irby et al., 2016; Kozma & Russell, 1997; Krieter et al., 2016).

For the card-sorting task, deep and surface features were formulated and incorporated in sixteen chemistry problems, all concerning structure-property reasoning. The deep features concerned the structure aspects of structure-property reasoning, i.e., the micro level. The surface features concerned the properties, i.e., the macro level. We would expect experts to sort the problems based on the micro level and novices to sort the problems based on the macro level (Chi et al., 1981). The design of the card deck was based on the approach of Irby et al. (2016) and Krieter et al (2016).

The sorting task was offered to participants framed (i.e., closed) in which they sorted a number of problem cards into pre-defined categories, and unframed (i.e. open) in which they sorted the problem cards into groups based on their own idea of the underlying chemical concepts.

The problems on the cards are all types of constructed response items, based on problems normally used in Dutch exams and books. However, the students were not expected to fully solve the problems. Both sorting tasks are used to indicate if the students can detect and describe underlying chemical concepts of the structure level to make decisions and evaluations. To achieve these tasks, the student had to be able to examine and break down information into parts to explore relationships and find generalizations.

3.4 Method

3.4.1. Participants and Context

To investigate whether the designed instrument was suitable for detecting differences in students' proficiency in structure-property reasoning, we selected two populations to apply the Structure-Property-Reasoning (SPR) instrument. The target group of the SPR instrument was secondary school students on the pre-university track. This target group was compared with a group of first-year university chemistry students, as they were expected to perform significantly better on the SPR instrument.

The target group comprised 60 students attending a state secondary school in a Dutch city. These students were following the pre-university track, which takes 6 years to complete. There were two groups: 24 students from year 4 and 36 students from year 5. They were taught chemistry by the first author or her teacher colleague.

The pre-university students' results were compared with those of 110 first-year chemistry students at Leiden University who were taking the General and Inorganic Chemistry course given by the second author. These students were almost at the end of this intensive course where the structure models learned in secondary education were repeated and elaborated. In total 108 of the 110 (98%) students completed the assignments of the entire instrument.

Table 3.1 shows a general overview of the two groups of participants: the pre-university students and the first-year chemistry students. At the time of completing the instrument, the pre-university students had studied nearly all the chemical concepts needed for this instrument.

Table 3.1: *General overview of the two groups: pre-university students (secondary school) and first-year chemistry students.*

	N	**male – female**	**Mean age in years (SD)**	**Mean final grade* for pre-university chemistry (SD final grade)**
Pre-university students	60	33 – 27	16.6 (0.78)	-
- Group Y4 (age 15-16)	24	12 – 12	16.0 (0.76)	-
- Group Y5 (age 16-17)	36	21 – 15	16.9 (0.52)	-
First-year chemistry students	108	75 – 33	18.4 (1.09)	7.67 (0.75)

*Note. * Students in the Netherlands take an exam at the end of their secondary school. This is combined with a part of the results they gained during the last two years of their education to produce their final grade. The range of this grade is from 1 (very bad) to 10 (no mistakes). The average final grade for chemistry of all pre-university students in the Netherlands was 6.5 in 2016 and 6.6 in 2017* (Cito, 2018).

3.4.2. The Instrument

Card-sorting task

A deck of 16 cards with chemistry problems was designed as a basis for the card-sorting task. Four categories of physical properties (conductivity, melting point, toughness, and solubility) that are typically used in the Dutch curriculum in relation to structure-property reasoning were selected as surface features. The four structure aspects were ionic (bonding and lattice), metallic (bonding and lattice), molecular bonding and molecular lattice, the deep features. Each problem card (the numbers in Table 3.2) contained a structure aspect (i.e., deep feature) and a property aspect (i.e., surface feature). The type of problems was to build an explanation of a structure-property relation. The choice was made because this type of problems is used by Dutch teachers in their lessons and exams to check students' structure-property reasoning.

Table 3.2: *Ideal sorts for the card-sorting task. The columns are the structure aspects each card contains, the rows represent the property aspects of each card. The numbers in the cells refer to the specific sample problem card. The design is based on the model of Krieter et al. (2016).*

		Structure aspects (deep features)			
		Molecular/atomic Bonding	Molecular/atomic Lattice	Ionic Bonding/Lattice	Metallic Bonding/Lattice
Property aspects (surface features)	Melting point	8	5	14	3
	Conductivity	11	7	2	12
	Toughness	16	13	4	10
	Solubility	1	6	9	15

The problems in the card deck were chosen and adapted from chemistry textbooks used in year 4 to 6 and from the Dutch national exams of the pre-university track of secondary education. The most common properties that pre-university students had to explain with the structure models were the four chosen property aspects (rows in Table 2). The four chosen structure aspects (columns in Table 2) were based on the structure models that students had to use to explain these properties. For example, card 13, shown in Figure 3, was designed with toughness as property aspect and molecular/atomic & lattice as structure aspect. When explaining the properties at the structure or micro level, the ionic lattice is inseparable from ionic bonding. Therefore, it was combined as one structure aspect when choosing the problems. The same applies for metal lattice and metal bonding.

> A pencil is made of carbon. Diamond is also made of carbon. You can sharpen a pencil with a simple iron sharpener but you have to polish a diamond with another diamond. Diamond is the hardest material in the world. Explain this.
>
> 13

Figure 3.3: *Sample problem card "13".*

Three experts, the second author and two chemistry teachers, were consulted about the chosen problems. The second author is an associate professor in the field of catalysis and surface chemistry. In addition, he has extensive experience in the field of secondary and higher education and educational research. Both the two chemistry teachers have a master's degree in chemistry and several years of experience with chemistry education in the pre-university track of the secondary education in the Netherlands. They sorted the problems independently and afterwards they gave feedback to the selected problems and the sorting task. After this consultation, the formulation of the situation on three cards of the original card set was adapted. The formulation of these original problems was suggested to be unclear.

Mapping task

In the unframed mapping task, the participants were asked to complete the starting version of the perspective for structure-property reasoning (Figure 3.1) with all the chemical concepts that they could come up with and which seemed suitable as answers to the questions formulated in the model. In the framed mapping task, the participants were given 30 chemical concepts that needed to be placed at the appropriate question related to structure-property reasoning. The ideal outcome of this task is shown in Figure 3.2. This ideal outcome was based on the chemistry curriculum of the pre-university track and on two experts – an experienced chemistry teacher with a master's degree in chemistry and the second author. The experts had no a priori knowledge of the task. From their unframed mapping task and the chemistry curriculum of the pre-university track the ideal outcome or the reference map was constructed. Next, this reference map was presented to these experts for feedback.

The participants were asked to complete the questions of the perspective unframed. The framed task, in which the questions of the model had to be completed using only the chemical concepts described as learning goals for pre-university students, was only performed by the pre-university students. To reduce the time needed for the experiment, the decision was made not to give this task to the first-year chemistry students. They were expected not to make any mistakes in this framed mapping task.

Procedure

The activities of the SPR instrument were carried out in a classroom setting. Each participant noted his or her results on entry sheets. Adult participants were provided with an informed consent document approved by the Ethics Review Committee (IREC) of the University. For the underage participants the parents received an informed consent letter approved by the IREC.

In Table 3.3 a short description and instruction is given for each task. The order in which the tasks were offered to the participants (unframed sorting task, framed sorting task, unframed mapping task and framed mapping task) was chosen deliberately. Reversing the order of the tasks would have meant that the participants would be directed in a certain direction.

The average time it took to take the test – including reading the instructions – was 50 minutes. The pre-university students were tested in groups of 17-24 participants. The first-year chemistry students took the test in one group, all 108 students at once. The worksheets were designed to make it easy to collect the results and to assess large groups all at once.

The SPR instrument and the corresponding worksheets to facilitate the administering of the SPR instrument are provided Appendix 1.

Table 3.3: *description of the procedure of the SPR instrument*

Order	Task	Performed by	Description	Instruction
1	Unframed Sorting task	Pre-university students and 1st year chemistry students	16 problems, all containing a structure aspect and a property aspect, must be sorted in groups. Each group should be given a name.	You received 16 cards with problems. Sort these cards in groups based on underlying common chemical concept. Give each group an appropriate name. Form at least 2 groups and maximal 15 groups.
2	Framed sorting task	Pre-university students and 1st year chemistry students	16 problems, same as unframed, must be sorted in four groups, namely molecular/bonding, molecular/lattice, ionic, metallic	Shuffle your 16 cards and sort them in the four groups as stated on your worksheet: molecular/bonding, molecular/lattice, ionic, metallic. Every group should contain at least one card.
3	Unframed mapping task	Pre-university students and 1st year chemistry students	Participants receive questions of perspective for structure-property reasoning (see figure 1). The questions should be complete by answers in form of chemical concepts. Creating hierarchy is allowed.	In front of you, you see the questions of the perspective for structure-property reasoning. A perspective is a way of questioning your topic or problem. Complete the questions with the appropriate chemical concepts. You are allowed to form a hierarchy.
4	Framed mapping task	Pre-university students	Participants receive questions of perspective for structure-property reasoning (see figure 1) and 30 chemical concepts. The concepts should be placed at the appropriate question. Creating hierarchy is allowed.	Again, you are given the questions of the perspective for structure-property reasoning. Complete the questions with the given 30 chemical concepts. You are allowed to form a hierarchy.

3.4.3. Data Analysis

To determine the extent to which a student sorts on structure aspects, and therefore is more proficient in structure-property reasoning, the percentage of pairs (%P) made by a student was determined (Krieter et al., 2016). For each sort we compared the number of pairs that were common with one of the ideal sorts (i.e., the ideal sort on structure aspects and the ideal sort on property aspects (see Table 3.2)). The formed pairs and the total number of pairs were determined for each participant. When a single card was placed in a group this was counted as a pair with a null card and considered as unexpected pairing. The pairs that the participant had in common with the ideal structure sort and the ideal property sort were counted to determine the number of pairs formed on structure aspect and on property aspect. The number of unexpected pairs consisted of the single cards and the pairs that were not in common with the ideal structure or property sort. The total number of pairs varied considerably between the participants. For this reason, the number of structure pairs, property pairs and unexpected pairs were divided by the total number of pairs in a sort. The closer the similarity of a participant's sort to an ideal sort, the higher the %P value. A high %P for the structure aspect pairs (%P-structure) indicates that the participant sorted the cards more on structure aspects i.e., deep features, meaning that the participant was thinking more like an expert.

In the unframed mapping task, the participants were asked to complete the questions related to structure-property reasoning (Figure 3.1) with the appropriate chemical concepts. The total number of answers or chemical concepts were counted as well as the total number of answers in accordance with the reference map (Figure 3.2). The number of extra chemical concepts given was also determined. The extra answers given by the participants were judged on correctness. In addition, the number of students who made one or more hierarchies in their answers were counted. The correctness of the hierarchy was also judged. For example, a student made a hierarchy in the question "Which particles?". The first answer "nucleus particles" was divided further into "protons" and "neutrons".

A second researcher independently counted and judged the total number of answers, the number of corresponding answers and the number of extra answers in the unframed maps of 38 participants (23%). The level of consistency among the researchers was then determined by comparing the determined numbers with those of the researcher. This resulted in 691 agreements out of a total of 808 answers. The percentage agreement is therefore 86%. The differences between the two researchers were discussed until agreement was reached. An example of discussion was whether an extra answer was correct, like soluble in water and through the air given with the question about the movement of the particles. It was agreed that these answers were not counted as a correct extra answer, because it refers to the macro level.

The framed mapping task was analyzed on the number of correctly placed chemical concepts compared to the reference map in Figure 3.2.

To determine whether the results of the pre-university students and the first-year chemistry students were different, t-tests assuming unequal variances were performed. In addition, effect sizes (Cohen's d) were calculated by dividing the absolute difference between the means by the SD_{within}.

The names given to the groups in the unframed sort were analyzed by systematic coding. First the names were coded by type of category name with the codes "referring to structure", "referring to property" and "other". The category names were then analyzed at a deeper level, i.e., the given group names were subdivided into the categories of ideal sort as shown in Table 3.4. Interrater reliability was estimated by double coding a pseudorandom sample of 48 participants: 32 first-year students and 16 pre-university students. 29% of the category names were double coded. Two raters assigned identical codes to 89% of the category names. The Cohen's kappa was 0.83.

Table 3.4: *Main codes used for analyzing the group names on a deeper level.*

Aspects of ideal sort	**Examples of group names**
Property – Melting point	Melting point, boiling point, or both
Property – Solubility	Solubility, hydrophobic, hydrophilic
Property – Conductivity	Conductivity
Property – Hardness	Hardness, Firmness
Structure – Molecular bonding	Hydrogen bond, Van der Waals bond
Structure – Molecular lattice	Lattice, atomic lattice
Structure – Ionic	Ions, ionic bond
Structure – Metallic	Metal lattice

3.5 Results

The analysis was focused on the comparison between pre-university students and first-year chemistry students. The results are presented in reverse order, starting with the framed mapping task.

3.5.1 Framed Mapping Task

Sixty pre-university students finished the framed mapping task in which they had to complete the questions from the perspective for structure-property reasoning (Figure 1) with 30 given concepts (ideal outcome shown in Figure 3.2).

Table 3.5 shows the pre-university students barely made any mistakes in this task. Out of 30 chemical concepts that had to be placed, they obtained an average score of 27 correct answers (90%). This suggests that all these students recognized the questions of the perspective for structure-property reasoning. Furthermore, they were able to place the appropriate chemical concepts at the questions, both a precondition for proficient structure-property reasoning.

Table 5: *Results of the framed mapping task (pre-university students only)*

Group	**Average correct answers**	**SD**
Y-12	26.4 (88%)	3.18
Y-11	27.7 (92%)	1.88
Total	26.9 (90%)	2.79

3.5.2. Unframed Mapping Task

Table 3.6 shows the results of the unframed mapping task. The average number of answers given in accordance with the reference map (Figure 2) was approximately the same for the pre-university students (9.3 answers) as the first-year chemistry students (9.7 answers). However, the average number of answers (in total) and the average number of additional answers were significantly different. The first-year chemistry students gave more correct answers (23.5 answers) than the pre-university students (17.7 answers) and, consequently, more additional answers (10.7 answers versus 5.9 answers). Moreover, 50% of the first-year chemistry students created a correct hierarchy in their answers compared to only 15% of the pre-university students. These results indicate that the first-year chemistry students gave more elaborated answers to the questions related to structure-property reasoning (Table 3.6).

Table 3.6: *Results of the unframed mapping task*

	Average number of answers given (SD)	**Average number of answers given in accordance with the reference map (SD)**	**Average number of additional answers given (SD)**	**Correct hierarchy present**
Pre-university students (N=60)	17.7 (4.6)	9.3 (2.9)	5.9 (3.8)	9 students* (15%)
First-year chemistry students (N=107)	23.5 (9.6)	9.7 (3.2)	10.7 (6.2)	53 students (50%)#
Significant?	Yes, p<0.0001	No, p=0.19	Yes, p<0.0001	

*Note. * One pre-university student made a hierarchy who was not judged as correct.*
 # Two first year chemistry students made a hierarchy who was not judged as correct.

The additional answers given by the pre-university students were mainly on the questions: ‘Which type of particle?’, ‘How does the particle move?’ and ‘How are the particles organized?’. When answering the question ‘Which type of particle?’ they often referred to the particles of the atomic model – neutrons, protons, and electrons.

A good proportion of the additional answers given by the first-year chemistry students were the same as those provided by pre-university students. They also showed more repertoire for the questions ‘Which substance?’ using terms such as acids, bases, and alloys. For the question ‘Which type of bond or force?’, they used, for example, London dispersion forces, Coulomb interactions, and ion-dipole interactions. For the question ‘Which organization?’, they used, for example, types of crystal lattices; and, for the question ‘Which movement’ terms such as vibration, rotation, and translation. These additional answers were directly related to the topics and terms discussed in the General and Inorganic Chemistry course.

Recognition of the chemical concepts affiliated with the questions from Figure 3.1 was not very high in the case of both the pre-university students and the first-year chemistry students. With six questions to be answered, the first-year chemistry students gave an average of four answers per question, the pre-university students only three answers per question. However, the results show that first-year chemistry students gave more additional corresponding chemical concepts compared to pre-university students. On average, the first-year chemistry students provided 4.8 additional answers. Furthermore, they incorporated more hierarchy into their answers. As data in Table 3.6 indicate that first-year chemistry students remembered, related, and identified more chemical concepts with the appropriate question, they are better equipped for structure-property reasoning.

3.5.3. Framed Sorting Task

Sixty pre-university students and 106 first-year chemistry students completed the framed sorting task. Two first-year students did not complete the task as intended and their framed sorts were excluded from the results.

The percentage of pairs (%P) for each participant was determined (Table 3.7 and Figure 3.4). The %P-structure was significantly lower for the pre-university students and the %P-property was significantly higher compared to the first-year chemistry students (both $p<0.0001$). The effect sizes (E) of both the %P-property as %P-structure were large (E-structure = 1,6; E-property = 1,2). These scores indicate that the first-year chemistry students were better at identifying and classifying the problems and categorizing and sorting them accordingly. This suggests that proficiency in structure-property reasoning may be higher in the first-year chemistry students.

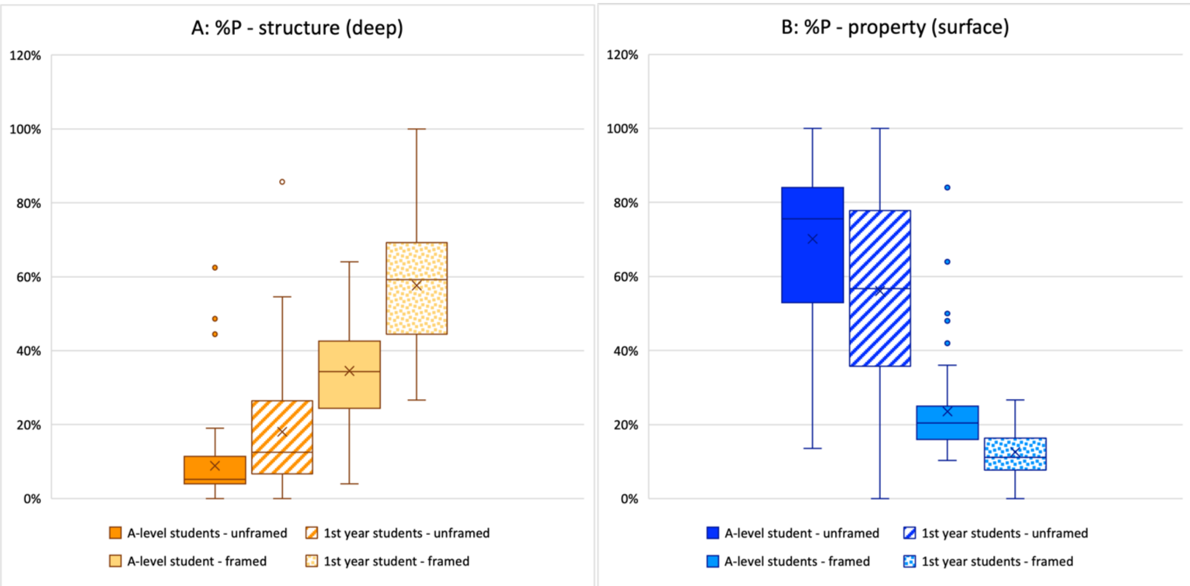


Figure 3.4: *Percentage pairs (%P) - comparison of the pre-university students' and the first-year chemistry students' sorts, both unframed and framed, relative to the ideal sort on structure (A) and property (B) aspects.*

Table 3.7: *Results of the framed card-sorting task.*

Framed sort	N	%P-structure Mean (SD)	%P-property Mean (SD)
Pre-university students	60	35% (13%)	24% (13%)
First-year chemistry students	106	58% (15%)	13% (6%)

3.5.4. Unframed Sorting Task

Sixty pre-university students and 107 first-year students completed the unframed sorting task. One first-year student did not complete the task as intended and was excluded from the results. Table 3.8 gives a summary of the results of this unframed card-sorting task. In the unframed sort, the pre-university students made 288 groups in total (mean 4.8 groups, SD=1.28). The first-year chemistry students made 590 groups in total (mean 5.5 groups, SD=1.65). There was no significant difference in the average between the two groups.

Analysis of the category names of the groups formulated by the participants (Table 3.8) showed that the first-year chemistry students more often used words relating to the structure aspect of the problem than the pre-university students (43% versus 8%). For pre-university students, words that referred to the property aspects of the problem dominated (74% versus 40%). Category names commonly given by the pre-university students were conductivity (10%), hardness (15%), solubility (20%) and melting point (19%). "Density" as a category name also appeared (5%). Pre-university students used "density" in the context of packing of particles, probably due to the Dutch word for density which also means packing or tightness. For categories specifying a structure aspect, pre-university students mainly used a category name referring to molecular bonding (62%) or molecular lattice (17%).

Table 3.8: *Results of the unframed card-sorting task.*

Unframed sort	N	Number of groups	%P-structure	%P-property	Group names: Words referring to		
		Mean (SD)	Mean (SD)	Mean (SD)	Structure	Property	Other
Pre-university students	60	4.8 (1.28)	9% (11%)	70% (20%)	8%	74%	18%
First-year chemistry students	107	5.5 (1.65)	18% (16%)	56% (24%)	40%	39%	21%

The category names given by the first-year chemistry students also referred frequently to the four groups on the property level: conductivity (22%), hardness (7%), solubility (24%) and melting point (14%). The category name “density” was given by 3% of them. For categories specifying a structure aspect, first-year chemistry students used category names referring to molecular bonding (24%) and molecular lattice (24%).

The average %P-structure (Table 3.8 and Figure 3.4) of the first-year chemistry students (18%) was significantly higher ($p<0.0001$) than that of the pre-university students (9%). As anticipated, the average %P-property of the first-year chemistry students (56%) was significantly lower ($p<0.0001$) than the pre-university students (70%). The effect size (E) for both %P-structure and %P-property were considered as medium (E-structure = 0,63; E-property = 0,61). First-year chemistry students sorted the problems more on structure aspects. Pre-university students sorted more on the property aspects of the problems. These findings corroborate previous research indicating that novices sort more on surface features, in this case the property aspects, and experts sort more on deep features, in this case the structure aspects(Chi et al., 1981).

Despite first-year chemistry students using many more category names referring to a structure aspect, the value of %P-structure was not as high as expected. Evidently first-year chemistry students still sorted the problems on property aspects rather than structure aspect. For example, one student made a group with all the problems with the property aspect conductivity and named the group ‘Electrons’. This could indicate that the student had misunderstood the concept. On the other hand, there may have been other levels of sorting possible which would indicate a certain proficiency in structure-property reasoning. To obtain insight into the proficiency of each student, it is important therefore to look at the individual scores.

3.6. Discussion and Conclusions

This chapter focuses on a tool for chemistry teachers to assess students’ ability in structure-property reasoning: the SPR instrument. The tool uniquely combines a sorting task and a concept mapping task, both framed and unframed. Results show that the SPR instrument clearly discriminates between secondary school students on the pre-university track and first-year chemistry students at university. The first-year chemistry students performed better on the instrument than the pre-university students. In the unframed mapping task, the first-year chemistry students gave more elaborated and richer answers to the questions related to structure-property reasoning than the pre-university students. In the framed sorting task, the %P-structure was higher for the first-year chemistry students, meaning that they sorted the problems more in line with the ideal structure sort compared to the pre-university students. In the unframed sorting task, the first-year chemistry students used more category names referring to structure aspects for their formed categories and their %P-structure was higher than the pre-university students. We conclude that the aim to develop an instrument to discriminate in students’ structure-property reasoning abilities was reached.

We also intended to critically review the instrument against the four criteria. With respect to the first criterion, the SPR instrument was indeed based on a rather comprehensive model for structure-property reasoning, namely the perspective for structure-property reasoning (Figure 3.1). This model covers the aspects of structure-property reasoning needed in the chemistry curriculum for secondary education. In designing the SPR instrument, we focused on the concepts needed for the last three years of the Dutch secondary education(*Syllabus Centraal Examen, Scheikunde Vwo*, 2016). This perspective for structure-property reasoning was used as the base for the design of a sorting task and a mapping task. Although the SPR instrument seems to work to discriminate between the educational levels included in this study, it is uncertain whether it could be extended for use in lower school years and for more experienced chemists, such as undergraduates and postgraduates. This could be done by adapting the situations in the sorting task and extending the questions and corresponding concepts in the perspective for structure-property reasoning and thus in the mapping task.

The used perspective in this study is one of four chemical perspectives identified by Landa et al (2020). The valence-shell-perspective can be well integrated in the perspective for structure-property reasoning. Further research should reveal to what extend the thermodynamic perspective and the kinetic perspective could be integrated in the perspective for structure-property reasoning.

Second, the SPR instrument was designed - as intended - to assess structure-property reasoning at two levels of use. It consists of a framed and unframed mapping task to assess the level of reproductive use of structure-property reasoning, and a framed and unframed sorting task to assess the level of productive use of structure-property reasoning as analyzing, evaluating, creating, and predicting. Structure-property reasoning was described as hierarchical problem solving and the perspective for structure-property reasoning could be used as scaffold for this. The card sorting task can be used to check whether students recognize a concrete problem as a certain type of abstract problem and its associated concepts. The mapping task can be used to check whether students have an adequate abstract structure of problems and subproblems and associated concepts.

One limitation of the study concerns the type of problems that were used in the sorting task. The problems were of the type to build an explanation for a structure-property relation. To address other aspects of structure-property reasoning, like making predictions and constructing models, other types of problems could be used. For example, a problem could be of the type of synthesizing: “Iron is a good material to make various utensils. How can the toughness of iron be increased?”.

Another limitation of the SPR instrument concerns the level of abstraction at which students construct explanations. The SPR instrument offers a rapid means to gain insights into the diverse range of models that students may consider when explaining chemical phenomena. For example, the results of the (framed) sorting task showed that students consider the atomic lattice to explain the conductivity of graphite. However, the SPR instrument does not actively engage students in the construction of mechanistic explanations using the provided model. Therefore, teachers should regularly ask students to construct specific mechanistic explanations to verify that they can also adequately specify and use the chosen model.

The instrument also complied with the third criterion: cost-effectiveness. Preparation and administration of the instrument was not time consuming. The average time a participant needed to complete the four tasks was 50 minutes. The instrument is suitable for large groups. In this study, the test was used in groups of 20 up to 110 participants. A disadvantage of the SPR instrument is that analyzing the test results is complex and time consuming. By using a computer applet for the test (Chen et al., 2020), the analysis time for teachers could be reduced significantly.

Finally, the SPR instrument is adaptable to a teacher’s own teaching goals. It can be adapted to the year group – for example to cater for the specific learning goals of year 6 – and the proficiency level of the students by, for example, adding more or fewer concepts to the framed mapping task. The set of problems used for the sorting task can also be easily adapted to school year, proficiency level or learning goals of participants, e.g., by taking problems from the textbook used in the chemistry class. In the framed sorting task, the categories could be chosen otherwise, for example the questions of the perspective for structure-property reasoning could be used.

Furthermore, the tool could be used repeatedly to estimate the development of students' structure-property reasoning. The bias which could occur because the student gets acquainted with the used problems and chemical concepts when performing the tasks on regular base can be intervened by adapting the chemical problems in more difficult ones. Furthermore, the number of chemical concepts or problems used could be expanded. When a student progresses in the curriculum and extends its structure-property reasoning, a growth in the number of chemical concepts could be expected. Disadvantage of this adapting and/or expanding of the items in the SPR instrument could be a decrease in cost-effectiveness. Nevertheless, we think that repeatedly offering the (slightly adapted) SPR instrument to students could give the teacher and the students insight into their progression in structure-property reasoning. To increase the cost-effectiveness, the framed mapping task could be dropped when using the SPR instrument repeatedly.

Many curricula are topic centered. Using the perspective for structure-property reasoning ensures that concepts typically offered fragmented are integrated into a perspective that facilitates structure-property reasoning. Using this perspective, teachers can build the curriculum to be more structure-property reasoning focused by making small adjustments. In another study, this was done for the introduction of the structure models for metals, salts, and molecular compounds by using POE-demonstrations and the perspective for structure-property reasoning as scaffold (den Otter et al., 2021).

Chapter 4:

Two Design Principles for the Design of Demonstrations to Enhance Structure–Property Reasoning

Abstract

Structure–property reasoning (SPR) is one of the most important aims of chemistry education but is seldom explicitly taught, and students find structure–property reasoning difficult. This study assessed two design principles for the development of structure–property reasoning in the context of demonstrations: (1) use of a POE task (predict–observe–explain) and (2) use of the domain-specific perspective for structure-property reasoning, both to increase student engagement and to scaffold micro-level modeling. The aim of the demonstration series was to teach structure–property reasoning more explicitly to pre-university students (aged 15–16). Demonstrations pertained to the properties of metals, salts, and molecular compounds. The SPR instrument was used as a pretest and posttest to gain insight into the effects on structure–property reasoning. In addition, one student (Sally) was followed closely to see how her structure–property reasoning evolved throughout the demonstrations. Results show that after the demonstrations students were more aware of the structure models at the micro-level. The students also knew and understood more chemical concepts needed for structure–property reasoning. Sally's qualitative data additionally showed how she made interesting progress in modeling micro-level chemical structures. As we used conventional demonstrations as a starting point for design, this could well serve as a practical tool for teachers to redesign their existing demonstrations.

This chapter was based on:

den Otter, M.-J., Dam, M., Juurlink, L.B.F., & Janssen, F.J.J.M (2021). Two Design Principles for the Design of Demonstrations to Enhance Structure–Property Reasoning. *Education Sciences*, *11*(9), 504-523.

4.1 Introduction

In chemistry, structure–property reasoning is considered to be one of the most important overarching constructs (Talanquer, 2018). It is a type of chemical reasoning in which chemists explain the macroscopic properties of a compound in terms of the structure level of this type of compound, namely the particles, their organization, and interactions. The properties refer to observable properties of compounds such as melting point, hardness, and solubility. Structure–property reasoning is important for explaining and predicting properties of compounds. It is also critical for designing new compounds with desired properties. Therefore, this type of reasoning takes a prominent place in various curricula over the world including in the Netherlands (National Research Council, 2012; Ottevanger et al., 2014).

Chemistry students generally have problems developing such reasoning resulting from rather particular difficulties. The first difficulty is the requirement to switch between different levels of thought within chemistry (Johnstone, 1982, 1991). When observable phenomena need to be explained and interpreted at the micro-level, students must connect the two levels using models of particles and their interactions. However, as students are mostly novices in structure–property reasoning, they tend to stick with the macro-level observations and simply use former experiences to explain the properties instead of using the micro-level models (Gabel, 1999). Reasons for this are being unfamiliar with the micro-level models and experiencing difficulties with their interpretation, e.g., precisely how micro-level particles interact to account for the observed properties at the macro-level.

The second difficulty in developing structure–property reasoning is that micro-level particles cannot be seen with the naked eye or even with the best optical microscope. Consequently, structure–property reasoning becomes rather abstract, and students draw on more general problem-solving skills to solve chemical problems instead of on a deep understanding of structure–property relationships (de Jong & Taber, 2015; Gabel, 1999).

The challenges associated with structure-property reasoning can largely be attributed to the instructional approaches and organization of chemistry curricula. As most national curricula are organized around chemical topics (chemical bonding, etc.) instead of explicit conceptual relationships or cross-cutting forms of chemical thinking, teachers are not facilitated to explicitly teach structure–property reasoning. As a result, students develop heuristics such as “surface similarity” (compounds with similar appearances are compounds of the same group and thus they have the same properties) to answer questions in this realm. However, students' comprehension of these structure-property relations remains inadequate. (Cooper et al., 2013; Kozma & Russell, 1997; Talanquer, 2014).

Literature suggests that the teaching of structure–property reasoning should be explicit and centered on the “core idea” of structure–property relationships (Stowe et al., 2019; Talanquer, 2018). Students should learn to connect the real with the modeled world and to use structure models to explain real chemical phenomena (Talanquer, 2018).

The use of demonstrations to show chemical phenomena has been suggested as a teaching practice to explicitly teach structure–property reasoning (Kelly & Jones, 2008; Ramsey et al., 2000; Treagust & Tsui, 2014). In conventional demonstrations, learning starts at a macro-level familiar to most students. Teachers demonstrate real chemical phenomena, and students are expected to observe what happens at the macro-level before the teachers provide a micro-level explanation for the chemical phenomenon at hand (observe–explain demonstration) (Tsaparlis, 2009).

What is lacking in most of the typical observe–explain demonstrations is that: (1) teachers do not let their students activate prior knowledge to build on what they already know and (2) most teachers do not ask students to model micro-level explanations themselves (Tsaparlis, 2009). These two imperfections of a conventional demonstration led to a twofold need: an approach in which students can actively build on what they already know and a means to stimulate and guide micro-level modeling by students in connection with a demonstration. The former may be done by predicting outcomes prior to performing a demonstration. For the latter, an explicit scaffold for students' micro-level modeling may be introduced (de Jong & Taber, 2015).

In the study presented in this chapter, we designed and tested a demonstration-based lesson series aimed at improving structure–property reasoning. For the design of the lesson series, we explicitly used conventional demonstrations as a basis and applied two design principles: (1) the introduction of a POE task (predict–observe–explain) to demonstrations (Hilario, 2015; Liew & Treagust, 1998; Treagust & Tsui, 2014; White & Gunstone, 1992) to stimulate students' engagement and their modeling process and (2) scaffolding of the POE task with a domain-specific perspective for structure-property reasoning (Janssen et al., 2020; Landa et al., 2020) in order to explicitly guide the modeling at the micro-level for students in the "explain" phase of the POE task. This perspective for structure-property reasoning consisted of a question agenda with questions on which type of compound, which properties, and which type of particles. Next, the demonstration-based lesson series was tested for the level of students' structure–property reasoning as reproduction, understanding, application and evaluation. We studied student engagement as they developed models for the structure level for three dominant types of chemical compounds: metals, salts, and molecular compounds. The learning objective for the students in the upper pre-university tier of secondary education was to acquire these structure models. We performed the lesson series and investigated how students reproduced, understood, applied, and evaluated structure–property reasoning.

4.2 Theoretical Framework

To improve students' structure–property reasoning, it should be taught explicitly and be in line with students' macroscopic orientation (Gabel, 1999). This can be achieved by using real chemical phenomena in which properties of substances are investigated (Talanquer, 2018). Students can be effectively engaged with such real-life chemical phenomena by using demonstration experiments (Hodson, 2014). Due to the way many teachers incorporate the demonstration into their teaching practice, learning efficiency for the students is low. Although the students are engaged by questions about what they have just observed, they are given few opportunities to discover for themselves how to explain the chemistry phenomena using the structure-level models, let alone to discover and create these models themselves. As a result, the demonstration is little more than a beautiful show and learning efficiency remains low (Roth et al., 1997).

The question arises: to what extent are teachers able to offer students opportunities to think for themselves during a demonstration? How can students be actively and explicitly engaged in structure–property reasoning? Teaching practices that use conventional demonstrations are often characterized by teachers presenting theory before the demonstration, thereby reducing students' explicit engagement with structure–property reasoning. Consequently, students passively observe the demonstration and opportunities for active learning are missed.

To overcome these problems described in the paragraph above, an active role for the student is necessary (Crouch et al., 2004). Our first design principle, the addition of a POE task (predict–observe–explain) (Hilario, 2015; Liew & Treagust, 1998; Treagust & Tsui, 2014; White & Gunstone, 1992) to conventional demonstrations was intended to achieve this. In a POE task, students are challenged to learn actively by predicting the outcome of a demonstration and justifying their predictions. Next, they describe what they observe during the demonstration, and, afterward, they explain their observations and reconcile any discrepancy between their predictions and observations. This technique has been frequently investigated over the years (Coştu et al., 2011; Crouch et al., 2004; Hilario, 2015; Kala et al., 2013; Karamustafaoğlu & Mamlok-Naaman, 2015; Kearney et al., 2001; Kibirige et al., 2014; Liew & Treagust, 1998; Mattox et al., 2006; Smith et al., 2010; Yaman & Ayas, 2015; Zakiyah et al., 2019, 2020). Therefore, it is a known approach in science education research, but the implementation is lacking. Besides fostering engagement, the POE task can be used to reduce misconceptions (Zakiyah et al., 2019, 2020) and it can help students to improve their learning outcomes (Kibirige et al., 2014). The POE task is also suitable for enabling students to model the structure level of a compound to explain a certain property (Tien et al., 2007). Finally, it encourages students to engage in explicit structure–property reasoning by connecting their macroscopic observations to their models of the structure level (Mattox et al., 2006). We believe that these characteristics of the POE task, such as students' active engagement and the opportunities for students to model themselves, give the POE task potential to reinforce demonstrations and improve students' structure–property reasoning.

Adding a POE task changes the order of teaching activities for demonstrations (Figure 4.1). A conventional demonstration has three steps: introduction or orientation, show and observe and explain. In all three steps, the teacher takes the lead. Even in the observation step, teachers direct the students' attention to important observations (and distract them from undesired observations).

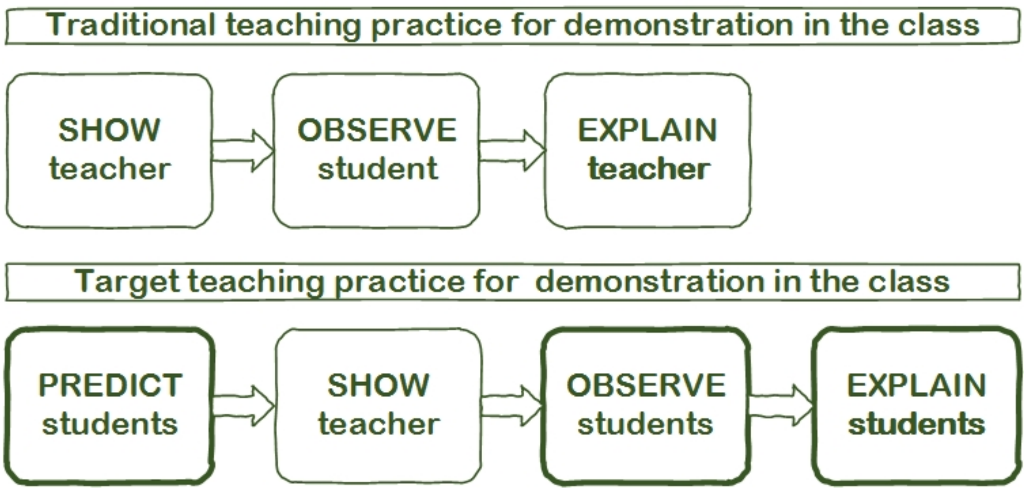


Figure 4.1. *Conventional and target practice for demonstration in the class.*

The target teaching practice of a POE task-based demonstration consists of an extra step "predict". In addition, all the steps (except for "show") have become student-centered to get students more engaged with the demonstration. In this way, students are challenged to reason using micro-level structures to explain the demonstrated properties on the macro-level. For this, they can create and use micro-level structure models.

When students start creating the micro-models in the "explain" step of the POE task, they need to know the conditions for a micro–macro explanation. The students need insight into the underlying structure of the explanation and the corresponding questions that can be asked to systematically address the problem. A scaffold can be of assistance (van de Pol et al., 2010). Hence, we introduced our second design principle: scaffolding of the POE task with a domain-specific perspective for structure-property reasoning (Janssen et al., 2020; Landa et al., 2020)

As illustrated in Figure 4.2, this perspective for structure-property reasoning consists of a set of questions (a question agenda) that experts in chemistry would unconsciously ask themselves when dealing with structure–property relations (Janssen et al., 2020; Landa et al., 2020). For example, when dealing with a problem about the potential solubility of poly-4-hydroxystyrene in a basic solution, one needs to know—besides which substance and which property—which type of particles is involved (polymer with hydroxy groups and basic particles) and which type of bonds (ion–dipole bonds) plays a role.

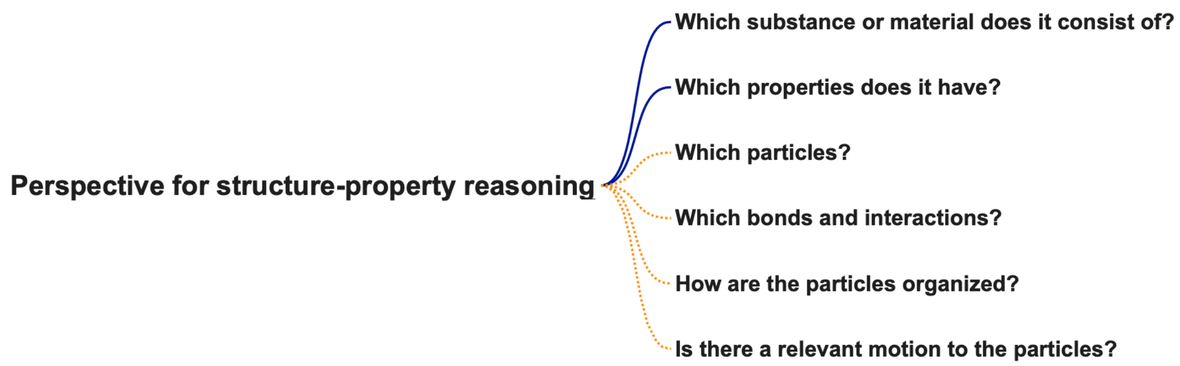


Figure 4.2: *The six main questions of the perspective for structure-property reasoning: dark blue lines for the macro-level questions, dotted orange lines for the micro-level questions.*

Relative novices, as students mostly are, can use the question agenda to interrogate the problem. In this way, the perspective for structure-property reasoning can act as a scaffold for the students to model the structure models of the micro-level, which in turn can be used for explaining the macro-level. Students need to get acquainted with the questions and the answers, i.e., chemical concepts of this perspective for structure-property reasoning, to become proficient in structure–property reasoning. In addition, the questions and answers can be seen as thinking tools for structure–property reasoning. Figure 4.3 shows an elaborated version of the perspective for structure-property reasoning with all the chemical concepts needed for structure–property reasoning explored in this study.

In the "explain" phase of the POE task, students need to explain their observations. The perspective for structure-property reasoning can therefore act as a scaffold to facilitate the students in this phase. By answering the questions of the perspective, the students are scaffolded to the appropriate chemical concepts needed to explain their observations.

The domain-specific perspectives can also act as a stepping stone to expand the required chemical concepts needed for structure–property reasoning. When used repeatedly in multiple settings such as lessons, new chemical concepts can be added to the question agenda, and questions can be divided into several sub-questions. As students' knowledge grows, the perspective for structure-property reasoning grows, and more complex problems can be investigated. Furthermore, the students' knowledge will be organized by the perspective for structure-property reasoning. This gives students an overview, and interdependences become clear (Janssen et al., 2020; Landa et al., 2020).

Figure 4.3. *Perspective for structure-property reasoning elaborated with the chemical concepts a student should master in the fifth year of the pre-university track.*

The two design principles served as the basis for our design study. We aimed to design demonstrations with a POE task and the scaffold of the perspective for structure-property reasoning to engage pre-university students in modeling the structure level of metals, salts, and molecular compounds and to enable them to learn how to perform structure–property reasoning.

4.3 Materials and Methods

4.3.1 Research Design

Using a one-group pretest–posttest design, the effectiveness of a demonstration-based lesson series with a POE task and the perspective for structure-property reasoning as scaffold was investigated. The aim of the demonstration-based lesson series was to stimulate and develop students' structure–property reasoning. To be more specific, the students had to learn the chemical concepts, e.g., hydrogen bridge or ions, that are associated with the micro-models of metals, salts, and molecular compounds. Figure 4.3 shows all the chemical concepts offered in these demonstrations and thus the learning objectives for the students. They also had to construct and apply the micro-models themselves with the associated chemical concepts.

The activities were designed by the first author and piloted in her own teaching practice. This pilot showed that the selected design worked well for the group metals and the group salts. For molecular compounds, however, we noticed that students generally were not able to predict properties. Consequently, we redesigned the lesson on molecular compounds (see "Overview of the Lesson Series" below). The adapted lessons were again provided by the first author.

4.3.2 Setting and Participants

The lesson series was performed in two cohorts in a Dutch secondary school: cohort 18–19 and cohort 19–20. Table 4.1 shows the number, gender, and ages of students in both cohorts.

The students were in the fourth year of the pre-university track. In the third year, they had been introduced to chemistry with an introduction to the topics: substances and their properties, particle models, separation methods, chemical reactions, atoms, molecules, metals, organic compounds, reaction heat, reaction rate, stoichiometry, fuels, and plastics. Our designed demonstration lessons were part of a topic about chemical bonding. Before this course, the students had learned about Bohr's atomic model, mole, stoichiometry, and concentration.

Table 4.1. *Composition of the two cohorts.*

	Year	Students	Male	Female	Age
Cohort 18–19	4	37	21	16	15–16
Cohort 19–20	4	16	9	7	15–16

4.3.3 Overview of the Lesson Series

The two design principles were incorporated into the lesson series which comprised three lessons of 50 min each. Properties of the three types of substances (metals, salts, and molecular compounds) were demonstrated. Students then engaged in activities to discover the structure models underlying some of the common properties of these three types of compounds (Figure 4.4).

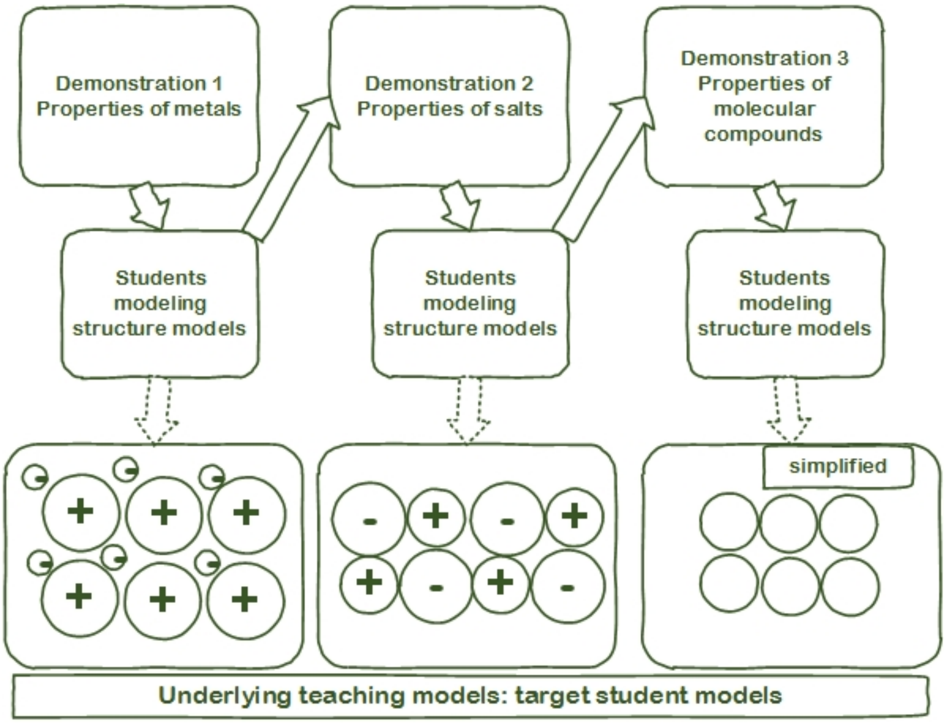


Figure 4.4 *Overview of the lesson series.*

Step 1: Predict (P)

The demonstration lesson series started with metals. Several metals were displayed on the teacher's desk, such as iron, copper, lead, aluminum, and zinc. First, the question agenda of the perspective for structure-property reasoning was handed out to the students, and the teacher asked them to complete this with answers suitable for the metals (to obtain their prior knowledge). Next, the students were asked to predict the properties of this group of substances. These predictions of the properties were collected in a class discussion.

Step 2: Observe (O)

Properties shown in this step were: general aspects such as color, phase at room temperature, malleability, hardness, and electrical conductivity. During the demonstration, there was a class discussion solely about the macroscopic properties of the metals. The order of the shown properties was chosen to facilitate a step-by-step development to build on what students had already studied in their third year (a more general particle model) toward a more sophisticated structure model of metals, the learning objective for this course. The students had to observe the demonstrated properties of each of these metals.

Step 3: Explain (E)

In this step, the students were asked to produce a structure model of the shown substance based on their observations of the properties. They could use the question agenda from the perspective for structure-property reasoning as a scaffold (Figure 4.1), and they discussed their models in small groups. After that, their structure models were discussed in a whole-class discussion to enable the students to test their own structure models. After approximately three iterations of the first student-generated models, their models were compared with the commonly accepted teaching models.

The students were asked to create a structure model for the metals that explained the properties shown in the demonstration. After the group discussions, the teacher discussed the common denominator of the student-generated structure models. Then, the teacher asked the students to show how the property malleability could be explained in the structure model. After group discussions, this was again discussed in the whole class. After that, the teacher asked the students to produce two iterations: (1) to adapt the structure model to explain the hardness of alloys and (2) to adapt the structure model to explain conductivity of electricity. Finally, students supplemented the question agenda of the perspective for structure-property reasoning from the beginning with the discovered concepts and structure models.

More information about the demonstration lesson series can be found in the Appendix, where the demonstration protocols for the metals, salts and molecular compounds are described (Appendix 2).

Based on the pilot, we used a slightly different approach for the molecular compounds. Students found it difficult to predict the various properties of the molecular compounds. Consequently, they found modeling of the underlying structures to be complicated, and thus less complex structure models were needed to enable a constructive modeling process. For this reason, we simplified the structure model of the molecular compounds by concentrating on the general molecular interaction. In later lessons, this simplified model was explored by giving instructions about the various types of molecular interactions. In addition, it appeared the students needed an explicit scaffold for the modeling process. To offer this, we used the question agenda of the perspective for structure-property reasoning to structure the demonstrations.

For these reasons, we adapted the structure of the demonstration lesson as follows: the lesson started with the questions of the perspective for structure-property reasoning, and the class was asked to give suggestions on which property should be demonstrated by the teacher for discovering the answer to those questions (P phase). For example, to discover the type of particles, students could argue that conductivity should be demonstrated to reveal whether the particles were charged. Subsequently, all necessary properties, such as boiling point and conductivity, were demonstrated (O phase) by the teacher, and the questions of the perspective for structure-property reasoning concerning the micro-level were discussed together with the associated chemical concepts (E phase). At the end of the demonstration for the molecular compounds, the students completed the perspective for structure-property reasoning again. An additional advantage of this approach was that it gave students the opportunity to explicitly practice the questions of the perspective for structure-property reasoning.

4.3.4. Data Collection and Data Analysis

We gathered several types of data about the level of proficiency in structure–property reasoning using a combination of quantitative and qualitative instruments. We gathered data using the SPR instrument (structure–property reasoning instrument) (den Otter et al., 2022), which was developed in previous research to estimate various aspects of structure–property reasoning at different levels of mastery. To provide insight into how the demonstration-based lesson series impacted learning, we also gathered data in the form of manifest student products (student structure models, perspectives) and audio recordings of student group discussions.

The SPR instrument was administered as a pretest and posttest for both cohorts. Student results on the pre- and posttests were compared statistically to determine significant growth in structure–property reasoning. The SPR instrument consists of four tasks (see Table 4.2): an unframed and framed sorting task and an unframed and framed mapping task, all four based on the perspective for structure-property reasoning.

Table 4.2. *Description of SPR instrument.*

Order	Task	Description	Instruction
1	Unframed sorting task	16 problems on cards, all containing a structure aspect and a property aspect, must be sorted into groups. Each group should be given a name.	You received 16 cards with problems. Sort these cards in groups based on underlying common chemical concept. Give each group an appropriate name. Form at least 2 groups and maximal 15 groups.
2	Framed sorting task	16 problems on cards, same as unframed, must be sorted into four groups, namely molecular/bonding, molecular/lattice, ionic, metallic.	Shuffle your 16 cards and sort them in the four groups as stated on your worksheet: molecular/bonding, molecular/lattice, ionic, metallic. Every group should contain at least one card.
3	Unframed mapping task	Participants receive questions of perspective for structure-property reasoning (see Figure 2). The questions should be completed by answers in form of chemical concepts. Creating hierarchy is allowed.	In front of you, you see the questions of the perspective for structure-property reasoning. A perspective is a way of questioning your topic or problem. Complete the questions with the appropriate chemical concepts. You are allowed to form a hierarchy.
4	Framed mapping task	Participants receive questions of perspective for structure-property reasoning (see Figure 2) and 30 chemical concepts. The concepts should be placed under the appropriate question. Creating hierarchy is allowed.	Again, you are given the questions of the perspective for structure-property reasoning. Complete the questions with the given 30 chemical concepts. You are allowed to form a hierarchy.

In the sorting tasks, the percent pairs (%P) for the structure level and the property level were determined. The percentages of pairs of cards equal to pairs found in the ideal structure or property sort formed by the participant were determined. The more similar a sort is to an ideal sort—either structure or property—the higher the percent pairs will be.

To provide insight into the type of group names the students used to categorize the formed groups in the unframed sorting task, the group names were coded by type of category name with the codes “referring to structure”, “referring to property” or “other”, as shown in Table 4.3. In the framed sorting task, the framed difference (FD) score was determined. The FD score is defined by the number of cards that are placed in a group other than the ideal sort.

Table 4.3. *Coding scheme.*

Codes	Example of Group Names
Referring to structure	Electrons, hydrogen bonds, atomic bond, lattice
Referring to property	Hardness, density, conductivity, phase, solubility
Other	Polymers…

In the unframed mapping, the number of given chemical concepts was counted and judged on correctness. The given chemical concepts were compared to the reference map (Figure 4.3). In the framed mapping task, the percentage of correctly placed chemical concepts was determined.

We also gathered qualitative data. These consisted of manifest student products (student structure models, perspectives) and audio recordings of student group discussions. To gain insight into how the demonstration-based lesson series impacted student learning, we chose to present a case study in which we described how one student’s learning (Sally, cohort 19–20) was impacted by the lesson series. Sally (a fictive name) was chosen because her learning progression was a clear example of how students developed during the demonstration lessons. This student, Sally, collaborated with three female students in one group. We collected Sally’s structure models about the topic of the group metals (first demonstration) and audiotaped Sally’s group discussions. Resulting drawings and group discussions were analyzed as follows. First, we transcribed Sally’s group discussions around the topic of metals and compared these to the drawings that Sally made to map how the modeling process of the structure level (for metals) progressed. Next, we analyzed in these transcripts how Sally’s group spoke about the properties of malleability, hardness, and electrical conductivity and how these properties were visible in their structure models. The main starting question for analysis was how the group adapted their first structure model of metals and how they progressed to the final structure model of metals.

4.4 Results

In this section, we first present the quantitative SPR instrument outcomes. After that, we present the case study of Sally.

4.4.1. Pre- and Posttest by the SPR Instrument

Framed mapping task

The framed mapping task tested whether the students acquired the offered chemical concepts of the perspective for structure-property reasoning. Table 4.4 shows that the number of correctly placed chemical concepts increased significantly in the posttest. Students barely made any mistakes after the demonstration series. This result shows that students acquired and understood the chemical concepts needed for structure–property reasoning. The students were able to connect the chemical concepts with the corresponding question of the perspective for structure-property reasoning.

Table 4.4: *Results of the framed mapping task.*

	Cohort	**Pre**	**Post**
Number of correct answers	Cohort 18–19	27	33
	Cohort 19–20	31	35
Percentage	Cohort 18–19	74%	93%
	Cohort 19–20	86%	97%

Unframed mapping task

Table 4.5 shows that the perspective maps created by the students were more comprehensive in the posttest compared to the pretest. The students provided more answers, i.e., chemical concepts, and their mapping was more comparable to the reference map. The results show that students were able to reproduce the learned concepts. Furthermore, they understood and applied the learned chemical concepts by connecting them to the corresponding question.

Table 4.5. *Results of the unframed mapping task.*

Number of	**Cohort**	**Pre**	**Post**	**Difference**
Answers	Cohort 18–19	14	20	+6
	Cohort 19–20	16	26	+10
Answers comparable with reference map	Cohort 18–19	6	15	+9
	Cohort 19–20	4	17	+13

Framed sorting task

The demonstration lesson contributed to greater proficiency in structure–property reasoning. Both cohorts showed an increase in the %P-structure score in the posttest. Students' sorts in the predetermined categories (framed mapping task) were more similar to the ideal structure sort. This probably means that after the demonstrations, students were more able to apply their acquired knowledge of the perspective for structure-property reasoning to problems concerning structure–property reasoning. Students were more able to evaluate these problems on the less visible structural aspects such as type of particles or bonding.

In the framed sorting task, the data showed a decrease in the FD score in both cohorts (Table 4.6). This means that after the demonstration-based lesson series students made fewer mistakes in sorting the problems into the appropriate predetermined categories. This applied specifically to the categories of metals and salts where students were found to make considerably fewer mistakes. This implies that the demonstration-based lesson series helped students to acquire structure models and, in their application, to solve problems. Students found the difference between bonds and lattices in the category of molecular compounds more difficult.

Table 4.6. *Overview of the results of the framed sorting task of the SPR instrument.*

		FD Score *	**Percent Pairs**			
				Pre	**Post**	**Difference**
Cohort 18–19	Pre	7.8	Property	21%	18%	−3pp
Cohort 19–20		6.8		20%	19%	−1pp
Cohort 18–19	Post	6.8	Structure	31%	46%	+15pp
Cohort 19–20		6.4		36%	38%	+2pp

*Note. * The FD score is defined by the number of cards that are placed in a group other than the ideal sort.*

These predetermined categories helped the students to sort the problems into a structure level. This can also be seen in the higher %P-structure score for the pretest and the posttest compared to the unframed sorting task (Table 4.6 for the framed sorting task and Table 4.7 for the unframed sorting task).

Table 4.7. *Overview of the results of the unframed sorting task of the SPR instrument.*

		Category Name is Referring to			**Percent Pairs**		
	Cohort	Pre	Post	Difference	Pre	Post	Difference
Property	18–19 *	74%	66%	−8pp	70%	61%	−9pp
	19–20 #	84%	58%	−26pp	82%	71%	−11pp
Structure	18–19 *	3%	12%	+9pp	8%	13%	+5pp
	19–20 #	0%	25%	+25pp	5%	9%	+4pp

*Note. * Cohort 18–19: Total number of categories produced in the pretest: 183; in the posttest: 189;*
 # Cohort 19-20: Total number of categories produced in the pretest: 75; in the posttest: 79.

Unframed sorting task

As shown in Table 4.7, students of both cohorts, mainly sorted on property aspects in both pretest and posttest. This finding confirmed the pre-university students' macroscopic orientation (Gabel, 1999; Johnstone, 1991). Examples of these category names were melting point, density, and solubility. This macroscopic orientation was also depicted in the high %P-property scores in the pretest and the posttest of both cohorts (Table 4.7).

At the same time, Table 4.7 shows a noteworthy increase in the mean %P-structure scores in the posttest. In other words, students' sorts in the posttest were more similar to the ideal structure sort. This result shows an increase in students' proficiency in structure–property reasoning after the demonstration lessons. As the questions of the perspective for structure-property reasoning were derived from the way an expert thinks 19, we could say that the students' evaluation of the problems became more similar to that of an expert.

4.4.2. Case Study Sally

To provide insight into how the demonstration-based lesson series impacted student learning, we present the case study of one student. Sally was a female student enrolled in the 19–20 cohort who was followed during the demonstration lesson on the topic of metals. She worked in a group with three other girls: Ryanna, Cathy, and Fatima (fictive names).

During the demonstration lesson

FIRST STEP: PREDICT

As the lesson started, Sally received an empty perspective for structure-property reasoning and was asked by the teacher to complete the questions for the group of metals. The resulting perspective (see Figure 4.5 for Sally's first perspective for structure-property reasoning, dotted underline) showed that her prior knowledge of the metals—properties and structure models—was quite comprehensive, meaning that her prior knowledge was good. Sally compared her personal perspective for structure-property reasoning with that of others from her group in the subsequent group discussion, in which the four girls discussed the six questions for the metals and tried to formulate appropriate answers.

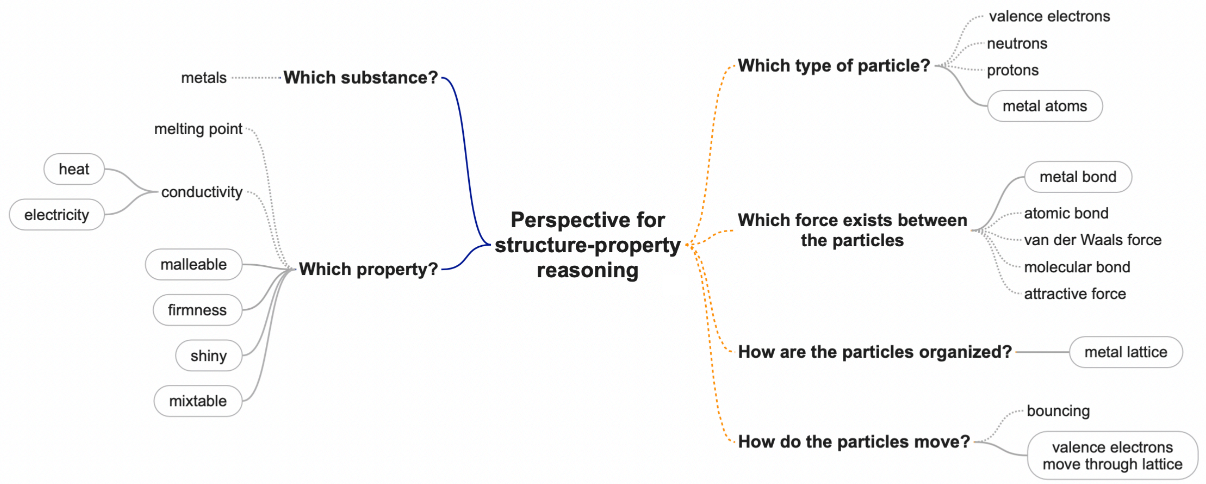


Figure 4.5. *Sally's complete perspective for structure-property reasoning before (gray dotted lines dots) and additions after (gray lines and circled with a gray line) the demonstration lesson on metals.*

The audio recordings of Sally's group discussion revealed that her group started with the question "type of substance" (Figure 4.5). Next, they discussed "type of particles", and they named, among others, valance electrons (Figure 4.5) because of their role in conductivity. They also discussed "type of organization", how the valence electrons move through the lattice and the regularity of this lattice. They constantly switched between these two questions: "type of particles" and "type of organization" (Figure 4.5). Then they switched to the properties of metals and talked about the malleability, conductivity and mixability of metals (Figure 4.5, "which properties?"). Again, they discussed the ability of valence electrons to move through the lattice (Figure 4.5, "type of particles" and "how the particles are organized?"). At this point, they also named metallic particles. Then they listed all the bonds they knew, looking for a bond that fitted for the metals (Figure 4.5, "which force between the particles?").

The teacher then brought the predictions of the properties together in a class discussion. Together, the class named all the important properties of the metals, i.e., gray-colored, shiny after polishing, hard, malleable, solid at room temperature and able to conduct electricity and heat.

SECOND STEP: OBSERVE

In the demonstration, the teacher showed the properties of the metals. These were general aspects such as color, phase at room temperature, malleability, hardness, and conductivity of electricity. There was a class discussion solely about the macroscopic properties of the metals.

THIRD STEP: EXPLAIN

Sally's group started with the general model for particles, as shown in the second column of Table 4.8, and in their discussion, they immediately tried to consider the conductivity of electricity, something they also named in their starting situation. They correctly suggested that valence electrons play a role in conductivity and that a neat lattice is needed for these electrons to move. They used the same size of circles for the particles in their drawing, showing that all the particles are equal. However, they paid no attention to the fact that a metal is malleable in their discussion of their first models (Table 4.8, column 2).

In the class discussion about the property malleability and the corresponding structure model, the teachers drew the common divisor of all the drawings she observed: equal round particles in a neat lattice. The teacher asked whether this structure model explained the property malleability. Sally mentioned that a row of particles can be moved without obstructions, and she showed it to her classmates in the drawing (Table 4.8, column 3).

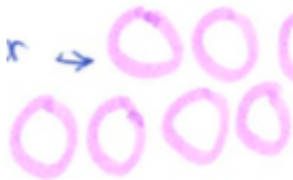
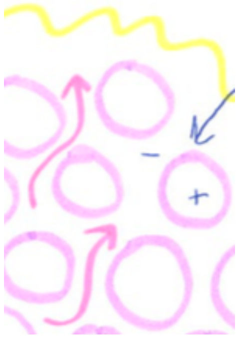
After this adaptation of the structure model, the teacher asked the students to adapt the model to explain the hardness of an alloy such as steel (Table 4.8, column 4). Sally's group now recognized that differently sized particles are not able to move along easily and that malleability decreases, as Sally remarked: "With another substance in it, other particles which are larger or smaller" (Table 4.8, column 4). In a short class discussion, the adaptation of the structure model was discussed.

To explain the conductivity of electricity, the students had to adapt their structure model again. Sally's group discussed the role of the negatively charged valence electrons again, but the girls did not discuss the existence of the positively charged metal atoms. (Table 4.8, column 5). They correctly recognized that these electrons move freely through the lattice.

In the class discussion, the role of valence electrons was discussed. The students said that these electrons move freely: "they are playing tag". The teacher discussed the positively charged metal atom that appeared when a negatively charged electron moves through the lattice. The teacher asked the students to explain the conductivity of heat using this knowledge. Sally's group found it difficult to explain, but they discussed that the shaking or movement of a particle might play a role.

The adapted structure model as drawn in Table 4.8 (column 4) was now used to explain the high boiling point of metals. The teacher asked the class what was necessary on the structure level to obtain a high melting point on the property level. Sally suggested a strong bond between the particles. She also suggested that this strong bond originates in the attraction of positive and negative charges.

Table 4.8. *Students' modeling of metals.*

First Model	1st Adaptation	2nd Adaptation	Final Model
			
T: Draw what a metal looks like at particle level. C: Something like a metal lattice, right? R: Nicely arranged lattice and space for the valence electrons. F: Are there neutrons, uh, is there a neutron and a proton together? C: It looks like... R: Current and heat conductivity has something to do with the valence electrons. S: So nicely arranged that it can therefore easily pass through. F: Valence electrons go just through. C: Nice circles, even, next to each other, nicely arranged. R: Do they have to be straight next to each other? F: I think so, so this way… S: And then like this, like building blocks. Building blocks are also arranged like this. F: What was this called again? S: A metallic lattice. S: A lattice is nicely arranged.	T: Now we have this model, can you explain why a metal is malleable? Draw! R: Well, yes S: Well, you can move those things like this. S: Look at this. This is what it looks like. Look, I moved it. R: I got that, too.	T: Adapt your drawing so that it is not malleable anymore. S: With another substance in it, other particles which are larger or smaller. F: Oh so. They are all different sizes now and then it can't deform anymore. R: If it is pure, it is easier to deform than if it is an alloy. S: An alloy can bend less easily than a pure substance.	T: Adapt your model so that it explains the property conductivity. C: That current that conducts between all those things, doesn't it? R: With those valance electrons that go everywhere in between. F: Are those valence electrons very small then? C: I don't know. R: They can move freely.

The last step of the lesson was the completion of the perspective for structure-property reasoning again, now with all the concepts learned in this lesson (see Figure 4.5 for Sally's result; circled with a gray line). In a class discussion, the appropriate concepts for the metals were formulated for each question of the perspective.

Results of SPR instrument of Sally's group before and after the demonstration lesson series

One week after the exam and five weeks after the last demonstration lesson, the students were asked to perform the SPR instrument as a posttest. Part of this test was the unframed mapping task, in which the students had to complete the questions of the perspective for structure-property reasoning with the appropriate chemical concepts. The personal perspective for structure-property reasoning showed the knowledge organization of the individual students. Sally's perspective for structure-property reasoning (Figure 4.6) was very complete and comparable to the reference perspective for structure-property reasoning (Figure 4.3). Some chemical concepts were missing from her perspective for structure-property reasoning, mainly on the question "which type of particle?" (Figure 4.6). This concerns the concepts of metal and non-metal atoms and molecules.

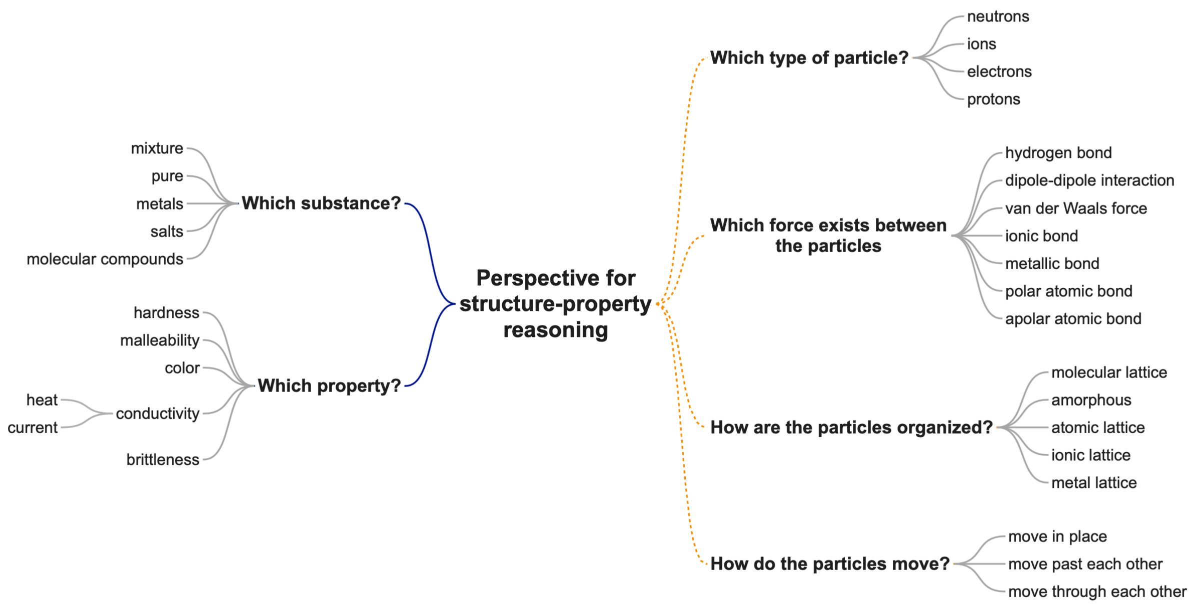


Figure 4.6. *Posttest perspective for structure-property reasoning of Sally, derived from the SPR instrument, unframed mapping task.*

Sally's unframed sorting task showed a macroscopically orientated sort in the pretest. She used four categories: solubility, conductivity, melting point, and hardness. These are the same categories that she also used in her posttest. Her %P-property scores in the pre- and posttest were 72% and 84%, respectively, meaning that her sorts were comparable with the ideal property sort, underlining her macroscopic orientation in these sorts. In the framed sorting task, she had a lower FD score in the posttest (decrease from 10 to 5). Her %P-structure increased from 29% in the pretest to 44% in the posttest. With the predetermined categories in the framed sort, Sally was able to evaluate the problems on structural aspects after the demonstration series. This suggests that Sally increased her proficiency in structure–property reasoning.

4.5. Conclusions and Discussion

This chapter describes two design principles for demonstration-based lessons aiming to help students develop structure–property reasoning. The two design principles were: (1) adding a POE task to demonstrations to stimulate students' engagement and their modeling process and (2) scaffolding of the POE task with a domain-specific perspective for structure-property reasoning (Janssen et al., 2020; Landa et al., 2020) to explicitly guide the modeling at the micro-level for students in the "explain" phase of the POE task. For the design of the lesson series, we explicitly used conventional demonstrations as a basis. The demonstration-based lesson series design with these two design principles was tested in two cohorts of upper pre-university students to investigate the effects of the two design principles on the level of their structure–property reasoning.

First, the results of the SPR instrument indicated that the demonstration 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. In the framed mapping task, all students matched 97% of the given chemical concepts with the associated question of the perspective for structure-property reasoning. 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. The unframed and the framed sort in the posttest bore a greater resemblance to an ideal structure sort. Students also placed more cards in the "correct" category in the framed sort. In the unframed sorting task, the students used more category names referring to the structure level.

Considering design principle 1, 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. The qualitative data of Sally and her classmates (cohort 19-20) started with the general model for solids to explain the first property demonstrated. Sally and her classmates extended this model step-by-step by reviewing the model for the other demonstrated properties. Finally, they came to a model that explained all demonstrated properties of metals. During classroom reasoning, we could see that the properties demonstrated—solid at room temperature, malleability, hardness, and conductivity of electricity—were used to create, extend, and test their structure models. Moreover, Sally's perspective for structure-property reasoning from the posttest (Figure 6) showed that she had acquired all the chemical concepts needed for proficient structure–property reasoning. In this study, we only followed the learning progression of one student. In further research, the learning progressions of a bigger group of students should be investigated.

Literature shows that one of the difficulties students experience with structure–property reasoning is the connection between the macroscopic level of the properties and the micro-level where the structure models emerge. Due to their inexperience, students tend to start their reasoning from their macroscopic orientation (Gabel, 1999; Johnstone, 1991). By adding the "predict" step and the student-centered "explain" step, in which students actively construct the structure models and explain the predicted and observed properties, students had to make explicit connections between the two levels of representations. This might increase their proficiency in structure–property reasoning.

The qualitative data—Sally's drawings and her discussions with her classmates—also showed that the addition of the POE task to the demonstrations gave the students the opportunity to model the structure level themselves. After adapting her prior particle model of a solid (see the second row in Table 4.8), Sally formulated a structure model of metals that explained the demonstrated properties. It appears that the POE task facilitated students in the modeling process. Interestingly, the data also showed that this modeling process appeared to consist of several stages. Sally and her classmates did not merge all the shown properties into one comprehensive structure model in one take. Instead, the group first constructed a tentative model based on their prior knowledge and a general particle model and then extended this tentative model step-by-step into a more extensive model so that it could continue to explain new properties. In this way, Sally and her classmates explicitly commuted back and forth between properties and structure models. Such an iterative modeling process and back-and-forth thinking between properties and structure require the teacher to scaffold this well, e.g., by showing the properties in an order that supports an iterative modeling process.

Considering design principle 2 (scaffolding of the POE task with a domain-specific perspective for structure-property reasoning) the SPR instrument—especially the unframed and framed mapping tasks—showed that students' perspective for structure-property reasoning was more developed in the posttest. Developing the perspective for structure-property reasoning also increased its value as a scaffold for the students. By obtaining the answers—the chemical concepts—to the question agenda, the students acquired the tools for structure–property reasoning. Furthermore, these chemical concepts were connected in functional coherence in the perspective for structure-property reasoning.

Normally, students learn the chemical concepts, and as a next step, they apply these concepts in specific situations. In these demonstrations, students developed the chemical concepts in a context of structure–property reasoning. During the modeling process, the students had to work through the question agenda of the perspective for structure-property reasoning several times, in an iterative process. Each time the perspective for structure-property reasoning was extended, more options became available. These added concepts increased their proficiency in structure–property reasoning, and the students were able to question more complex and increasingly varied problems.

It is known from literature that one of the difficulties of structure–property reasoning that students experience is the invisibility of the structure level 5. The structure level cannot be seen with the naked eye or through a microscope and models are needed to describe it. Because of this, structure–property relations become abstract and students are prone to misconceptions and experience various difficulties in solving problems (de Jong & Taber, 2015; Gabel, 1999). In our study, the use of the perspective for structure-property reasoning gave the students a scaffold to support the reasoning process by offering the concepts and the questions from the question agenda in coherence. Furthermore, the question agenda of the perspective gave the students insight into domain-specific reasoning. It enabled them to reason more like experts by questioning the problems with the aid of the question agenda. In sum, the perspective for structure-property reasoning with its questions and the associated chemical concepts will increase the proficiency in students' structure–property reasoning and will help them to solve problems with structure–property relations in the future.

The design of the demonstrations and the modeling process by the students worked best for metals and salts, as can be seen in the results of the framed and the unframed sorting tasks. These groups of compounds are well-defined groups with clear structure–property relations and hardly any exceptions. The molecular compounds group was more difficult to demonstrate due to its complexity in terms of properties but also in terms of structure models: various types of bonds and lattices. This could probably be solved by dividing this group into several sub-groups of molecular compounds based on properties such as solubility and/or boiling points. In our demonstration, the problem was solved by reversing the design. Instead of asking them to model the structure level of molecular compounds, the students were asked to design appropriate demonstrations to help them find the answer to the questions of the perspective for structure-property reasoning. This change of design was beneficial for teaching the students the perspective for structure-property reasoning and thus for the explicit teaching of structure–property reasoning.

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. We know from the literature that teachers judge innovations to be practical based on three criteria: (1) the teaching practice needs to contain instrumental content so that teachers know how it will work in their setting; (2) the teaching practice needs to be congruent with teachers' goals and regular teaching practice; and (3) the teaching practice should be low-cost in terms of time and energy that need to be invested (Doyle & Ponder, 1977; Janssen et al., 2014). In the present study, we used existing demonstrations as a starting point for redesign. We used the design principles to adapt these demonstrations. We expect that using existing elements (high instrumentality), a redesign close to teachers' existing teaching practices and materials already present (high congruency and cost-effectiveness) and the small change of the order of existing building blocks (Figure 1) amounts to high practicality for teachers. As demonstrations could be an important online teaching method in the present time of COVID-19, and as a weakness of online teaching is the lack of interaction with students, the addition of a POE task to demonstrations could increase the interactions with students making the online demonstration minds-on.

The combination of the two design principles together could be used in any situation in which students (from primary school to higher education) are asked to develop a model to explain phenomena. This is not only the case for science-related subjects but also, for example, in economics, social studies, geography or linguistics (as part of teaching a language). For the modeling of phenomena, the POE task could be used in the same manner each time, but for each domain, a different domain-specific perspective should be used. The perspective could act as a thinking frame for the students, and this might enhance the domain-specific way of thinking. Further research is needed for the development and implementation of both the perspective for structure-property reasoning and the other domain-specific perspectives.

One lesson series to develop the perspective for structure-property reasoning, associated chemical concepts and proficiency in using the question agenda of the perspective for structure-property reasoning is clearly not enough. Repetitive use of the question agenda and application of the chemical concepts in several assignments and tasks would be needed to mature structure–property reasoning. The lesson series described here could be the start of systematic use of the perspective for structure-property reasoning for explicit teaching of structure–property reasoning. Further research could aim to develop strategies (tools) for teachers to design additional lessons using the perspective for structure-property reasoning.

Chapter 5:

Estimated Practicality of a Redesigned Demonstration for Teaching Structure-Property Reasoning

Abstract

Acquiring structure-property reasoning is difficult for novice chemistry students. Teachers can help them by explicitly teaching structure-property reasoning and using demonstrations to show the chemical phenomena. However, a traditional demonstration lacks opportunities for students to think for themselves, or teachers do not offer enough scaffolding when students think for themselves. Teachers' usual presentation of demonstrations needs to be redesigned. For such an innovation to be implemented in teachers' own teaching practice, however, the innovation should be experienced as practical, with clear procedures, high congruency with their own teaching goals, and high cost-effectiveness. In this study, the practicality of an innovation with two design principles, i.e., POE task and the perspective for structure-property reasoning, was judged by eight participants. The results show that the redesigned demonstration was perceived to be about as practical as traditional demonstrations. Also, many of the intended benefits were recognized by the teachers. Because the redesign of the demonstration used bridging methodology, a first step towards designing a professional development training course showing teachers how to implement this innovation was taken. This will enable the two design principles for demonstrations to become part of chemistry teachers' teaching practice.

5.1 Introduction

Chemical reasoning is one of the most important, yet challenging, skills chemistry students need to acquire. The main difficulty of chemical reasoning is so-called multilevel thought, i.e., being able to think over multiple levels simultaneously. According to Johnstone (1982, 1991), three levels of thought are important: the micro (the level of particles and their interactions), the macro (the level of the observable), and the symbolic (the level of symbols, equations, etc.) levels. When teaching chemical reasoning, therefore, one important goal of teachers is to teach their students so-called micro-macro thinking, better known as structure-property reasoning: explaining observable properties and changes of compounds (macro) in terms of particles and their interactions (micro) (Meijer et al., 2013; Talanquer, 2018).

Students experience difficulties with structure-property reasoning. First, while experts in chemistry are able to use all the levels simultaneously (Treagust et al., 2003) and unconsciously transfer between levels, students mainly think from a macroscopic point of view (Gabel, 1999). Second, students find it difficult to think using structure models, as these oppose the macroscopic level where things are tangible and visible to the naked eye (de Jong & Taber, 2015). Structure models at the micro level are also often represented using symbolic, microscopic, or mixed features which are sometimes implicit or ambiguous (Gkitzia et al., 2011). Students have difficulties in understanding such representations (Kozma & Russell, 1997).

Earlier studies suggest that showing chemical phenomena and teaching the micro level explicitly aid students in acquiring structure-property reasoning as these provide opportunities to teach at all three levels simultaneously (Gabel, 1993; Kozma et al., 1997; Talanquer, 2018). Consequently, chemical phenomena are often embedded in teachers' daily teaching practice, primarily as practical work (Becker et al., 2015; Hodson, 1993, 2014; Hofstein, 2004). Practical work, however, is often not very effective in teaching structure-property reasoning (Abrahams & Millar, 2008; Hodson, 2014; Hofstein & Lunetta, 2004), among other reasons due to the high cognitive load for students of performing practical work (Hodson, 2014; Paterson, 2019): they must pay attention to various factors, e.g., following instructions (verbal and written), dealing with apparatus and materials, and obtaining and processing the right data.

A demonstration of a chemical phenomenon, on the other hand, lowers distractions, and hence the cognitive load, for students (Logar & Ferk Savec, 2011; McKee et al., 2007; Meyer et al., 2003; Ramsey et al., 2000). As the teacher performs the procedures, students can concentrate on the chemical phenomenon and the underlying micro-level explanation. This enables students to practice structure-property reasoning. However, a demonstration has the disadvantage of lower student engagement and interaction. Students are impressed by the show, but they are not greatly stimulated to think for themselves. The lack of interaction and the low student engagement during a demonstration impedes students in learning to reason explicitly between the various levels (Roth et al., 1997). This indicates the need for a different design of demonstration lessons, to increase their effectiveness in helping students to acquire structure-property reasoning skills. Existing approaches to demonstrations need to be redesigned for this purpose, so students are enabled to think for themselves during the demonstration. As in any innovation, it is critical that is this also done in a way that is practical for teachers.

Practicality theory (Doyle & Ponder, 1977) shows that an innovation will only be accepted and implemented by teachers if it is judged to be practical. Three criteria are important for practicality. First, it should be instrumental. An innovation should comprise clear procedures to enable teachers to quickly implement it in their own teaching practice. Second, it should be congruent with teachers' regular teaching practice. Finally, it should be cost-effective. Innovations should have low costs in both time and resources.

In the present study, we describe a practical method to redesign existing demonstrations, leading to demonstration experiments aimed at promoting students' structure-property reasoning. After redesigning a demonstration, we asked teachers to compare the practicality of our design with that of their delivery of a demonstration. Furthermore, we aimed to gain insight into teachers' motivational beliefs underlying their estimation of practicality. Our research question for this study was, how do teachers assess the practicality of redesigned demonstrations aimed at promoting students' structure-property reasoning?

5.2 Redesigning Demonstrations to Strengthen Structure-Property Reasoning

In a traditional demonstration, a chemical phenomenon is shown by the teacher, while the students observe. During and after the demonstration, the teacher explains the chemical concepts related to the chemical phenomenon. A teacher often starts a traditional demonstration by posing a question as a means of introducing the topic (Hilario, 2015). Such an activating question introduces the students to the subject and the learning objectives. The theory behind the chemical concepts addressed by the demonstration is mostly explained before the demonstration. Sometimes, the teacher uses the demonstration to introduce the theory. In a traditional demonstration, the teacher is lecturing most of the time, and interaction with students is low (Roth et al., 1997). When observing the demonstration, students are impressed by the show, but they are not stimulated enough to think for themselves. This impedes the students in learning to reason over multiple levels. To stimulate students to engage in structure-property reasoning, their interaction in the demonstration should be increased (Bowen & Phelps, 1997; Crouch et al., 2004; Pierce & Pierce, 2007; Ramsey et al., 2000).

Traditional demonstrations should be redesigned to enable students to think for themselves. In an effective demonstration, there should be explicit attention for students' structure-property reasoning. However, an effective demonstration should also be practical for teachers. Both aspects should be accomplished simultaneously, without promoting one at the expense of the other. To make the educational reform practical without losing the essential elements of the innovation, a bridging methodology was developed (Dam et al., 2013; Janssen et al., 2013). In this methodology, the existing and the new teaching practices are described in comparable building blocks (Dam & Janssen, 2021; Janssen et al., 2013). The innovation can then be realized through a stepwise recombination or adaptation of the existing building blocks. Every step in which a building block is adapted or recombined should be experienced by teachers as an improvement of their daily teaching practice.

Teachers typically strive to improve their daily teaching practice, but they find it hard to strive for realization of all their teaching goals. Therefore, for a teacher to consider an innovation or redesign as an improvement, the expected value of the redesign should be estimated to be higher than that of the original teaching practice. This expected value is defined as the product of desirability (the extent to which a person considers the expected outcome of the redesign to be desirable) and probability (the extent to which a person expects that he or she will be able to realize the expected outcome) (Pollock, 2006).

Bridging methodology can help make an innovation practical because it gives teachers access to a procedure which enables them to realize the innovation in their own teaching practice. In addition, this procedure costs little in terms of extra time and resources because it starts with existing building blocks (cost-effectiveness). Furthermore, it explicitly builds on what teachers normally do and what they find important (congruence). Bridging methodology has been applied and tested in multiple settings, such as teacher education (Janssen et al., 2014, 2015; Janssen et al., 2014) and teacher professional development training (Dam & Janssen, 2021) in the fields of biology (de Graaf et al., 2018) and modern foreign languages (de Vrind, et al., 2019). In this study, we applied bridging methodology to the redesign of traditional demonstrations, creating demonstrations aimed at developing structure-property reasoning in chemistry.

When applying bridging methodology to the redesign of existing demonstrations, we first need to define the typical teaching practice in a traditional demonstration lesson in terms of building blocks comparable with those of the intended innovation. Such a lesson typically consists of the following five building blocks: Question, Show, Observe, Explain, and Theory (Figure 5.1, first row). First, teachers ask students a question about a certain chemical phenomenon, in this way introducing them to the subject and the learning objectives of the lesson. Next, the teacher explains the theory behind the concepts addressed by the demonstration. The chemical phenomenon is demonstrated to the students, who observe the show. Last, the teacher explains the demonstrated phenomenon in relation to theory about the associated chemical concepts.

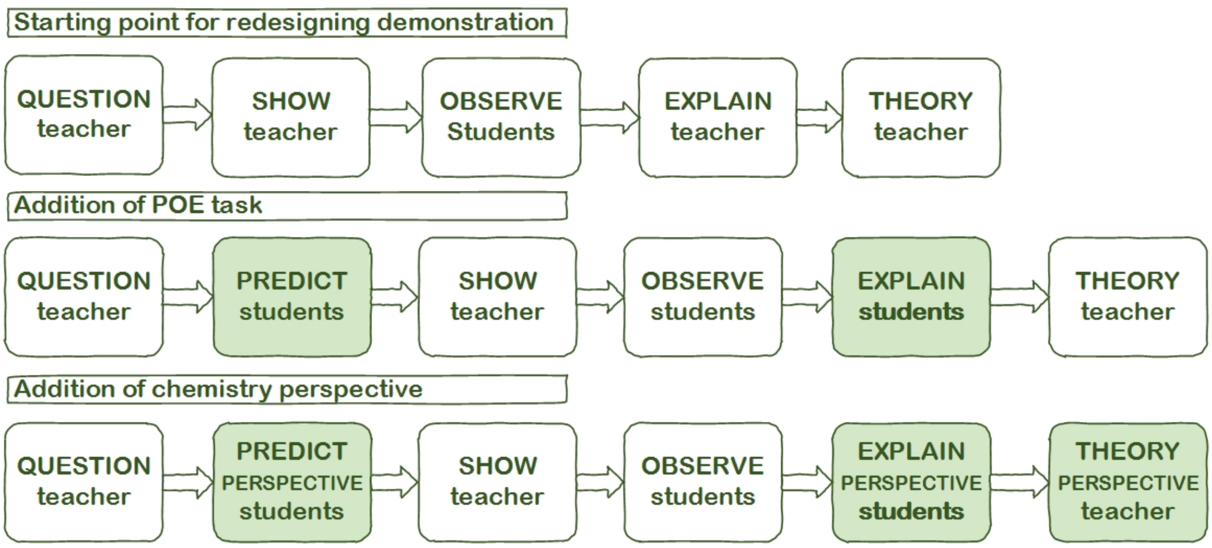


Figure 5.1: *Building blocks for traditional demonstration and steps for redesign.*

The first design principle we introduced was aimed at enabling students to think for themselves (increased student engagement) during the demonstration: the POE task (Crouch et al., 2004; den Otter et al., 2021; Kibirige et al., 2014; Liew & Treagust, 1998; Shiland, 1999; Treagust, 2007). The POE task adds a building block to the teaching practice: namely, the Predict phase. Before the demonstration, the teacher asks the students to predict the outcome of the experiment. Students preferably explain their predictions using reasoning at the micro level. The teacher then performs the demonstration. Afterwards, the students explain their observations, again with help of the micro level. In this way, students are asked to link the outcome of the demonstration to the addressed chemical concepts, making the building block Explain more student-directed. The addition of the POE task is the first step in the bridging methodology (Figure 5.1, second row).

To scaffold students' structure-property reasoning in the Predict and Explain phases, we introduced the second design principle, a domain-specific perspective for structure-property reasoning (Figure 2) (den Otter et al., 2021). Perspectives are a way of looking at, thinking about, and working on complex problems, based on scientific perspectivism (Giere, 2010; Wimsatt, 2007). A hierarchically organized perspective starts with a central core reasoning idea. For structure-property reasoning, the core reasoning scheme could be defined as follows:

"The **properties** of **substances** can be explained by the nature of the **particles** of which they consist, the **bonds and forces** between them, and the **movement** and **organization** of those particles."

Six basic questions can be formula ted based on the words in bold from the core reasoning scheme (Figure 2) (den Otter et al., 2021, 2022; Janssen et al., 2020; Landa et al., 2020). The answers to these questions are specific chemical concepts such as electrons, protons (particles), or Van der Waals bond, hydrogen bond (forces, interactions). The advantage of such a perspective is that chemical concepts are coherently organized. The domain-specific perspective can act as a scaffold for students' structure-property reasoning and modelling. Students can use the questions of the perspective to consider the problem, and the answers in the form of the applicable chemical concepts can help students to formulate a solution to the problem.

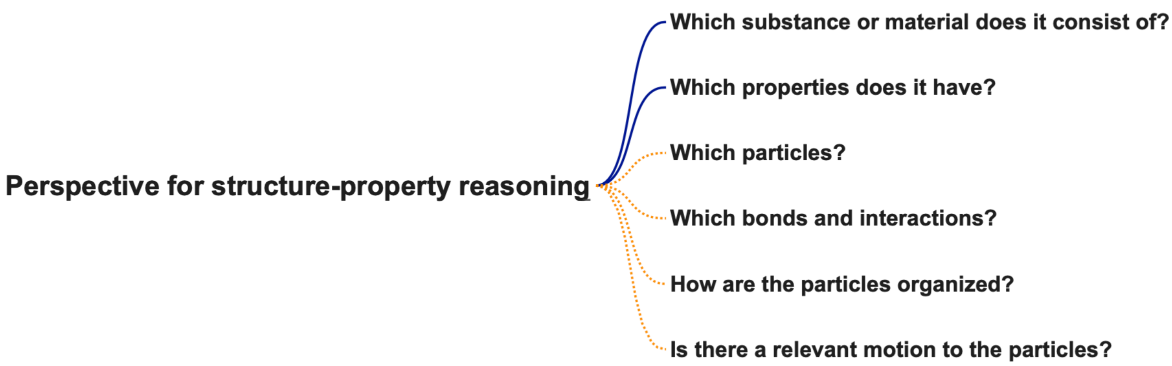


Figure 5.2: *The domain-specific perspective for structure-property reasoning. The blue lines lead to questions at the macro level, the orange lines to questions addressing the micro level.*

The perspective for structure-property reasoning enables the teacher to reorganize the chemical content he or she would normally address. The chemical concepts can also be seen as building blocks, i.e., content building blocks (de Boer et al., 2019). Using a perspective leads to the content building blocks being organized coherently through questions and makes the bigger picture of the demonstrated structure-property relation clear to students. Figure 5.3 shows how the content building blocks addressed in the disturbance of the equilibrium of cobalt (IV) chloride by adding some drops of hydrochloric acid are organized in the perspective. The questions about the macro level describe the macroscopic situation. The questions about the micro level make clear to students which structure models they need to explain the shown phenomenon. In this way, the perspective helps students to develop structure-property reasoning and, therefore, enables teachers to explicitly teach structure-property reasoning.

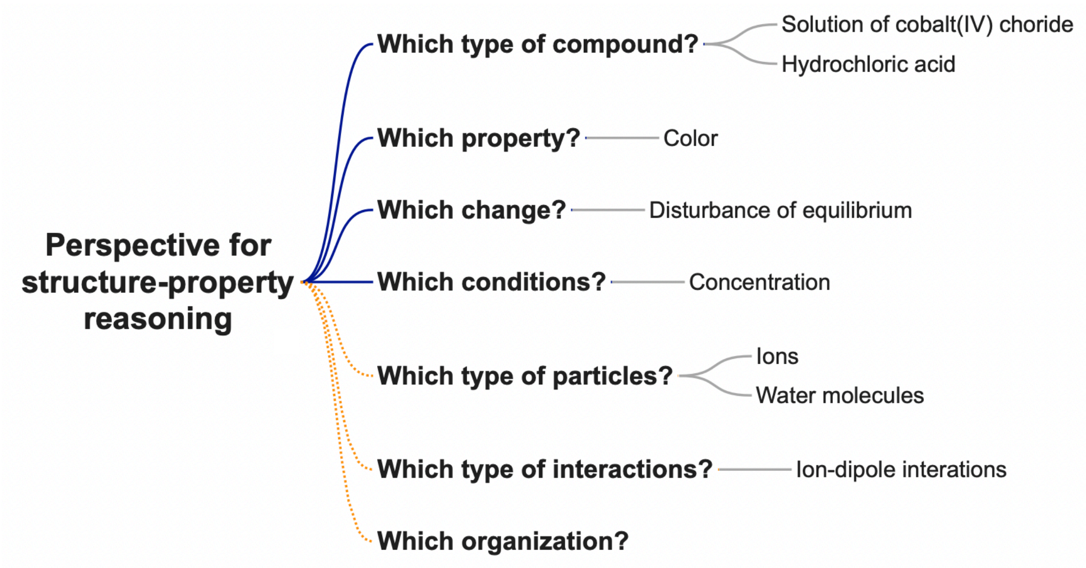


Figure 5.3: *The domain-specific perspective for structure-property reasoning used in this study and elaborated for the disturbance of a cobalt (IV) chloride equilibrium by adding some drops of hydrochloric acid. Because the demonstration concerned the disturbance of an equilibrium, two questions about change and conditions were added to the perspective for structure-property reasoning as depicted in Figure 5.2. The blue lines lead to questions at the macro level, the orange lines to questions addressing the micro level.*

In a previous study, we showed that a redesigned demonstration including a POE task (Predict-Observe-Explain) and the domain-specific perspective for structure-property reasoning aided students in acquiring the skill of structure-property reasoning (den Otter et al., 2021). The POE task and the perspective for structure-property reasoning enabled the teacher to engage students in the demonstration, while providing the students with opportunities to develop structure models of metals, salts, and molecular compounds, and to explain the demonstrated properties using these structure models.

5.3 Redesign of a Demonstration Lesson Using the Two Design Principles

In the present study, an existing demonstration lesson used in the lessons of the first author was redesigned as discussed above. We selected the topic of the disturbance of equilibrium. Normally, the first author would show a video of the disturbance of the $CoCl_4^{2-}$ equilibrium (equation 5.1) as the demonstration.[1] The effect of a change in concentration as well as a change in temperature on the equilibrium would be demonstrated. The teaching practice for this demonstration lesson is depicted in Figure 5.1, row 1. The concept would be introduced with a short description of the demonstration to be shown and an activating question. The video would then be shown and stopped at certain points to ask the students to explain their observations. After the demonstration video, the theory of Le Chatelier's principle would be explained to the students. Finally, the students would work on some assignments related to this principle.

$$\text{Heat} + [Co(H_2O)_6]^{2+} + 4\ Cl^- \rightleftarrows [CoCl_4]^{2-} + 6\ H_2O \qquad \text{(equation 5.1)}$$

[1] This video was found on YouTube: https://youtu.be/dmOif5MUPcE.

In redesigning the demonstration lesson, the building block Predict was added to the original teaching practice (as in Figure 5.1, row 2). Therefore, in the redesigned demonstration, students were asked to predict the color change and other possible observations when (1) hydrochloric acid, and (2) a solution of silver nitrate were added, and (3) the temperature was changed. The questions of the perspective for structure-property reasoning (Figure 5.3) were shown on the screen and used to explore and describe the macroscopic situation. Because the demonstration concerned a disturbance of an equilibrium, two questions about the change and the conditions were added. The questions remained on the screen during the demonstration. Students' predictions were shared, and students were asked to explain their predictions. The teacher used the questions of the perspective for structure-property reasoning to scaffold these explanations. After the demonstration phase, the teacher discussed the observations with the students to check their explanations of their observations. Again, the teacher used the questions of the perspective for structure-property reasoning to scaffold the explanations put forward by the students. This redesign changed the traditional demonstration practice to our target teaching practice, as in Figure 5.1, row 3.

5.4 Methods

5.4.1. Research Design and Participants

First, a demonstration lesson was chosen for this study. The original demonstration lesson was redesigned using the steps described above (see Figure 5.1). The redesigned demonstration lesson was given by the first author of this chapter to a Y4 (aged 15-16 years) pre-university-level class of 18 students, during the COVID-19 period. Therefore, the demonstration was showed to the students using a video from YouTube. The lesson was taught remotely via an MS Teams meeting.

Next, seven teachers and one teacher educator agreed to be interviewed. The teachers taught at seven different secondary schools. Table 5.1 summarizes the participants' characteristics. All names have been anonymized.

5.4.2. Data Collection and Analysis

To investigate the practicality of the demonstration including POE and the perspective for structure-property reasoning, the participants were interviewed. The interviews were semi-structured and lasted about one hour. The interviews were audio-taped, and the interviewer made notes.

We started the interviews with questions to gather information about the teachers' background and experience. We then explained the two design principles we used for the redesign of the demonstration: namely, the POE and the perspective for structure-property reasoning. Next, the lesson demonstration performed by the first author was explained by showing two key sheets of the PowerPoint used in the lesson. After this, the estimated practicality of the demonstration was determined according to a procedure described in previous studies (de Graaf et al., 2018; Janssen et al., 2014). First, we asked the participants to score the estimated desirability and probability on a seven-point Likert scale (1 to 7) for both the traditional demonstration and the redesigned one.

The expected value was calculated by multiplying the scores given for desirability and probability, because the expected value is determined by the extent to which a teacher thinks the expected outcome of a design is desirable and by the extent to which a teacher expects to be able to realize the design in their own teaching practice (Pollock, 2006). Teachers consider a design an improvement if the expected value of the design is higher than the expected value of their original plan (de Graaf et al., 2018).

Next, to get insight into participants' motivational beliefs underlying their scores for desirability and probability, we asked every teacher to name specific advantages and disadvantages of both the traditional and the redesigned demonstrations. The estimated advantages and disadvantages also provided insight into the extent to which the teachers considered the two design principles practical for their own teaching practices.

Next, two researchers analyzed these beliefs and clustered them into groups based on their content, without losing too many of the original words. When the two researchers disagreed, they reached consensus through discussion. Five participants mentioned disadvantages of giving assignments for home experiments. These disadvantages were removed from the list.

Table 5.1: *Characteristics of interviewed teachers*

	Felix	Imani	Anna	Julia	Jason*	Isabel	Alissa#	Simon
Teaching experience (years)	8	23	1	8	1	8	1[b]	12
Grade level[a]	PUE	PUE	PUE	PUE	PUE	PUE	PUE	PUE
Upper/lower secondary education	Both	Upper	Both	Upper	Upper	Both	-	Both
School	A	B	C	D	E	F	-	G
Performed online demonstrations	Yes	Yes	Yes	Yes	No	Yes	-	Yes
Made practical assignments for students at home	Yes	Yes	No	No	No	Yes	-	No

*Note. * Jason is a student teacher; # Alissa is a teacher educator*
a PUE = pre-university education, GSE = general secondary education
b Experience in teacher education

5.5. Results

5.5.1. Estimation of the Expected Value

The average estimated desirability and probability of the traditional demonstration and the redesigned demonstration are shown in Table 5.2, together with the calculated expected value of both the traditional demonstration and our design.

The participants found a demonstration desirable for their lessons, whether taught remotely or not, as can be seen in the rather high average scores (5.5 and 6.1) for the desirability of both the traditional demonstration and the redesigned demonstration. In addition, it was clear from the scores that participants found the redesigned demonstration more desirable than a traditional design, as can be seen in the increased value (+0.6) for desirability (Table 5.2). However, Table 5.2 also shows a decrease (-0.5) in the average score for probability of the redesigned demonstration, including POE and perspective, compared with the traditional demonstration. On average, the expected value of our redesigned demonstration is slightly higher than that of the traditional demonstration.

Table 5.2: *Participants' estimated desirability and probability scored on a seven-point Likert scale (1-7) for a) Traditional Demonstration, b) Redesigned demonstration (n=8). Expected Value = Desirability x Probability*

	Desirability	**Probability**	**Expected value (DxP)**
	Mean	Mean	Mean
Traditional demonstration	5.5	5.9	32.5
Redesigned demonstration	6.1	5.4	32.9
Difference	+ 0.6	- 0.5	+ 0.4

The individual scores for desirability, probability, and expected value are shown separately in Table 5.3 for the eight participants.

Table 5.3: *Participants' estimated desirability and probability scored on a seven-point Likert scale (1-7) for a) Traditional Demonstration, b) Demonstration with POE and Perspective*

	Felix	**Imani**	**Anna**	**Julia**	**Jason***	**Isabel**	**Alissa#**	**Simon**
Traditional Demonstration								
Desirability	7	4	5	3	5	6	7	7
Probability	7	6	7	4	4	7	6	6
Expected Value (DxP)	49	24	35	12	20	42	42	42
Demonstration with POE and Perspective								
Desirability	5,5	7	6	5	6	6	7	6
Probability	6	6	5	2	6	6	7	5
Expected Value (DxP)	33	42	30	10	36	36	49	30
Difference Expected Value	- 16	+ 18	- 5	- 2	+ 16	- 6	+ 7	- 12

*Note. * Jason is a student teacher; # Alissa is a teacher educator*

5.5.2. Motivational Beliefs Underlying the Scores for the Expected Values

The results show that the average expected value (=desirability x probability) increased by a marginal difference of 0.4 points (Table 5.2). This means that the eight participants found the redesigned demonstration including the two design principles to be approximately as practical as traditional demonstrations. Table 5.4 shows the perceived advantages and disadvantages of the traditional demonstration (Table 5.4a) and of the redesigned demonstration (Table 5.4b), giving insight into the participants' motivational beliefs; these beliefs explain the scores for both the desirability component and the probability component of the expected value. We discuss the advantages and disadvantages mentioned by the participants below and relate these motivational beliefs to the aims of the two design principles.

Four participants named as advantages of a traditional demonstration that students learn more and understand better when observing a demonstration in the lesson compared with instruction without a demonstration. Four participants mentioned that a demonstration makes a concept, a procedure, and the micro level more visible compared with instruction without a demonstration. A disadvantage of a traditional demonstration that was mentioned is that students only must observe; they are less stimulated to think for themselves.

Table 5.4a: *Participants' estimated advantages and disadvantages of the traditional demonstration with the design principles POE and Perspective (n=8)*

Advantages	Number	Disadvantages	Number
It is timesaving, efficient, cost-effective	2	Students don't have to think, only to watch	3
Video gives opportunity to pause and watch again*	1	Learning effect is less compared with doing it yourself in a student experiment	1
Nice to do, motivating for the students	3	Difficult to differentiate between students	1
Students will learn more, understand better, students are challenged to think for themselves compared with instruction without demonstration	4	Lack of guidance, scaffold options, and check while watching an asynchronous demonstration video*	3
Demonstration makes procedure / concept / micro level more visible, illustrates better compared with instruction without demonstration	4	Demonstration on screen is less impressive, students cannot smell, feel, etc., compared with demonstration in the classroom*	3
Students have same starting point	1	Interaction with students is poor and demonstration is teacher-directed	2
		Selecting correct demonstration video and timing of video in online lesson design is difficult*	1

*Note. * Statement concerns online demonstration*

Table 5.4b: *Participants' estimated advantages and disadvantages of the demonstration with the design principles POE and Perspective (n=8)*

Advantages	Number	Disadvantages	Number
Students are challenged to think for themselves (before seeing it)	7	Difficult to engage every student in class, difficult to let every student predict, not only the ones asked. Students must learn to work with this method.	4
Students will remember better or learn more when thinking for themselves or when they create their own knowledge (compared with a traditional demonstration)	3	Less interaction due to online environment*	2
Perspective gives thinking frame, gives coherence, and is a toolbox for students to solve problems	5	Many questions in perspective. (Open) perspective is uncomfortable, students do not know which direction. Perspective is difficult to use, especially when pre-knowledge is poor	5
Predict and perspective give opportunities for thinking for themselves and increase engagement of students	5	Demonstration is a complex elaboration of theory, maybe too complex for students	1
Internal conflict helps with learning the concepts	1	Students create their own knowledge, so misconceptions could arise	2
Students learn micro aspects better; perspective helps them learn structure-property reasoning	2		
Opportunities for formative assessment	3	Students are forced into a certain thinking frame	2
Perspective connects to pre-knowledge	1	Other domain-specific perspectives are also needed	1
Engagement of students by predicting the outcome	3		
Perspective offers structure for the teacher to discuss and teach chemical concepts	1		

Seven participants named as advantages of the redesigned demonstration including the two design principles that students are challenged to think for themselves. Five participants mentioned that the perspective for structure-property reasoning gives students a thinking frame. Another advantage that was named five times is that the two design principles give students the opportunity to think for themselves, the opposite of a mentioned disadvantage of the traditional demonstration. Five participants said there were too many questions in the perspective and that they, therefore, found the perspective difficult to use.

5.6 Discussion

Teaching students to engage in structure-property reasoning is an important goal of chemistry education in secondary schools. This can be achieved by performing practical work with chemical phenomena, which should be explained through the structure models underlying them (Gabel, 1993; Kozma et al., 1997; Talanquer, 2018). However, when students perform practical work themselves, cognitive overload may impair their learning (Hodson, 2014; Paterson, 2019). Furthermore, practical work is time-consuming for teachers. Performing a demonstration can solve these problems (Logar & Ferk Savec, 2011; McKee et al., 2007; Meyer et al., 2003; Ramsey et al., 2000), but students' learning of structure-property reasoning is less well facilitated by the way a demonstration is typically taught.

The abovementioned indicates the need to redesign existing demonstration lessons. Therefore, we introduced two design principles: the POE task and the perspective for structure-property reasoning. We demonstrated the effectiveness of these design principles for teaching structure-property reasoning in a previous study (den Otter et al., 2021). In the current study, we examined the extent to which teachers considered the redesigned demonstration to be practical. This is not a given: many innovations fail to make it to the classroom because they are rejected as impractical. Bridging methodology (Dam et al., 2013; Dam & Janssen, 2021; Janssen et al., 2013), the recombination and adaptation of existing building blocks, was applied to a regular demonstration to design a demonstration which could improve students' structure-property reasoning. Eight participants were asked to score the estimated probability and desirability of using this approach in their own teaching practice.

The findings show that the redesigned demonstration was perceived to be about as practical as traditional demonstrations. Also, many of the intended benefits were recognized by the teachers. The redesigned demonstration enables students to think for themselves; consequently, they will remember and learn better. The participants estimated that student engagement would increase as a result of using the redesigned demonstration. In addition, the perspective for structure-property reasoning was recognized as a thinking tool for students.

Some disadvantages were also mentioned: for example, that the perspective for structure-property reasoning might be difficult to use due to the large number of questions. When starting with structure-property reasoning, novices have only a limited set of simple main questions at their disposal. When progressing in structure-property reasoning, students expand the perspective step-by-step by adding sub-questions to the main questions, and later sub-questions to the sub-questions. In this way, a perspective branches out into a coherent set of questions. Using this step-by-step construction of the questions in the perspective, the teacher can have the students practice structure-property reasoning gradually, and the perspective will develop into a growing thinking frame for them. In this way, a perspective-based learning progression (Duschl et al., 2011) will appear. A more branched out perspective with too many questions at once would cause an excessive increase in cognitive load for novices (Jin et al., 2019). So, for novices starting to acquire structure-property reasoning, the perspective should consist of a limited number of questions. This step-by-step construction of the perspective should be investigated in future research.

Some disadvantages of the redesigned demonstration point to a limitation of the study as a whole: namely, the context in which we performed the research. The interviews were conducted at the end of the first Covid-19 lockdown in the Netherlands (June 2020). The participants were at the end of a rough period in which they had had to acquire a completely new teaching practice, giving lessons in an online setting. The participants were tired and overwhelmed by all the changes. The prognosis at that time was that normal teaching at school would resume after the summer holidays. This possibly gave the participants a distorted view and influenced their estimations of the practicality, especially the cost-effectiveness, of an online demonstration with or without the two design principles. This view could also be seen in the disadvantages mentioned of both the traditional demonstration and the redesigned demonstration. It is clear from the participants' naming of these disadvantages that this online setting lacked opportunities for much-needed student-teacher interactions. Nevertheless, the scores and the advantages mentioned of the two design principles are promising regarding the practicality of the innovation, suggesting that there is a place for the redesigned demonstration in the teaching practices of the participants.

Another limitation of this study is that it concerns teachers' estimated practicality of the demonstration. It is not based on teachers' personal experience. However, the scores for the estimated desirability and probability of the redesigned demonstration look promising. In addition, the current study described a small trajectory in which teachers could expand their repertoire step by step. This bridging trajectory could be used in a professional development program. Further research may reveal how teachers estimate the practicality of the redesigned demonstration compared with their traditional demonstrations.

The results of this study have some practical implications. For successful implementation of the two design principles, it may be important to introduce the participants to the approach. This might reduce feelings of uncertainty caused by the unfamiliarity of the approach. This can be done by designing a professional development course for participants who wish to use the two design principles. In this training, the incorporation of modularity enables participants to incrementally modify their teaching practice, facilitating the development of a personalized and customized bridging trajectory, as illustrated in Figure 2. (Dam & Janssen, 2021). In further research, therefore, a professional development training course should be designed to investigate the actual use of the two design principles by participants. A personal bridging trajectory should be deployed in this. In addition, it could be useful to refine the procedures of both design principles, adding a design template and examples of good practice. In this way, the two design principles may become part of a teaching approach that enables participants to (re)design their demonstration lessons to increase students' proficiency in structure-property reasoning.

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.

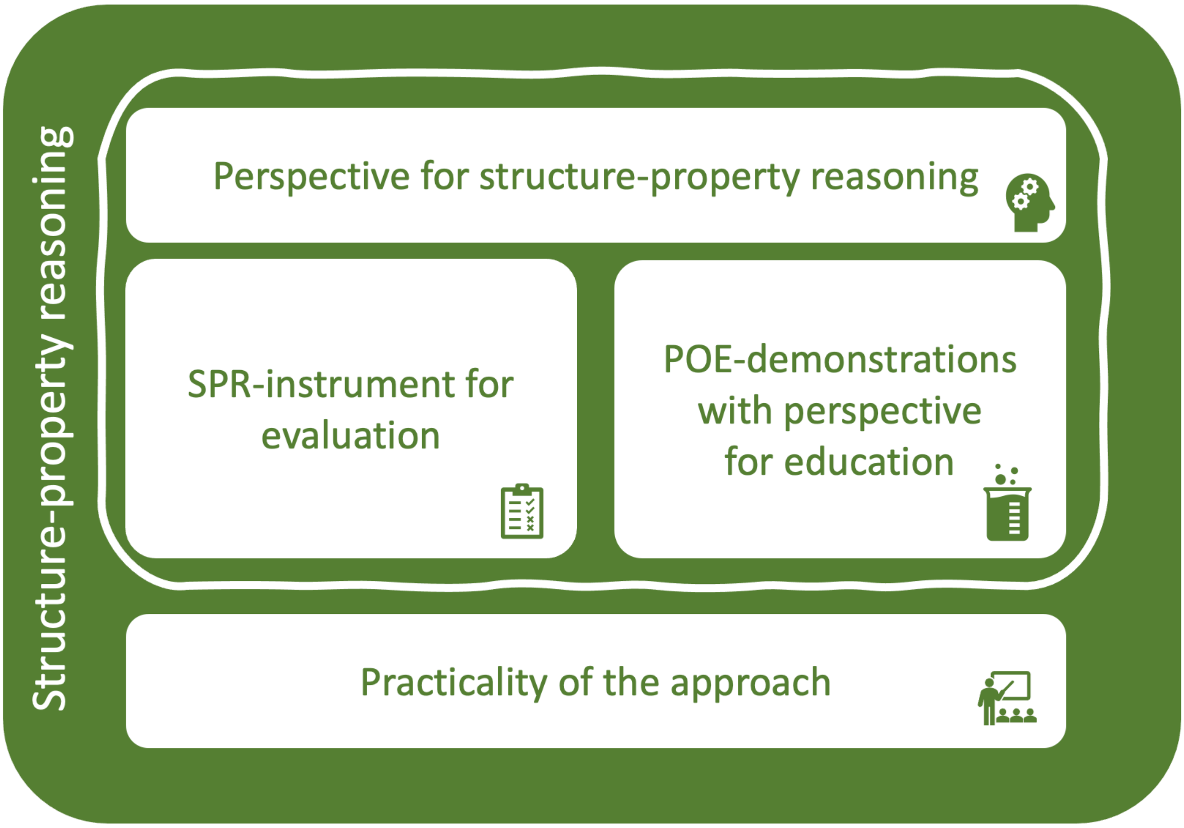


Figure 6.1: *graphical overview of the study described in this thesis.*

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.

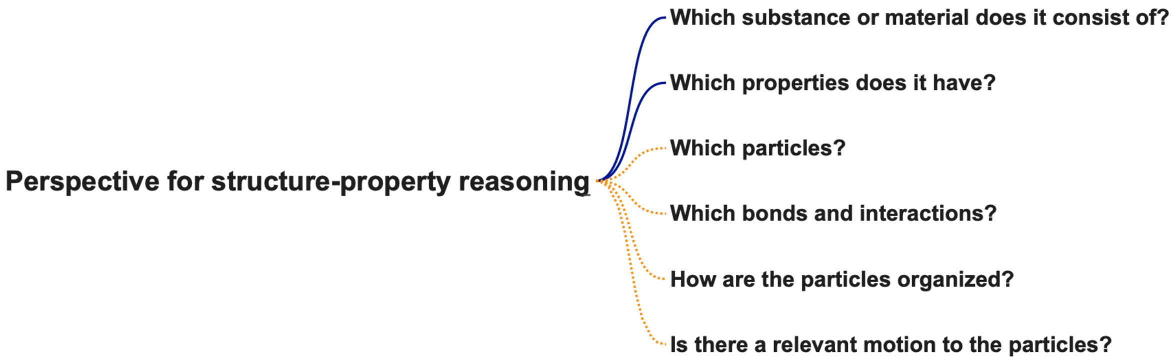


Figure 6.2: *Perspective for structure-property reasoning used in the studies of this thesis, elaborated for the first level.*

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.

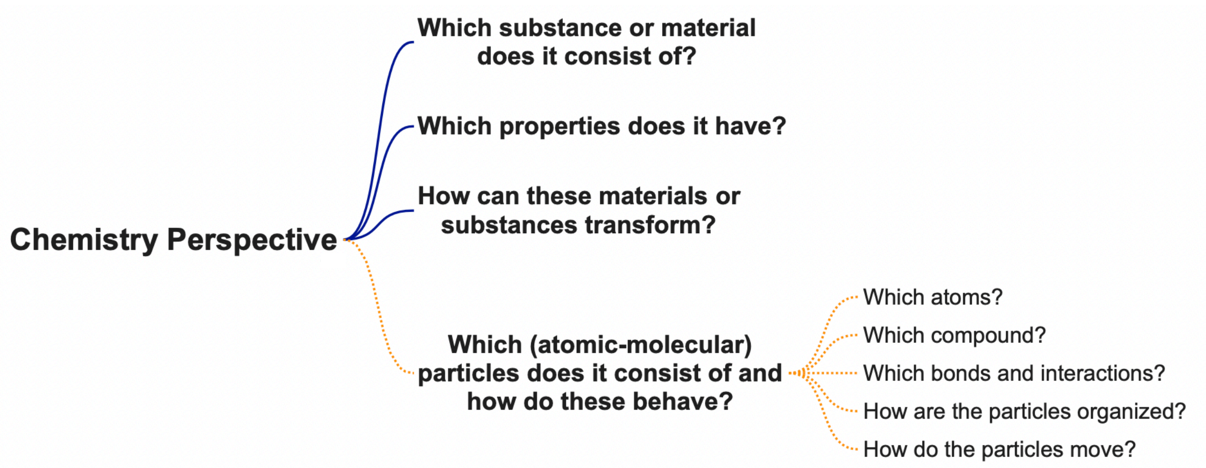


Figure 6.3: Perspective for structure-property reasoning elaborated into the chemical perspective.

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).

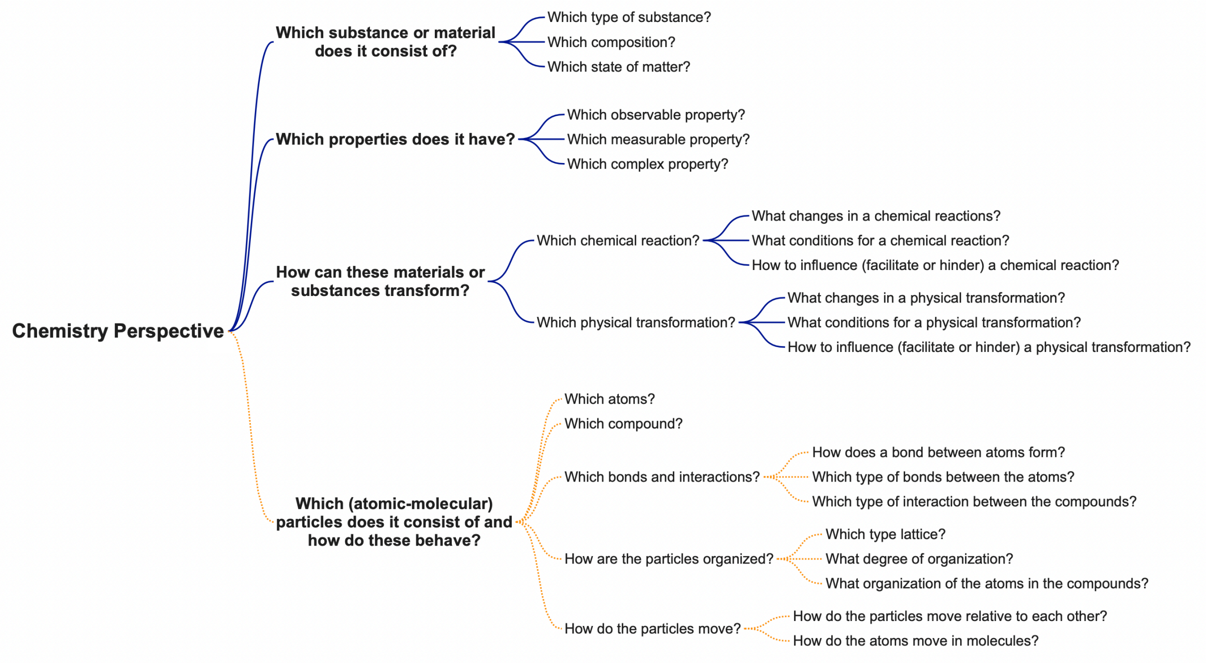


Figure 6.4: *chemistry perspective elaborated to two or three levels.*

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)

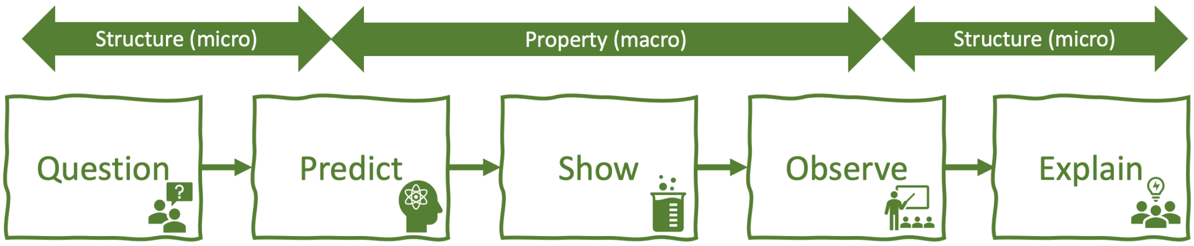


Figure 6.5: Building blocks of a demonstration with a POE task.

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).

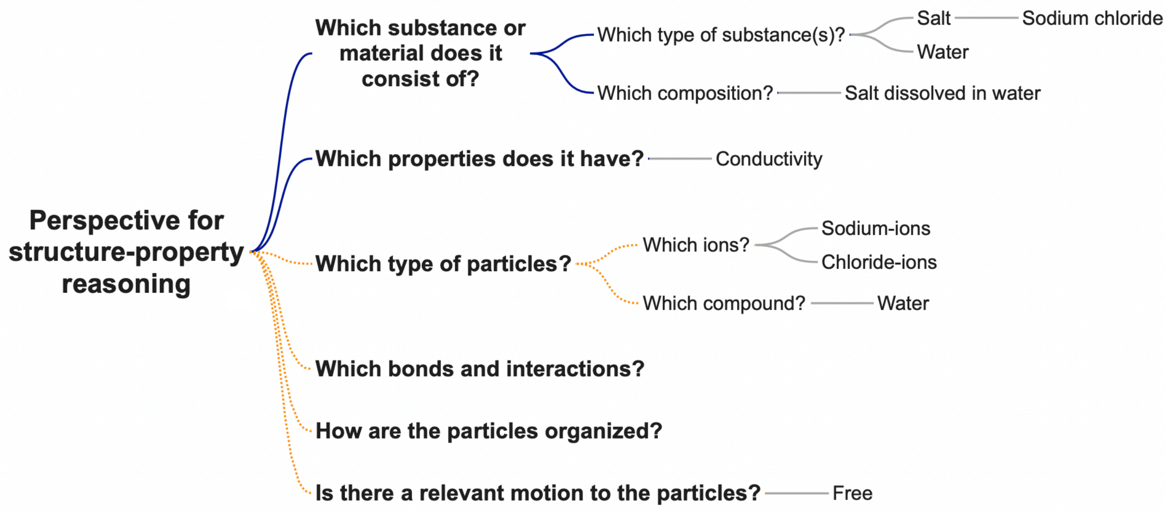
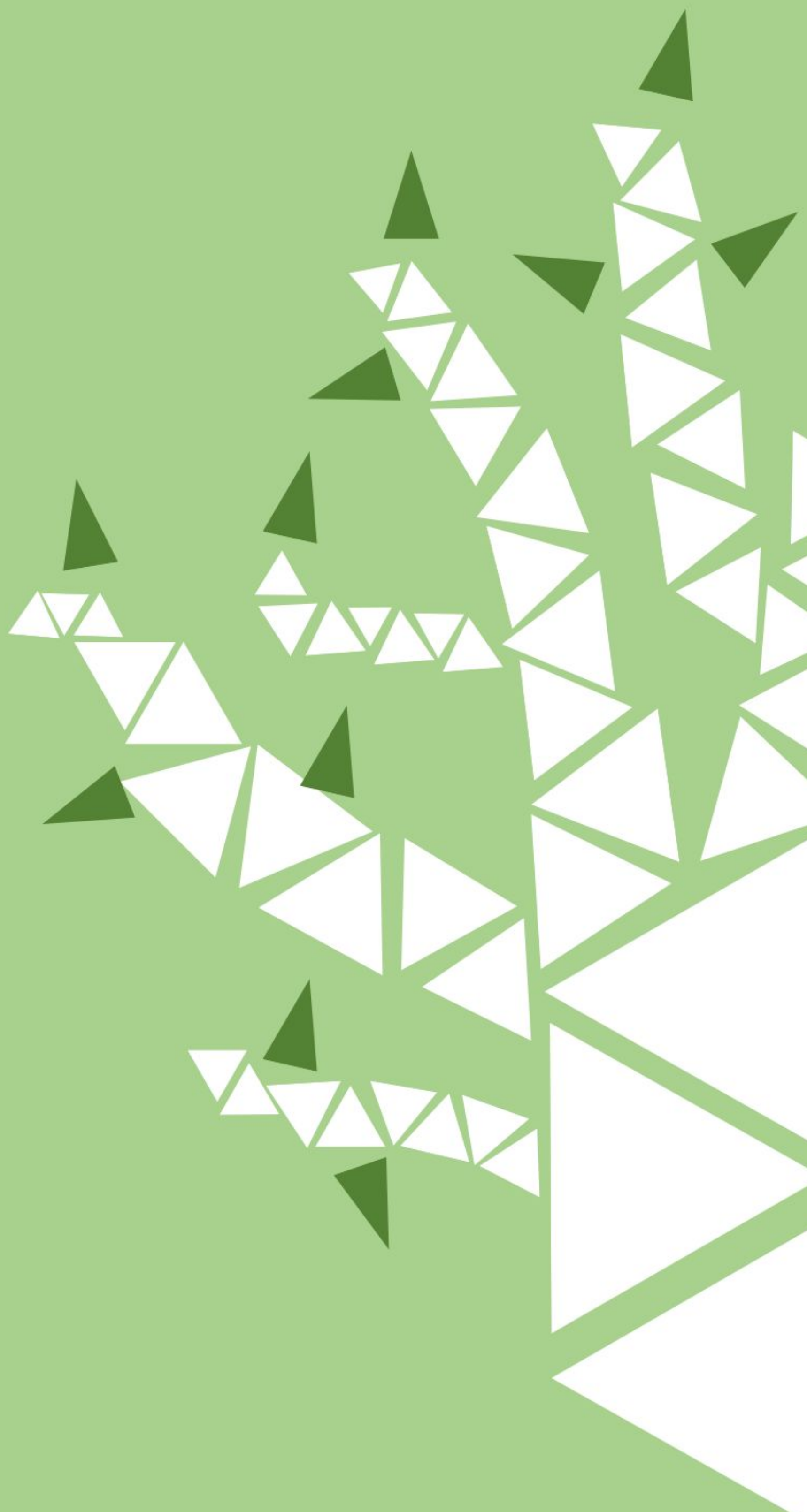


Figure 6.6: perspective for structure-property reasoning after the demonstration experiment 'conductivity'.



References

Abrahams, I., & Millar, R. (2008). Does Practical Work Really Work? A study of the effectiveness of practical work as a teaching and learning method in school science. *International Journal of Science Education*, *30*(17), 1945–1969. https://doi.org/10.1080/09500690701749305

Achieve. (2010). *Taking the Lead in Science Education: Forging Next-Generation Science Standards. September*, 1–66.

Adbo, K., & Taber, K. S. (2009). Learners' Mental Models of the Particle Nature of Matter: A study of 16-year-old Swedish science students. *International Journal of Science Education*, *31*(6), 757–786. https://doi.org/10.1080/09500690701799383

Atkins, P. (2010). Chemistry's core ideas. *Chemistry Education in New Zealand*, *2*(3), 8–12.

Becker, N., Stanford, C., Towns, M., & Cole, R. (2015). Translating across macroscopic, submicroscopic, and symbolic levels: the role of instructor facilitation in an inquiry-oriented physical chemistry class. *Chemistry Education Research and Practice*, *16*(4), 769–785. https://doi.org/10.1039/C5RP00064E

Ben-Zvi, R., Eylon, B.-S., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education*, *63*(1), 64. https://doi.org/10.1021/ed063p64

Ben-Zvi, R., Silberstein, J., & Mamlok, R. (1990). Macro-micro relationships: A key to the world of chemistry. In P. L. Lijnse, P. Licht, W. De Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 183–197). University of Utrecht, Centre for Science and Mathematics Education.

Bissonnette, S. A., Combs, E. D., Nagami, P. H., Byers, V., Fernandez, J., Le, D., Realin, J., Woodham, S., Smith, J. I., & Tanner, K. D. (2017). Using the Biology Card Sorting Task to Measure Changes in Conceptual Expertise during Postsecondary Biology Education. *CBE Life Sciences Education*, *16*(1). https://doi.org/10.1187/cbe.16-09-0273

Boer, E. De, Janssen, F. J. J. M., Van Driel, J. H., & Dam, M. (2019). Ontwikkeling van agency van docenten-in-opleiding: Een ecologisch perspectief. *Pedagogische Studiën*, *2019*(96), 354–377.

Borko, H., Jacobs, J., & Koellner, K. (2010). Contemporary approaches to teacher professional development. *International Encyclopedia of Education*, *7*(2), 548–556.

Bowen, C. W., & Phelps, A. J. (1997). Demonstration-Based Cooperative Testing in General Chemistry: A Broader Assessment-of-Learning Technique. *Journal of Chemical Education*, *74*(6), 715. https://doi.org/10.1021/ed074p715

Chandrasegaran, A. L., Treagust, D. F., & Mocerino, M. (2007). The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school students' ability to describe and explain chemical reactions using multiple levels of representation. *Chemistry Education Research and Practice*, *8*(3), 293–307. https://doi.org/10.1039/B7RP90006F

Chen, D. A., Hoople, G. D., Ledwith, N., Burlingame, E., Bush, S. D., & Scott, G. E. (2020). Exploring Faculty and Student Frameworks for Engineering Knowledge Using an Online Card Sorting Platform. *International Journal of Engineering Pedagogy (IJEP)*, *10*(1 SE-Papers), 62–81. https://doi.org/10.3991/ijep.v10i1.11336

Cheng, M. M. W., & Gilbert, J. K. (2017). Modelling students' visualisation of chemical reaction. *International Journal of Science Education*, 1–21. https://doi.org/10.1080/09500693.2017.1319989

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, *5*(2), 121–152. https://doi.org/10.1207/s15516709cog0502_2

Chittleborough, G., & Treagust, D. F. (2007). The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level. *Chemistry Education Research and Practice*, *8*(3), 274–292. https://doi.org/10.1039/B6RP90035F

Cito. (2018). *Central Exam Reports*. https://www.cito.nl/onderwijs/voortgezet-onderwijs/centrale-examens-voortgezet-onderwijs/tools-en-informatie-voor-docenten/examenverslagen/examenverslag-2018

Claesgens, J., Scalise, K., Wilson, M., & Stacy, A. (2009). Mapping student understanding in chemistry: The Perspectives of Chemists. *Science Education*, *93*(1), 56–85. https://doi.org/10.1002/sce.20292

College Board. (2022). *AP Chemistry Course and Exam Description*. https://apcentral.collegeboard.org/pdf/ap-chemistry-course-and-exam-description.pdf

Cooper, M. M. (2020). The Crosscutting Concepts: Critical Component or "Third Wheel" of Three-Dimensional Learning? *Journal of Chemical Education*, *97*(4), 903–909. https://doi.org/10.1021/acs.jchemed.9b01134

Cooper, M. M., Corley, L. M., & Underwood, S. M. (2013). An investigation of college chemistry students' understanding of structure-property relationships. *Journal of Research in Science Teaching*, *50*(6), 699–721. https://doi.org/10.1002/tea.21093

Coştu, B., Ayas, A., & Niaz, M. (2011). Investigating the effectiveness of a POE-based teaching activity on students' understanding of condensation. *Instructional Science*, *40*(1), 47–67. https://doi.org/10.1007/s11251-011-9169-2

Crouch, C., Fagen, A. P., Callan, J. P., & Mazur, E. (2004). Classroom demonstrations: Learning tools or entertainment? *American Journal of Physics*, *72*(6), 835.

Dam, M., & Janssen, F. (2021). Modularity in teacher professional development – building blocks for bridging everyday teaching practices and reform ideals centered around whole tasks. *Professional Development in Education*, 1–18. https://doi.org/10.1080/19415257.2021.1972435

Dam, M., Janssen, F. J. J. M., & Driel, J. H. van. (2013). Concept-contextonderwijs leren ontwerpen en uitvoeren – een onderwijsvernieuwing praktisch bruikbaar maken voor docenten. *Pedagogische Studiën*, *90*(2), 63–77.

Dangur, V., Avargil, S., Peskin, U., & Dori, Y. J. (2014). Learning quantum chemistry via a visual-conceptual approach: students' bidirectional textual and visual understanding. *Chemistry Education Research and Practice*, *15*(3), 297–310. https://doi.org/10.1039/C4RP00025K

de Graaf, A., Westbroek, H., & Janssen, F. (2018). A Practical Approach to Differentiated Instruction: How Biology Teachers Redesigned Their Genetics and Ecology Lessons. *Journal of Science Teacher Education*, 1–18. https://doi.org/10.1080/1046560X.2018.1523646

de Jong, O., Blonder, R., & Oversby, J. (2013). How to Balance Chemistry Education Between Observing Phenomena and Thinking in Models. In I. Eilks & A. Hofstein (Eds.), *Teaching Chemistry -- A Studybook: A Practical Guide and Textbook for Student Teachers, Teacher Trainees and Teachers* (pp. 97–126). SensePublishers. https://doi.org/10.1007/978-94-6209-140-5_4

de Jong, O., & Taber, K. S. (2015). The many faces of high school chemistry. *Handbook of Research on Science Education Volume II*, 457–480. https://doi.org/10.4324/9780203097267

de Vrind, E., Janssen, F. J. J. M., de Jong, N. H., van Driel, J. H., & Stoutjesdijk, E. T. (2019). Naar een praktische adaptieve aanpak voor spreekvaardigheidsonderwijs in moderne vreemde talen. *Pedagogische Studiën*, *96*(1), 15–39.
den Otter, M.-J., Dam, M., Juurlink, L. B. F., & Janssen, F. J. J. M. (2021). Two Design Principles for the Design of Demonstrations to Enhance Structure–Property Reasoning. *Education Sciences*, *11*(9), 504. https://doi.org/10.3390/educsci11090504
den Otter, M.-J., Juurlink, L. B. F., & Janssen, F. J. J. M. (2022). How to Assess Students' Structure–Property Reasoning? *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.2c00234
Dolfing, R., Bulte, A. M. W., Pilot, A., & Vermunt, J. D. (2011). Domain-Specific Expertise of Chemistry Teachers on Context-Based Education About Macro–Micro Thinking in Structure–Property Relations. *Research in Science Education*, *42*(3), 567–588. https://doi.org/10.1007/s11165-011-9211-z
Dori, Y. J., & Hameiri, M. (2003). Multidimensional analysis system for quantitative chemistry problems: Symbol, macro, micro, and process aspects. *Journal of Research in Science Teaching*, *40*(3), 278–302.
Doyle, W. (2006). Ecological Approaches to Classroom Management. In C. M. Evertson & C. S. Weinstein (Eds.), *Handbook of Classroom Management: Research, practice and contempory issues* (pp. 97–125). Lawrence Erlbaum. https://doi.org/10.4324/9780203874783.ch5
Doyle, W., & Ponder, G. A. (1977). The practicality ethic in teacher decision-making. *Interchange*, *8*(3), 1–12. https://doi.org/10.1007/BF01189290
Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: a review and analysis. *Studies in Science Education*, *47*(2), 123–182. https://doi.org/10.1080/03057267.2011.604476
Gabel, D. L. (1993). Use of the particle nature of matter in developing conceptual understanding. *Journal of Chemical Education*, *70*(3), 193. https://doi.org/10.1021/ed070p193
Gabel, D. L. (1999). Improving Teaching and Learning through Chemistry Education Research: A Look to the Future. *Journal of Chemical Education*, *76*(4), 548. https://doi.org/10.1021/ed076p548
Giere, R. N. (2010). *Scientific perspectivism.* University of Chicago Press.
Gilbert, J. K., & Treagust, D. F. (2009). Introduction: Macro, Submicro and Symbolic Representations and the Relationship Between Them: Key Models in Chemical Education. In J. K. Gilbert & D. Treagust (Eds.), *Multiple Representations in Chemical Education* (pp. 1–8). Springer Netherlands. https://doi.org/10.1007/978-1-4020-8872-8_1
Gillespie, R. J. (1997). The Great Ideas of Chemistry. *Journal of Chemical Education*, *74*(7). https://doi.org/10.1021/ed074p862
Gkitzia, V., Salta, K., & Tzougraki, C. (2011). Development and application of suitable criteria for the evaluation of chemical representations in school textbooks. *Chemistry Education Research and Practice*, *12*(1), 5–14. https://doi.org/10.1039/C1RP90003J
Goedhart, M. J. (2007). A New Perspective on the Structure of Chemistry as a Basis for the Undergraduate Curriculum. *Journal of Chemical Education*, *84*(6), 971. https://doi.org/10.1021/ed084p971
Gunstone, R. F., & Champagne, A. B. (1990). Promoting conceptual change in the laboratory. *The Student Laboratory and the Science Curriculum*, 159–182.
Harlen, W., Devès, R., Dyasi, H., de la Garza, G. F., Lèna, P., Millar, R., Reiss, M., Rowell, P., & Yu, W. (2015). Working with Big Ideas of Science Education. *Science Education Programme*.

Harrison, A. G., & Treagust, D. F. (2003). The Particulate Nature of Matter: Challenges in Understanding the Submicroscopic World. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical Education: Towards Research-based Practice* (pp. 189–212). Springer Netherlands. https://doi.org/10.1007/0-306-47977-X_9

Hilario, J. S. (2015). The Use of Predict-Observe-Explain-Explore (POEE) as a New Teaching Strategy in General Chemistry-Laboratory. *International Journal of Education and Research*, *3*(2), 37–48.

Hodson, D. (1993). Re-thinking Old Ways: Towards A More Critical Approach To Practical Work In School Science. *Studies in Science Education*, *22*(1), 85–142. https://doi.org/10.1080/03057269308560022

Hodson, D. (2014). Learning Science, Learning about Science, Doing Science: Different goals demand different learning methods. *International Journal of Science Education*, *36*(15), 2534–2553. https://doi.org/10.1080/09500693.2014.899722

Hofstein, A. (2004). The Laboratory in Chemistry Education: Thirty Years of Experience with Developments, Implementation, and Research. *Chemistry Education Research and Practice*, *5*(3), 247–264. https://doi.org/10.1039/B4RP90027H

Hofstein, A. (2017). The Role of Laboratory in Science Teaching and Learning. In *Science Education*. https://doi.org/10.1007/978-94-6300-749-8_26

Hofstein, A., & Lunetta, V. N. (2004). The Laboratory in Science Education: Foundations for the Twenty-First Century. *Science Education*, *88*(1), 28–54. https://doi.org/10.1002/sce.10106

Irby, S. M., Phu, A. L., Borda, E. J., Haskell, T. R., Steed, N., & Meyer, Z. (2016). Use of a card sort task to assess students' ability to coordinate three levels of representation in chemistry. *Education in Chemistry*, *17*(2), 337–352. https://doi.org/10.1039/C5RP00150A

Janssen, F. J. J. M., Grossman, P., & Westbroek, H. B. (2015). Facilitating decomposition and recomposition in practice-based teacher education: The power of modularity. *Teaching and Teacher Education*, *51*, 137–146. https://doi.org/10.1016/J.TATE.2015.06.009

Janssen, F. J. J. M., Hulshof, H., & van Veen, K. (2019). *Wat is echt de moeite waard om te onderwijzen? Een perspectiefgerichte benadering*. ICLON, Leiden University.

Janssen, F. J. J. M., Westbroek, H. B., & Doyle, W. (2014). The Practical Turn in Teacher Education. *Journal of Teacher Education*, *65*(3), 195–206. https://doi.org/10.1177/0022487113518584

Janssen, F. J. J. M., Westbroek, H. B., & Doyle, W. (2015). Practicality Studies: How to Move From What Works in Principle to What Works in Practice. *The Journal of the Learning Sciences*, *24*(March), 176–186. https://doi.org/10.1080/10508406.2014.954751

Janssen, F. J. J. M., Westbroek, H. B., Doyle, W., & van Driel, J. H. (2013). How to make innovations practical. *Teachers College Record*, *115*(7), 1–42.

Janssen, F. J. J. M., Westbroek, H. B., Landa, I., Ploeg, B. van der, & Muijlwijk-Koezen, J. van. (2020). Perspectives for Teaching About How Science Works. In W. McComas (Ed.), *Nature of Science in Science Instruction* (pp. 253–269). Springer International Publishing.

Janssen, F. J. J. M., Westbroek, H. B., & van Driel, J. H. (2014). How to make guided discovery learning practical for student teachers. *Instructional Science*, *42*(1), 67–90. https://doi.org/10.1007/s11251-013-9296-z

Janssen, F. J. J. M., in preparation. Perspectieven als fundament voor leerplanontwikkeling.

Jensen, W. B. (1998). Logic, History, and the Chemistry Textbook: I. Does Chemistry Have a Logical Structure? *Journal of Chemical Education*, *75*(6), 679. https://doi.org/10.1021/ed075p679

Jin, H., Mikeska, J. N., Hokayem, H., & Mavronikolas, E. (2019). Toward coherence in curriculum, instruction, and assessment: A review of learning progression literature. *Science Education*, *103*(5), 1206–1234.

Johnstone, A. H. (1982). Macro- and Micro-Chemistry. *School Science Review*, *64*, 377–379.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*(2), 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Johnstone, A. H. (2000). Teaching of Chemistry - Logical or Psychological? *Chemistry Education Research and Practice*, *1*(1), 9–15. https://doi.org/10.1039/A9RP90001B

Kala, N., Yaman, F., & Ayas, A. (2013). The Effectiveness of Predict-Observe-Explain Technique in Probing Students' Understanding about Acid-Base Chemistry: a Case for the Concepts Of pH, pOH, and Strength. *International Journal of Science and Mathematics Education*, *11*(3), 555–574. https://doi.org/10.1007/s10763-012-9354-z

Karamustafaoğlu, S., & Mamlok-Naaman, R. (2015). Understanding Electrochemistry Concepts using the Predict-Observe-Explain Strategy. *EURASIA Journal of Mathematics, Science & Technology Education*, *11*(5), 923–936. https://doi.org/10.12973/eurasia.2015.1364a

Kearney, M., Treagust, D. F., Yeo, S., & Zadnik, M. G. (2001). Student and Teacher Perceptions of the Use of Multimedia Supported Predict–Observe–Explain Tasks to Probe Understanding. *Research in Science Education*, *31*(4), 589–615. https://doi.org/10.1023/A:1013106209449

Kelly, R. M., Barrera, J. H., & Mohamed, S. C. (2010). An Analysis of Undergraduate General Chemistry Students' Misconceptions of the Submicroscopic Level of Precipitation Reactions. *Journal of Chemical Education*, *87*(1), 113–118. https://doi.org/10.1021/ed800011a

Kelly, R. M., & Jones, L. L. (2007). Exploring How Different Features of Animations of Sodium Chloride Dissolution Affect Students' Explanations. *Journal of Science Education and Technology*, *16*(5), 413–429. https://doi.org/10.1007/s10956-007-9065-3

Kelly, R. M., & Jones, L. L. (2008). Investigating Students' Ability To Transfer Ideas Learned from Molecular Animations of the Dissolution Process. *Journal of Chemical Education*, *85*(2), 303. https://doi.org/10.1021/ed085p303

Kibirige, I., Osodo, J., & Tlala, K. M. (2014). The effect of predict-observe-explain strategy on learners' misconceptions about dissolved salts. *Mediterranean Journal of Social Sciences*, *5*(4), 300–310. https://doi.org/10.5901/mjss.2014.v5n4p300

Kohn, K. P., Underwood, S. M., Cooper, M. M., & Loertscher, J. (2018). Connecting Structure–Property and Structure–Function Relationships across the Disciplines of Chemistry and Biology: Exploring Student Perceptions. *CBE—Life Sciences Education*, *17*(2). https://doi.org/10.1187/cbe.18-01-0004

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*(9), 949–968. https://doi.org/10.1002/(SICI)1098-2736(199711)34:9<949::AID-TEA7>3.0.CO;2-U

Kozma, R. B., Russell, J. W., Jones, T., Wykoff, J., Marx, N., & Davis, J. (1997). Use of Simultaneous-Synchronized Macroscopic, Microscopic, and Symbolic Representations to Enhance the Teaching and Learning of Chemical Concepts. *Journal of Chemical Education*, *74*(3), 330. https://doi.org/10.1021/ed074p330

Krieter, F. E., Julius, R. W., Tanner, K. D., Bush, S. D., & Scott, G. E. (2016). Thinking Like a Chemist: Development of a Chemistry Card-Sorting Task to Probe Conceptual Expertise. *Journal of Chemical Education*, *93*(5), 811–820. https://doi.org/10.1021/acs.jchemed.5b00992

Lambiotte, J. G., Dansereau, D. F., Cross, D. R., & Reynolds, S. B. (1989). Multirelational semantic maps. *Educational Psychology Review*, *1*(4), 331–367. https://doi.org/10.1007/BF01320098

Landa, I., Westbroek, H. B., Janssen, F. J. J. M., Muijlwijk-Koezen, J. van, & Meeter, M. M. (2020). Scientific Perspectivism in Secondary-School Chemistry Education. *Science & Education*, *29*(5), 1361–1388. https://doi.org/10.1007/s11191-020-00145-3

Liew, C.-W., & Treagust, D. F. (1998). *The Effectiveness of Predict-Observe-Explain Tasks in Diagnosing Students' Understanding of Science and in Identifying Their Levels of Achievement.*

Logar, A., & Ferk Savec, V. (2011). Students' Hands-on Experimental Work School Chemistry. *Acta Chimica Slovenica*, *58*(4), 866–875.

Maeyer, J., & Talanquer, V. (2010). The Role of Intuitive Heuristics in Students' Thinking: Ranking Chemical Substances. *Science Education*, *94*(6), 963–984. https://doi.org/10.1002/sce.20397

Mahaffy, P. (2004). The Future Shape of Chemistry Education. *Chemistry Education Research and Practice*, *5*(3), 229–245. https://doi.org/10.1039/B4RP90026J

Mahaffy, P. (2006). Moving Chemistry Education into 3D: A Tetrahedral Metaphor for Understanding Chemistry. Union Carbide Award for Chemical Education. *Journal of Chemical Education*, *83*(1), 49. https://doi.org/10.1021/ed083p49

Mattox, A. C., Reisner, B. A., & Rickey, D. (2006). What happens when chemical compounds are added to water? An introduction to the model-observe-reflect-explain (MORE) thinking frame. *Journal of Chemical Education*, *83*(4), 622. https://doi.org/10.1021/ed083p622

McComas, W. F. (2014). Benchmarks for Science Literacy. In *The Language of Science Education* (pp. 12–12). SensePublishers. https://doi.org/10.1007/978-94-6209-497-0_11

McKee, E., Williamson, V. M., & Ruebush, L. E. (2007). Effects of a Demonstration Laboratory on Student Learning. *Journal of Science Education and Technology*, *16*(5), 395–400. https://doi.org/10.1007/s10956-007-9064-4

Meijer, M. R. (2011). Macro-meso-micro thinking with structure-property relations for chemistry. An explorative design-based study. In *Faculty of Sciences, Freudenthal Institute* (Issue FIsme Scientific Library 65). Utrecht University.

Meijer, M. R., Bulte, A. M. W., & Pilot, A. (2013). Macro–Micro Thinking with Structure–Property Relations: Integrating 'Meso-levels' in Secondary Education. In G. Tsaparlis & H. Sevian (Eds.), *Concepts of Matter in Science Education* (pp. 419–436). Springer. https://doi.org/10.1007/978-94-007-5914-5_20

Meyer, L. S., Panee, D., Schmidt, S., & Nozawa, F. (2003). Using Demonstrations to Promote Student Comprehension in Chemistry. *Journal of Chemical Education*, *80*(4), 431. https://doi.org/10.1021/ed080p431

National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. The National Academies Press. https://doi.org/10.17226/13165

National Research Council. (2013). *Next Generation Science Standards: For States, By States*. The National Academies Press. https://doi.org/10.17226/18290

Nokes, T. J., Schunn, C. D., & Chi, M. T. H. (2010). Problem Solving and Human Expertise. In *International Encyclopedia of Education*. https://doi.org/10.1016/B978-0-08-044894-7.00486-3

Novak, J. D., & Gowin, D. B. (1984). *Learning how to learn* (p. 199). Cambridge University Press. https://doi.org/10.1037/e362742004-020

Nyachwaya, J. M., Mohamed, A.-R., Roehrig, G. H., Wood, N. B., Kern, A. L., & Schneider, J. L. (2011). The Development of an Open-Ended Drawing Tool: an Alternative Diagnostic Tool for Assessing Students' Understanding of the Particulate Nature of Matter. *Chemistry Education Research and Practice*, *12*(2), 121–132. https://doi.org/10.1039/C1RP90017J

Ohlsson, S. (2011). *Deep learning: How the mind overrides experience*. Cambridge University Press.

Ottevanger, W., Oorschot, F., Spek, W., Boerwinkel, D. J., Eijkelhof, H., de Vries, M., van der Hoeven, M., & Kuiper, W. (2014). *Kennisbasis natuurwetenschappen en technologie voor de onderbouw vo: een richtinggevend leerplankader.*

Paterson, D. J. (2019). Design and Evaluation of Integrated Instructions in Secondary-Level Chemistry Practical Work. *Journal of Chemical Education*, *96*(11), 2510–2517. https://doi.org/10.1021/acs.jchemed.9b00194

Pierce, D. T., & Pierce, T. W. (2007). Effective Use of Demonstration Assessments in the Classroom Relative to Laboratory Topics. *Journal of Chemical Education*, *84*(7), 1150. https://doi.org/10.1021/ed084p1150

Pollock, J. L. (2006). *Thinking about acting: Logical foundations for rational decision making.* Oxford University Press.

Pols, C. F. J. (2023). *Development of a teaching-learning sequence for scientific inquiry through argumentation in secondary physics education.* [TU Delft]. https://doi.org/https://doi.org/10.4233/uuid:df26ce2c-4b0f-41ee-93ff-301aa82457c3

Ramsey, L. L., Walczyk, J., Deese, W. C., & Eddy, D. (2000). Using Demonstration Assessments to Improve Learning. *Journal of Chemical Education*, *77*(11), 1511. https://doi.org/10.1021/ed077p1511

Reid, N. (2021). *The Johnstone Triangle*. The Royal Society of Chemistry. https://doi.org/10.1039/9781839163661

Reigeluth, C. M. (2007). Order, first step to mastery: An introduction to sequencing in instructional design. *In Order to Learn: How the Sequence of Topics Influences Learning*, 19–40.

Roth, W.-M., Mcrobbie, C. J., Lucas, K. B., & Boutonné, S. (1997). Why May Students Fail to Learn from Demonstrations? A Social Practice Perspective on Learning in Physics. *Journal of Research in Science Teaching*, *34*(5), 509–533. https://doi.org/10.1002/(SICI)1098-2736(199705)34:5<509::AID-TEA6>3.0.CO;2-U

Ruiz-Primo, M. A., & Shavelson, R. J. (1996). Problems and Issues in the Use of Concept Maps in Science Assessment. *Journal of Research in Science Teaching*, *33*(6), 569–600. https://doi.org/10.1002/(SICI)1098-2736(199608)33:6<569::AID-TEA1>3.0.CO;2-M

Sevian, H., & Talanquer, V. (2014). Rethinking chemistry: a learning progression on chemical thinking. *Chemistry Education Research and Practice*, *15*(1), 10–23. https://doi.org/10.1039/C3RP00111C

Shavelson, R. J., Young, D. B., Ayala, C. C., Brandon, P. R., Furtak, E. M., Ruiz-Primo, M. A., Tomita, M. K., & Yin, Y. (2008). On the impact of curriculum-embedded formative assessment on learning: A collaboration between curriculum and assessment developers. *Applied Measurement in Education*, *21*(4), 295–314. https://doi.org/10.1080/08957340802347647

Shiland, T. W. (1999). Constructivism: The Implications for Laboratory Work. *Journal of Chemical Education*, *76*(1), 107. https://doi.org/10.1021/ed076p107

Sjöström, J. (2013). Towards Bildung-Oriented Chemistry Education. *Science and Education*. https://doi.org/10.1007/s11191-011-9401-0

Sluijsmans, D., Kneyber, R., & Warrink, E. (2016). *Toetsrevolutie: Naar een feedbackcultuur in het voortgezet onderwijs*. Phronese.

Smith, C. L., Wiser, M., Anderson, C. W., & Krajcik, J. (2006). Implications of Research on Children's Learning for Standards and Assessment: A Proposed Learning Progression for Matter and the Atomic-Molecular Theory. *Measurement: Interdisciplinary Research & Perspective*, *4*(1–2), 1–98. https://doi.org/10.1080/15366367.2006.9678570

Smith, J. I., Combs, E. D., Nagami, P. H., Alto, V. M., Goh, H. G., Gourdet, M. A. A., Hough, C. M., Nickell, A. E., Peer, A. G., Coley, J. D., & Tanner, K. D. (2013). Development of the biology card sorting task to measure conceptual expertise in biology. *CBE Life Sciences Education*, *12*(4), 628–644. https://doi.org/10.1187/cbe.13-05-0096

Smith, K. C., Edionwe, E., & Michel, B. (2010). Conductimetric titrations: A predict-observe-explain activity for general chemistry. *Journal of Chemical Education*, *87*(11), 1217–1221. https://doi.org/10.1021/ed100538q

Stowe, R. L., Herrington, D. G., McKay, R. L., & Cooper, M. M. (2019). The Impact of Core-Idea Centered Instruction on High School Students' Understanding of Structure–Property Relationships. *Journal of Chemical Education*, *96*(7), 1327–1340. https://doi.org/10.1021/acs.jchemed.9b00111

Surma, T., Vanhoyweghen, K., Sluijsmans, D., Camp, G., Muijs, D., & Kirschner, P. A. (2019). *Wijze lessen: twaalf bouwstenen voor effectieve didactiek*. Ten Brink Uitgevers.

Syllabus Centraal Examen, Scheikunde vwo (Vol. 2016, Issue December 2011). (2016).

Taber, K. S. (2013). Revisiting the chemistry triplet: drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice*, *14*(2), 156–168. https://doi.org/10.1039/C3RP00012E

Taconis, R. (1995). *Understanding based problem solving: Towards qualification oriented teaching and learning in physics education = (Probleemoplossen op basis van begrip)*. https://doi.org/http://dx.doi.org/10.6100/IR439275

Talanquer, V. (2008). Students' predictions about the sensory properties of chemical compounds: additive versus emergent frameworks. *Science Education*, *92*(1), 96–114. https://doi.org/10.1002/sce.20235

Talanquer, V. (2011). Macro, Submicro, and Symbolic: The many faces of the chemistry "triplet." *International Journal of Science Education*, *33*(2), 179–195. https://doi.org/10.1080/09500690903386435

Talanquer, V. (2014). Chemistry Education: Ten Heuristics To Tame. *Journal of Chemical Education*, *91*(8), 1091–1097. https://doi.org/10.1021/ed4008765

Talanquer, V. (2018). Progressions in reasoning about structure–property relationships. *Chemistry Education Research and Practice*. https://doi.org/10.1039/C7RP00187H

Talanquer, V., & Pollard, J. (2010). Let's teach how we think instead of what we know. *Chemistry Education Research and Practice*, *11*(2), 74–83. https://doi.org/10.1039/C005349J

Thagard, P. (2012). *The cognitive science of science: Explanation, discovery, and conceptual change*. Mit Press.

Thomas, G. P. (2017). 'Triangulation:' an expression for stimulating metacognitive reflection regarding the use of 'triplet' representations for chemistry learning. *Chemistry Education Research and Practice*, *18*(4), 533–548. https://doi.org/10.1039/C6RP00227G

Tien, L. T., Teichert, M. A., & Rickey, D. (2007). Effectiveness of a MORE Laboratory Module in Prompting Students To Revise Their Molecular-Level Ideas about Solutions. *Journal of Chemical Education*, *84*(1), 175. https://doi.org/10.1021/ed084p175

Tienken, C. H., Goldberg, S., & Dirocco, D. (2009). Questioning the questions. *Kappa Delta Pi Record*, *46*(1), 39–43.
Treagust, D., Chittleborough, G., & Mamiala, T. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353–1368. https://doi.org/10.1080/0950069032000070306
Treagust, D. F. (2007). General instructional methods and strategies. In *Handbook of research on science education* (pp. 373–391).
Treagust, D. F., & Tsui, C. (2014). General instructional methods and strategies. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of Research on Science Education, Volume 2* (pp. 303–320). Routledge.
Tsaparlis, G. (2009). *Learning at the Macro Level: The Role of Practical Work* (pp. 109–136). https://doi.org/10.1007/978-1-4020-8872-8_6
van de Pol, J., Volman, M., & Beishuizen, J. (2010). Scaffolding in teacher-student interaction: A decade of research. In *Educational Psychology Review*. https://doi.org/10.1007/s10648-010-9127-6
White, R., & Gunstone, R. (1992). *Probing understanding*. The Falmer Press.
Wiliam, D. (2020). Research into practice: The case of classroom formative assessment. In *Getting Evidence into Education* (pp. 119–135). Routledge.
William, D. (2011). Formative assessment: Definitions and relationships. *Studies in Educational Evaluation*, *37*(1), 3–14.
Wimsatt, W. C. (2007). *Re-Engineering Philosophy for Limited Beings*. Cambridge: Havard University Press.
Yaman, F., & Ayas, A. (2015). Assessing changes in high school students' conceptual understanding through concept maps before and after the computer-based predict–observe–explain (CB-POE) tasks on acid–base chemistry at the secondary level. *Chemistry Education Research and Practice*, *16*(4), 843–855. https://doi.org/10.1039/C5RP00088B
Zakiyah, I., Widodo, W., & Tukiran, T. (2019). Implementation of Predict-Observe-Explain (POE) Strategy to Reduce Misconception in Thermochemistry. *International Journal for Educational and Vocational Studies*, *1*(7), 754–759. https://doi.org/10.29103/ijevs.v1i7.1757
Zakiyah, I., Widodo, W., & Tukiran, T. (2020). Profile of student's conception in implementation of predict-observe-explain (POE) strategy on thermochemistry concept. *Journal of Physics: Conference Series*, *1567*(3). https://doi.org/10.1088/1742-6596/1567/3/032104

Appendices

Appendix 1: The SPR Instrument

Cards for the sorting task

Table A.1: *Ideal sorts for the card-sorting task. The columns are the structure aspects each card contains, the rows represent the property aspects of each card. The numbers in the cells refer to the specific sample problem card. The design is based on the model of Krieter et al. (2016).*

		Structure aspects (deep features)			
		Molecular/atomic Bonding	Molecular/atomic Lattice	Ionic Bonding/Lattice	Metallic Bonding/Lattice
Property aspects (surface features)	Melting point	8	5	14	3
	Conductivity	11	7	2	12
	Toughness	16	13	4	10
	Solubility	1	6	9	15

Figure A.1: *used card set in the unframed and framed sorting task.*

Polyethylene (~C=C-C=C-C~)n is a polymer that can conduct electricity. The applications of such polymers are numerous, for example wafer-thin displays. Explain how it is possible that polyethylene can conduct current. 11	Graphite is composed of carbon atoms and can conduct current. Therefore, it is used in electrodes in batteries. Explain how graphite can conduct current. 7	Table salt (sodium chloride) can conduct electricity in a liquid state only. Solid kitchen salt cannot do this. Explain this conductivity of table salt. 2	In smartphones, gold is used as a material for contact points on the circuit board. Explain why gold is used in these contact points. 12
Water striders are small insects that can walk on water. The water looks like a glass plate to these insects. But if you secretly add some soap to the water they probably drown. Explain. 16	A pencil, like a diamond, consists of carbon. However, you can cut a pencil with a simple iron pencil sharpener and you have to cut a diamond with another diamond. Diamond is the hardest material in the world. Explain this. 13	Concrete is created because cement (Ca_3SiO_5) absorbs crystal water. Concrete is non-combustible, but after a fierce fire, the concrete skeleton must still be broken down, because all its strength has disappeared. Explain. 4	Stainless steel contains iron and carbon. Explain why stainless steel is harder than pure iron. 10
Acrylonitrile (C_2H_3CN) is a liquid and it is used as a raw material to make a polymer for toy bricks. The melting point of acrylonitrile is 191K. Explain why acrylonitrile is a liquid at room temperature. 8	The glass of your smartphone contains crystalline silicon dioxide (SiO_2). Compared to diphosphorus pentaoxide (P_2O_5), SiO_2 has a high melting point, namely 1720°C. Explain the high melting point of SiO_2. 5	Copper (II) sulphate is a white solid. When it has absorbed crystal water, the color has turned blue. Blue copper (II) sulphate has a lower melting point than white copper (II) sulphate. Explain this. 14	Molten metals are easily miscible. An alloy is formed. For example, bronze can be formed by mixing copper and tin. However, bronze has a lower melting point than pure copper. Explain this. 3
A blotch of crude oil at sea is difficult to remove. Oil is not soluble in water. You can burn it or finely disperse it and then hope it breaks down slowly. Explain why petroleum is not soluble in water. 1	Quartz is a form of silicon dioxide (SiO_2) that is commonly found in the earth's crust (12% by volume). You can find quartz in sand, for example. Silicon dioxide is a crystalline powder that is virtually insoluble in water. Explain this. 6	Water can be contaminated with heavy metals. These metals are dissolved in water as charged particles. You can remove them by precipitating them with saline solutions. Explain how this works. 9	Dissolving gold in water is very difficult. You can dissolve gold in royal water (a mixture of hydrochloric acid and nitric acid). In this way George de Hevesy hid two Nobel medals from the Nazis. After the war he had the gold beaten down again and the Nobel Foundation had two new medals beaten from it for the original owners. Explain why gold does not dissolve in ordinary water. 15

Work sheets and instruction

Date: ____________________ Code: ______________

Sorting task A

In front of you are 16 problems. Read the problems thoroughly, but do not try to solve them. Arrange (sort) these problems in such a way that the problems - which need a **similar underlying chemical concept** to solve the problem – are grouped together.
An example: you have the following problem - Sugar is made of 12 C atoms, 22 hydrogen atoms and 11 oxygen atoms. What percentage of the mass consists of carbon atoms? You could sort this problem with the chemical concept mole, but also with mass ratios.

Make at least 2 groups and no more than 15 groups. A problem (a card) cannot be part of more than one group at the same time. There are different ways to sort these problems.

When you are finished, **give the groups formed by you a name** that describes the group best for you.

Give each group you have created a name. Number the groups. Write down the numbers of the cards you put in that group after the group name.

Example:

1. Keep in fridge - 3, 5, 7
2. Store in cupboard - 1, 2, 4, 6
3. ….

Attention, have you sorted 16 cards?

Date: ______________________ Code:_______________

Sorting task B

In front of you are the same 16 problems as in the previous task. I would like to ask you again to sort these problems. However, I will now give you the categories in which you can sort these problems:

- Molecular compounds - bonding
- Molecular compounds - lattices
- Salts - ionic bonding / ionic lattice
- Metals - metallic bonding / metallic lattice

A problem (one card) cannot be part of more than one group at the same time. Eventually, each problem must be placed in one of the four categories.

Write down the numbers of the cards in the boxes. **Attention, have you sorted 16 cards?**

Molecular compounds **Bonding**	**Molecular compounds** **Lattices**	**Salts** **ionic bonding / lattice**	**Metals** **metallic bonding / lattice**

Ready? Now collect all 16 cards and slide them back into the paper clip.

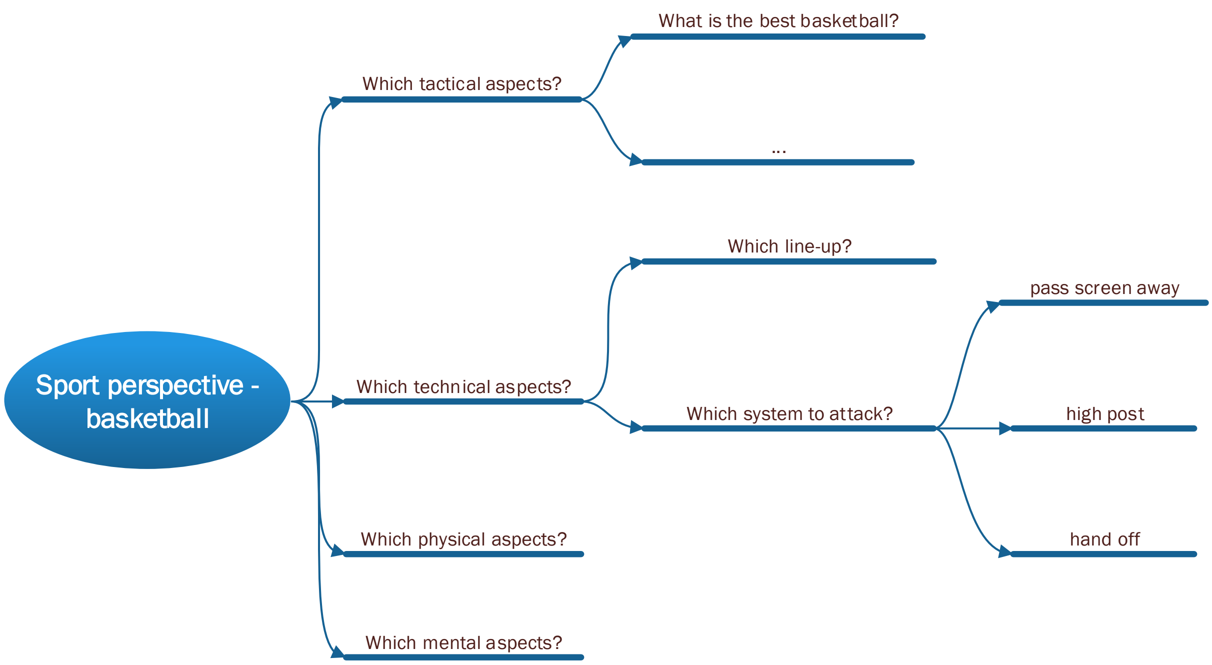
Perspective map – task C

In front of you are the questions of the perspective for structure-property reasoning. A **perspective** is a way of looking at, thinking about, and working with problems. An example is the sports perspective. You can look at your sport, for example basketball, from a technical perspective (what is the best basketball? what are the best shoes?), a tactical perspective (which setup? Which system?) etc. By answering the questions from for example the tactical perspective, you can solve a problem within basketball. The better you get, the more elaborate your perspective is and the better (and faster) you can solve a problem.

Within chemistry you can also distinguish several perspectives including the perspective for structure-property reasoning and the energy perspective. So, you use such a perspective to question your chemical problem and consequently solve this problem.

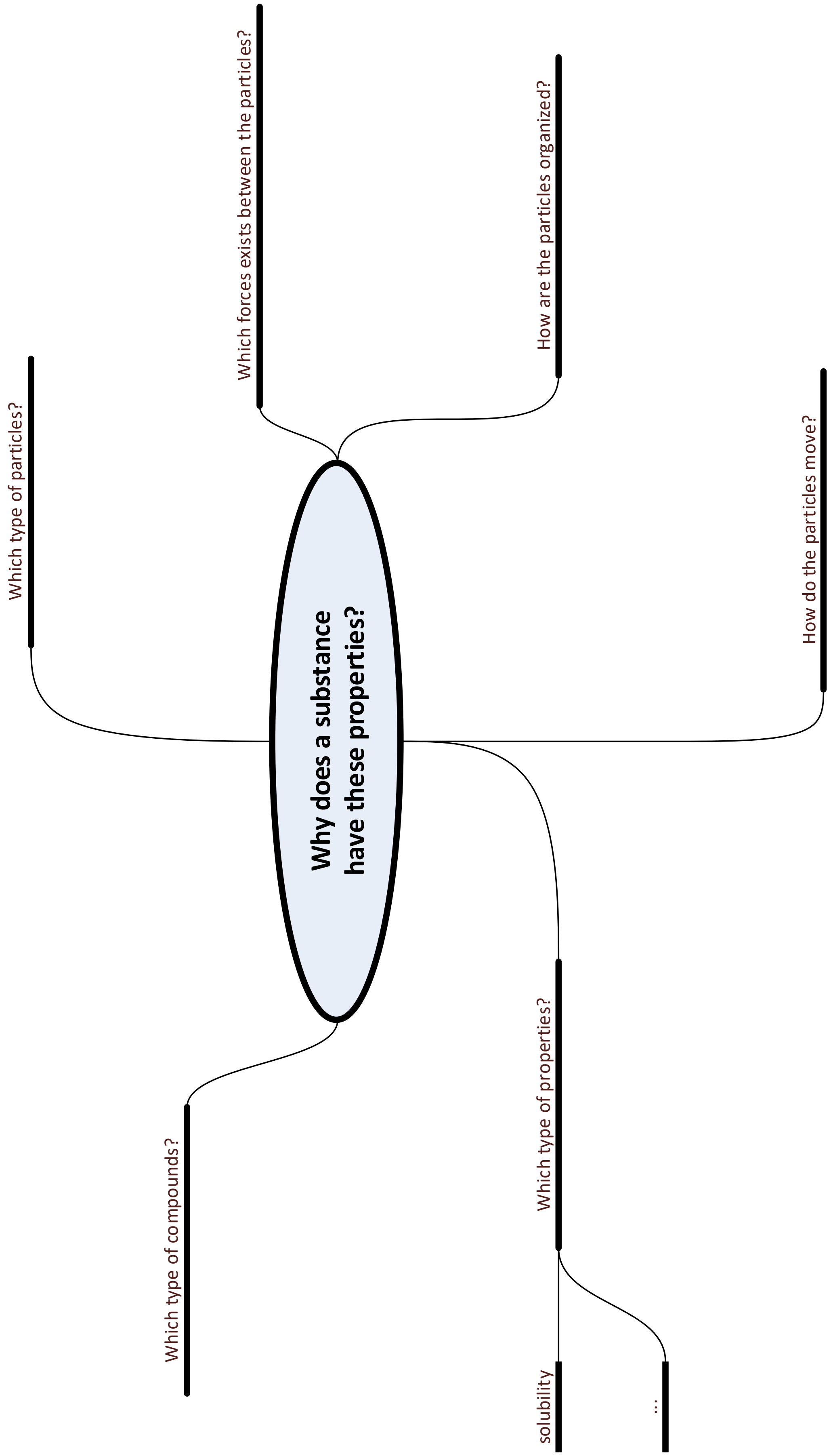
Complete this initial perspective for structure-property reasoning by answering the questions with the appropriate chemical concepts. You may give as many answers as necessary. You are also allowed to create a hierarchy if necessary.

An example: A question in the tactical perspective is 'with which attack system can we win the basketball game' – possible answers are: pass-screen-away; high post; hand-over; etc.



Date: _______________ Code:_________

C


Why does a substance have these properties?
Which type of particles?
Which forces exists between the particles?
How are the particles organized?
How do the particles move?
Which type of compounds?
Which type of properties?
solubility
…

Perspective map – task D

In front of you is the beginning of the perspective for structure-property reasoning. Again, I want to ask you to complete this perspective for structure-property reasoning, but this time I want you to use **the concepts below**. You are allowed to create a **hierarchy** if necessary.

amorph	crystal lattice with impurities	solubility
atomic bond	mixture	melting / boiling point
atomic lattice	metal	fast / slow
dipole-dipole interaction	metal atoms	conductivity
hardness	metal bond	Van der Waals force
intermolecular interaction	metal lattice	free / bound
ionic bond	molecular compound	hydrogen bond
ions	molecules	salt
ionic lattice	molecular lattice	pure crystal lattice
crystal lattice	non-metal atoms	pure compound

This was the last task. Thank you for filling it in.

Appendix 2: Demonstration Protocols for Teachers

In Tables A2–A4, the demonstration protocols for the demonstration experiments are provided. In these protocols, for each property, an accompanying demonstration is described. The structure model concept which could be modeled by the students is also indicated. These demonstrations fit in the "observe" phase in the POE task as described in "3.3. Overview of the Lesson Series".

For each demonstration, the properties of several substances of that group are demonstrated. The choice of substances depends on what is available at school to properly demonstrate the properties. The substances mentioned in the demonstration protocols are therefore only indicative.

Table A2. *Demonstration protocol for metals.*

Property	Demonstration Instructions	Structure Model
Appearance	The teacher shows different metals (sheets, rods, etc.), such as iron, copper, lead, zinc. The teacher polishes the metal plates and shows the results.	n/a
Phase at room temperature	The teacher shows the metal plates and asks about the phase.	Metallic lattice
Strength	The teacher works the metal plates with a hammer.	Metallic lattice
Malleability	The teacher tries to bend the metal plates.	Metallic lattice
Melting point	The teacher holds the metal lead (mp = 327 K) or zinc (mp = 420 K) in a blue flame. The metal becomes soft. Next, the teacher holds the metals copper (mp = 1083 K) and/or iron (mp = 1535 K) in the flame. These melting points are above the temperature (1273 K) of the blue flame and will not soften.	Metallic bond
Conductivity of electricity	The teacher builds the setup to measure current conductivity: lamp, voltage source, wires and, if necessary, adds a conductivity meter. The teacher measures the current conductivity of various metals.	Metallic lattice, metallic bond
Behavior when heated	The teacher keeps a ribbon of magnesium in the flame. The teacher sprinkles some metal powders (such as iron or magnesium) through the flame.	n/a

Table A3. *Demonstration protocol for salts.*

Property	**Demonstration**	**Structure Model**
Appearance	The teacher shows different salts, such as sodium chloride, sodium nitrate, iron (III) nitrate, copper sulfate.	n/a
Strength/malleability	The teacher hits lump of salt with a hammer. At the school of the first author, the assistant found an old bottle with big lumps of iron (III) nitrate, which was suitable to hit it with a hammer.	Lattice with uneven particles
Phase at room temperature	The teacher shows different salts with attention to the phase at room temperature.	Lattice with strong bonds
Melting point	The teacher heats a salt such as sodium chloride and iron (III) nitrate.	Lattice with strong bonds
Conductivity of electricity	The teacher tests a solid salt, a liquid salt and a dissolved salt for conductivity.	The particles are charged and stuck in a grid

Table A4. *Demonstration protocol for molecular compounds.*

Property	Demonstration	Structure Model
Appearance	The teacher shows different molecular substances, such as sugar, glucose, ethanol, water, methane (burning), oil.	n/a
Conductivity of electricity	The teacher makes a sugar solution and an ethanol solution and tests the current conduction. The teacher also tests the conductivity of water and oil.	No charged particles: molecules
Behavior when heated (sugar)	The teacher heats sugar until it caramelizes and burns.	The molecules consist of atoms The atomic bond is very strong
Phase at room temperature	The teacher shows liquid and gaseous molecular substances such as water, CO_2 in soft drinks, methane gas, ethanol, acetone.	Weak bond between the molecules
Boiling point	The teacher boils water and ethanol and uses a sensor to measure the temperature. The students search the boiling points of the liquids and search for links.	Van der Waals bond and hydrogen bond
Solubility	The teacher tries to dissolve various substances, such as sugar, oil in water. Two groups emerge.	Van der Waals bond and hydrogen bond
Behavior when heated	The teacher heats up sugar and carbon in a rustling flame.	Molecular lattice/molecular bond vs. atomic lattice/atomic bond

English Summary

Teaching students chemical reasoning is one of the main goals of chemistry education (Talanquer, 2018). An important part of this chemical reasoning is structure-property reasoning, in Dutch referred to as micro-macro thinking. In the context of chemical reasoning, structure-property reasoning involves the task of elucidating macroscopic properties using the micro level, the level of particles and the interactions between them (Cooper et al., 2013; Meijer, 2011; Talanquer, 2018).

An expert in chemistry smoothly and almost unconsciously moves back and forth between these two levels when thinking about chemical questions and problems. A novice, in this thesis a secondary school student, encounter significant difficulty in achieving this cognitive task (Johnstone, 1991). There are several reasons for this. First, the micro level, the level of particles, cannot be seen by the naked eye. Chemists employ models to describe the micro level, however, students face difficulties in understanding and working with these models. They tend to interpret these models as an exact representation of reality. Furthermore, learners struggle to comprehend the limitations of these models. Second, because of their previous experiences, learners have a macroscopic orientation. Third, students have various misconceptions about particle models. This hinders the learning and development of structure-property reasoning (Adbo & Taber, 2009; Ben-Zvi et al., 1986; Cheng & Gilbert, 2017; de Jong & Taber, 2015; Gabel, 1999; Gilbert & Treagust, 2009; Harrison & Treagust, 2003; Johnstone, 1991).

To facilitate the learning and development of structure-property reasoning among students, teachers require effective and practical teaching approaches. However, educational research provides insufficient guidance in this regard. Several studies have highlighted the significance of demonstrating chemical phenomena (the macro level) and subsequently explaining them at the micro level. This approach enables the explicit teaching of structure-property reasoning (Dolfing et al., 2011; Gabel, 1999; Kelly et al., 2010; Talanquer, 2018).

Practical work in the form of student experiments would be appropriate to demonstrate those chemical phenomena. However, the efficacy and practicality of such experiments for learning are often inadequate. The inherent complexity involved in conducting experiments can result in significant noise, which may hinder the acquisition of conceptual knowledge during practical sessions. This noise can be reduced by using demonstration experiments (Becker et al., 2015; Hodson, 2014; Johnstone, 2000; Kelly & Jones, 2007; Kozma & Russell, 1997; Pols, 2023; Ramsey et al., 2000; Treagust & Tsui, 2014).

A demonstration experiment often consists of two steps: show and explain, both conducted and led by the teacher. The problem is that during the show, students often observe the demonstration passively, and therefore their attention is on the external features of the chemical phenomenon. They find it difficult to explain the phenomenon at the micro level and, in addition, there are few opportunities for students to test their ideas. As a result, students struggle to develop appropriate conceptual knowledge. Therefore, teachers benefit from approaches that overcome the shortcomings of a demonstration experiment (Becker et al., 2015; Treagust & Tsui, 2014).

Doyle and Ponder (1977) suggest that an innovation will not be adopted by teachers until it is perceived as being practically useful. To achieve this, they identified three dimensions that must be considered: instrumental, congruent, and cost-effective. The instrumental dimension refers to the innovation having a clear and recognizable procedure. The congruent dimension pertains to the innovation being aligned with the teacher's teaching goals. Finally, the cost-effective dimension involves the innovation being beneficial to the teacher in terms of time, resources, and energy. If these conditions are met, teachers are more likely to perceive the innovation as being practically useful and therefore implement it (Borko et al., 2010; Doyle, 2006; Doyle & Ponder, 1977; Janssen et al., 2013; Shavelson et al., 2008).

The purpose of this research was to explore an effective and practical approach to teaching and evaluating structure-property reasoning in chemistry classes at the secondary school level. Based on the previous considerations regarding structure-property reasoning and its teaching and learning, as well as considerations regarding the design of effective chemical demonstrations, we anticipated that teaching in structure-property reasoning could benefit from the use of appropriate demonstrations. To test this hypothesis, the following central research question was formulated: "what are the characteristics of an effective and practical approach that supports chemistry teachers in designing, enacting, and evaluating demonstration lessons to increase students' micro-macro thinking? To answer this research question, four studies were conducted, namely 1) the development and use of the perspective for structure-property reasoning to make structure-property reasoning explicit, 2) the design of an evaluation tool to assess students' progress in structure-property reasoning, 3) the design and implementation of a demonstration-based lesson series to explicitly teach structure-property reasoning, and 4) an interview with eight chemistry teachers to estimate the practicality of the approach. The results of the sub studies will be used to offer teachers recommendations on how to evaluate and teach structure-property reasoning to students.

The first study described the development of a model structure-property reasoning (**Chapter 2**). With this model, we aimed to represent the relationship between chemical concepts and the skill of structure-property reasoning. Scientific perspectivism is used for this purpose (Landa et al., 2020). The core idea of structure-property reasoning is: The **properties** of **substances** can be explained by the nature of the **particles** of which they consist, the **bonds and forces** between them, and the **movement** and **organization** of those particles (Smith et al., 2006). From the bold words, six questions can be formulated (Figure 1). The answers to these questions are the chemical concepts you need for structure-property reasoning. This organizes chemical knowledge in coherence.

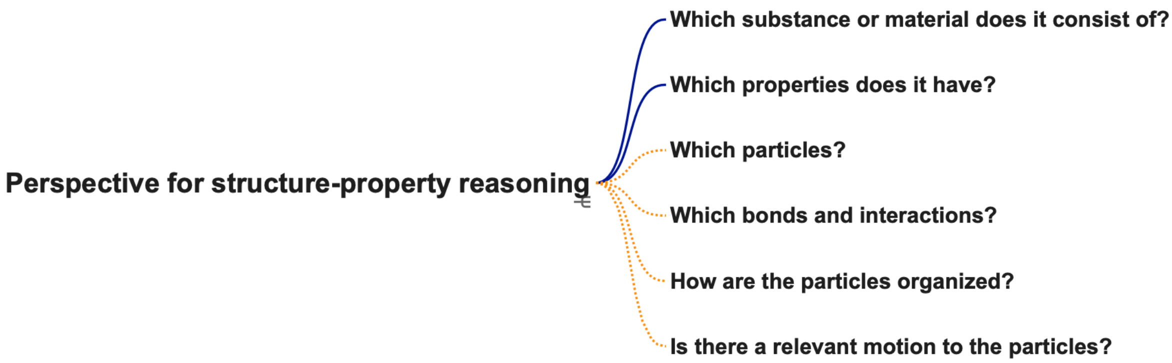


Figure 1: *Perspective for structure-property reasoning used in the studies of this thesis.*

Four cases increasing in difficulty demonstrated how the perspective for structure-property reasoning and its elaborations can stimulate reasoning about these cases. This causes an implicit learning progression as the perspective's questions branch out further and further. With each further differentiation, the strategy becomes increasingly powerful. In addition, the perspective increases horizontal and vertical coherence. Horizontal coherence here refers to the alignment of the chemical concepts and skills within a grade. Vertical coherence refers to the alignment of chemical concepts and skills across grade levels (Jin et al., 2019).

Chapter 3 described the development of an evaluation tool for chemistry teachers to assess students' level of structure-property reasoning. Three criteria were established for this SPR (SPR stands for structure-property reasoning) instrument, namely 1) the instrument must be based on a comprehensive model of structure-property reasoning, 2) the instrument must be cost-effective, and 3) the instrument must be adaptable by teachers to their own teaching goals. To achieve these goals, the SPR instrument combined a sorting task (Irby et al., 2016; Krieter et al., 2016) and a mapping task, both unframed and framed.

Results showed that the SPR instrument can discriminate between pre-university track students (age 15-17) and first-year chemistry students. In addition, it showed that the perspective for structure-property reasoning can serve as a comprehensive model that covers the necessary aspects of structure-property reasoning. The instrument also met the second criteria set, i.e., the instrument is cost-effective. Preparation and implementation of the SPR instrument was not time-consuming and the instrument was suitable for larger groups. However, analyzing the results still took time. Also, the final criterion has been met: the instrument is adaptable to the teacher's own instructional goals.

Chapter 4 described the design and implementation of a demonstration lesson series aimed at teaching students' structure-property reasoning. Two design criteria were established for this purpose, namely 1) using a POE task (Treagust & Tsui, 2014) to encourage students to think for themselves and model the micro-level and 2) supporting POE task with the perspective for structure-property reasoning to guide students in reasoning in the explain phase. Existing demonstrations were redesigned using these two design principles. The lesson series was tested in two cohorts (age 15-16) to determine the effect of the two design principles. The SPR instrument was used to determine the progress in structure-property reasoning of the whole class. The results of this instrument show that the lesson series contributed to the development of structure-property reasoning. The mapping tasks of the SPR instrument showed that students were able to reproduce and understand more chemical concepts necessary for structure-property reasoning. In addition, the sorting tasks of the SPR instrument showed that students were better at applying and evaluating knowledge to problems requiring structure-property reasoning. Following a student, named Sally, and her groupmates, the progression in structure-property reasoning was qualitatively analyzed.

The findings demonstrated that the two design principles yielded the intended outcomes. Specifically, the utilization of the POE task led to a higher level of active participation among students in the process of modeling the structure models during the explain phase. As a result, students will have more knowledge of the required micro-models. In addition, the SPR instrument showed that the perspective for structure-property reasoning was developed in students. This increases the value of perspective as a scaffold for structure-property reasoning. Therefore, one could say that both design principles helped students in developing the skill of structure-property reasoning.

Chapter 5 investigated the estimated practicality (Doyle & Ponder, 1977; Janssen et al., 2013) of the two design principles of Chapter 4. For this purpose, eight chemistry teachers were interviewed and asked to compare the practicality of their own approach with our approach. The results showed that the teachers rated the practicality of the redesigned demonstration as high as that of "traditional" demonstration. As advantages of the redesign, it was mentioned that in this way students are enabled to think for themselves and that the perspective for structure-property reasoning can act as a thinking framework for the students. A frequently mentioned disadvantage is that the perspective consisted of a large number of questions.

Chapter 6 presents a comprehensive description and discussion of the findings from all the sub studies. The results of the four sub studies showed that that perspective is suitable as a model for structure-property reasoning. The perspective consists of questions that can be used to describe and explain the macroscopic properties of a substance using the micro-level. Teachers can use the perspective as a design tool when (re)designing lessons or ear the design of assessment instruments in which the perspective acts as the basis of the instrument.

In addition, the results of the four sub studies showed that the POE task allows the teacher to engage students more during the demonstration. The POE demonstration allows teachers to start at students' macroscopic orientation. Through the predict phase of the POE task, students are actively engaged in the demonstration. The student-centered explain phase of the POE task allows students to think for themselves and model the micro-level so that the demonstrated chemical phenomenon can be described and explained. Using the perspective in the explain phase supports students in formulating micro-level explanations. The perspective questions can be used to describe and question the phenomenon. The chemical concepts that emerge in response to the questions can help students formulate a good answer and micro-model. The POE demonstration combined with the perspective allow the teacher to explicitly teach structure-property reasoning.

The two design principles combined are also perceived by teachers as practical. The practicality of the approach is enhanced by the fact that existing demonstrations can be used for the redesign. The POE task only adds one building block to the approach. The perspective for structure-property reasoning reorganizes the chemical concepts to be taught so that there is more consistency among these concepts. The innovation will be perceived as instrumental due to the minor modifications to usual teaching practice. By giving students more opportunity to think for themselves through the POE task, the innovation will be congruent with the teacher's teaching goals. Lastly, the innovation is cost-effective due to the use of (existing) demonstrations that are less costly in terms of time, resources and energy compared to practical work performed by students.

Every study has inherent limitations, and this study is no exception. First, there was a small group of students who participated in the studies of Chapters 3 and 4. Therefore, it is recommended that this study should be repeated with larger groups. In addition, a lesson series to develop structure-property reasoning in students is obviously not enough. The lesson series from Chapter 4 will have to serve as a starting point to develop a learning progression for structure-property reasoning. A limitation of Chapter 5 is that it concerns the estimated practicality. Follow-up research that includes professional development could examine how teachers implement the innovation and then how they rate the practical usefulness of the approach. Finally, the suitability of the perspective for structure-property reasoning has only been demonstrated through a limited number of examples. This makes the scope of the perspective limited to structure-property reasoning in K-12 chemistry education. Further research should clarify whether the perspective for structure-property reasoning can be expanded to encompass the entire domain of structure-property reasoning and then expanded even further to include all subjects in K-12 chemistry education.

Several theoretical and practical implications follow from this research. First, the perspective for structure-property reasoning appears to be a useful explication of structure-property reasoning. This allows the perspective to be used as a thinking framework, a knowledge organizer, and a scaffold for students. Teachers can use the perspective as a design tool for designing lessons, lesson series and curricula. In addition, the perspective can be used to design evaluation tools. The perspective is part of the overarching chemistry perspective for K-12 chemistry education, which will broaden the scope for both students and teachers. The POE task allows teachers to use demonstrations more effectively and thereby teach structure-property reasoning more explicitly. Such a POE task is not new, but the combination with the perspective structure-property reasoning increases the value and practicality of the demonstration. In addition, the two design principles, the POE task and the perspective are also applicable in other situations where students need to develop structure-property reasoning such as student practices and assignments.

Nederlandse Samenvatting

Een van de belangrijkste doelen van het scheikunde-onderwijs is leerlingen leren chemisch te redeneren (Talanquer, 2018). Een belangrijk onderdeel van dit chemisch redeneren is het micro-macrodenken, in het Engels 'structure-property reasoning' genoemd. Bij het micro-macrodenken wordt er van de chemicus gevraagd om macroscopische eigenschappen te beschrijven en te verklaren met behulp van het microniveau, het niveau van de deeltjes en de interacties daartussen (Cooper et al., 2013; Meijer, 2011; Talanquer, 2018).

Een expert in scheikunde beweegt soepel en bijna onbewust tussen deze twee niveaus heen en weer bij het denken over chemische vraagstukken. Een beginner, in dit proefschrift een leerling van de middelbare school, heeft hier veel moeite mee (Johnstone, 1991). Dit heeft een aantal redenen. Allereerst, het microniveau, het niveau van de deeltjes, is niet met het blote oog te zien. Dit betekent dat scheikundigen gebruik moeten maken van modellen om dit niveau te beschrijven. Leerlingen hebben moeite met deze modellen. Ze vertalen de modellen vaak een-op-een naar de werkelijkheid. Daarnaast kunnen leerlingen niet goed omgaan met de grenzen van zulke modellen. Ten tweede hebben leerlingen door hun eerdere ervaringen een macroscopische oriëntatie. Ten derde hebben leerlingen diverse misconcepties over de deeltjesmodellen. Hierdoor wordt het aanleren en ontwikkelen van het micro-macrodenken gehinderd (Adbo & Taber, 2009; Ben-Zvi et al., 1986; Cheng & Gilbert, 2017; de Jong & Taber, 2015; Gabel, 1999; Gilbert & Treagust, 2009; Harrison & Treagust, 2003; Johnstone, 1991).

Om leerlingen te ondersteunen in het aanleren en ontwikkelen van micro-macrodenken, is er voor docenten een (effectieve en praktische) lesaanpak nodig. Echter, in het onderwijsonderzoek worden hier maar beperkt handvatten voor aangereikt. Een aantal studies wijst op het belang van het laten zien van chemische fenomenen (het macroniveau) die vervolgens op het microniveau worden uitgelegd. Hierdoor kan het micro-macrodenken expliciet worden onderwezen (Dolfing et al., 2011; Gabel, 1999; Kelly et al., 2010; Talanquer, 2018).

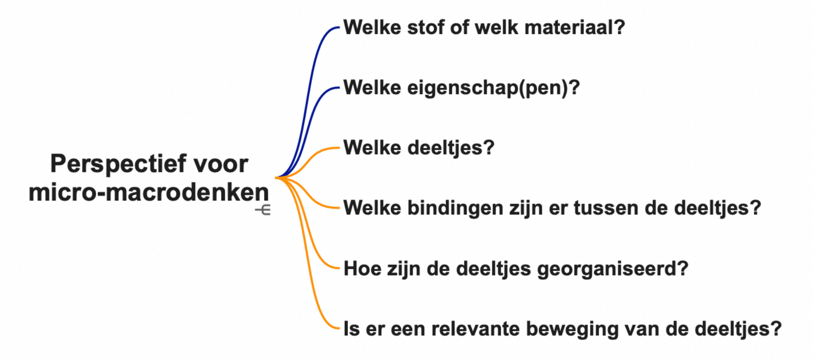
Praktisch werk in de vorm van leerlingpractica zouden geschikt zijn om die chemisch fenomenen te laten zien. Echter, het leerrendement en de praktische bruikbaarheid van leerlingpractica laten weleens te wensen over. Er ontstaat ruis veroorzaakt door de complexiteit van het zelf uitvoeren van een experiment. Hierdoor komen leerlingen niet of nauwelijks tot het leren van concepten tijdens een practicum. Deze ruis kan verminderd worden door gebruik te maken van demonstratie-experimenten (Becker et al., 2015; Hodson, 2014; Johnstone, 2000; Kelly & Jones, 2007; Kozma & Russell, 1997; Pols, 2023; Ramsey et al., 2000; Treagust & Tsui, 2014).

Een demonstratie-experiment bestaat vaak uit twee stappen: show en explain, beide uitgevoerd en geleid door de docent. Het probleem is dat leerlingen tijdens de show van de demonstratie vaak passief observeren. Daardoor is de aandacht van de leerlingen bij de uiterlijke kenmerken van het chemische fenomeen. Ook vinden leerlingen het lastig om het fenomeen uit te leggen op microniveau en zijn er daarnaast weinig mogelijkheden voor de leerlingen om hun ideeën te testen. Hierdoor hebben leerlingen moeite om de juiste conceptuele kennis te ontwikkelen. Docenten hebben daarom baat bij een aanpak die de tekortkomingen van een demonstratie-experiment overkomen (Becker et al., 2015; Treagust & Tsui, 2014).

Een nieuwe aanpak (een innovatie) zal pas door docenten geïmplementeerd worden als deze wordt ervaren als praktisch bruikbaar. Doyle & Ponder (1977) onderscheiden hierin drie dimensies, namelijk de innovatie is instrumenteel, hetgeen inhoudt dat de innovatie een duidelijke en herkenbare procedure heeft, de innovatie is congruent, wat betekent dat docent zijn eigen lesdoelen ermee kan behalen en de innovatie is kosteneffectief, hetgeen betekent dat de kosten in termen van tijd, middelen en energie voor de docent gunstig uitvallen. Als aan deze voorwaarden is voldaan, zal de docent de innovatie als praktisch bruikbaar worden ervaren (Borko et al., 2010; Doyle, 2006; Doyle & Ponder, 1977; Janssen et al., 2013; Shavelson et al., 2008).

Het doel van dit onderzoek was het exploreren van een effectieve en praktische aanpak voor het onderwijzen en evalueren van micro-macrodenken in de scheikundelessen van de middelbare school. Op basis van de voorgaande overwegingen met betrekking tot micro-macrodenken en het onderwijzen en leren ervan, evenals de overwegingen met betrekking tot het ontwerp van effectieve chemische demonstraties, verwachtten we dat het onderwijs in micro-macrodenken baat kan hebben bij het gebruik van geschikte demonstraties. Om deze hypothese te toetsen, werd de volgende centrale onderzoeksvraag gebruikt: “wat zijn de karakteristieken van een effectieve en praktische aanpak die scheikundedocenten ondersteunt in het ontwerpen, vaststellen en evalueren van demonstratielessen om het micro-macrodenken van de leerlingen te vergroten?” Om deze onderzoeksvraag te kunnen beantwoorden, zijn er vier studies uitgevoerd, namelijk 1) de ontwikkeling en het gebruik van het perspectief voor micro-macrodenken om micro-macrodenken te expliciteren, 2) het ontwerp van een evaluatie-instrument om de voortgang van leerlingen in micro-macrodenken in kaart te brengen, 3) het ontwerp en implementatie van een op demonstraties gebaseerde lessenserie om het micro-macrodenken expliciet te onderwijzen en 4) een inventarisatie onder acht scheikunde-docenten naar de praktische bruikbaarheid van de aanpak. De resultaten van de deelstudies zullen worden gebruikt om docenten handvatten te geven over hoe micro-macrodenken van leerlingen geëvalueerd en onderwezen kan worden.

In de eerste studie is de ontwikkeling van een model voor micro-macrodenken beschreven (**hoofdstuk 2**). Met dit model willen we de samenhang tussen de chemische concepten en de vaardigheid van het micro-macro redeneren weergeven. Hiervoor is wetenschappelijk perspectivisme gebruikt (Landa et al., 2020). De kerngedachte van micro-macrodenken is: de **eigenschappen** van **stoffen** kan worden beschreven en verklaard door de aard van de **deeltjes** waar de stof is uitgemaakt, de **bindingen en krachten** tussen de deeltjes en de **beweging** en **organisatie** van die deeltjes (Smith et al., 2006). Uit de vetgedrukte woorden kunnen zes vragen worden geformuleerd (Figuur 1). De antwoorden op deze vragen zijn de chemische concepten die je nodig hebt voor het micro-macrodenken. Hierdoor wordt de chemische kennis in samenhang georganiseerd.



***Figuur 1**: het perspectief voor micro-macrodenken*

Aan de hand van vier in moeilijkheid oplopende cases is gedemonstreerd hoe het perspectief voor micro-macrodenken en de uitbreiding daarvan het redeneren over de casus kan stimuleren. Dit veroorzaakt een impliciete leerprogressie doordat de vragen van het perspectief steeds verder vertakken. Bij elke verdere differentiatie wordt de strategie steeds krachtiger. Daarnaast wordt met het perspectief de horizontale en verticale samenhang vergroot. Horizontale samenhang refereert hierbij naar de samenhang van de kennis van een vak binnen een leerjaar. De verticale samenhang verwijst naar de samenhang van een vak over de leerjaren heen (Jin et al., 2019).

In **Hoofdstuk 3** is de ontwikkeling van een evaluatietool beschreven. Deze tool kan gebruikt worden door scheikundedocenten om het niveau van micro-macrodenken van hun leerlingen en studenten vast te stellen. Voor dit SPR-instrument (SPR staat voor structure-property reasoning) werden drie criteria opgesteld, namelijk 1) het instrument moet gebaseerd zijn op een alomvattend model voor micro-macrodenken, 2) het instrument moet kosteneffectief zijn en 3) het instrument moet door docenten aan te passen zijn aan de eigen lesdoelen. Om deze doelen te bereiken is er een een sorteertaak (Irby et al., 2016; Krieter et al., 2016) gecombineerd met een mappingtaak. Beiden taken werden zowel unframed als framed aangeboden.

Resultaten lieten zien dat het SPR-instrument in staat is om te discrimineren tussen leerlingen van 4vwo en 5vwo en eerstejaars scheikundestudenten. Daarnaast liet het zien dat het perspectief voor micro-macrodenken kan dienen als omvattend model dat de benodigde aspecten van het micro-macrodenken afdekt. Het instrument voldeed ook aan het tweede criterium, d.w.z. het instrument is kosteneffectief. Voorbereiding en uitvoeren van het SPR-instrument was niet tijdrovend en het instrument is geschikt voor grotere groepen. Echter, het analyseren van de resultaten nam meer tijd in beslag dan verwacht. Ook aan het laatste criterium is voldaan, het instrument is aanpasbaar aan de docent zijn eigen lesdoelen.

In **hoofdstuk 4** is het ontwerp en de uitvoering van een demonstratielessenserie beschreven met als doel leerlingen het micro-macrodenken aan te leren. Hiervoor zijn twee ontwerpcriteria vastgesteld, namelijk 1) het gebruik van een POE-taak (Treagust & Tsui, 2014) om leerlingen te stimuleren voor zichzelf te denken en het microniveau te modelleren en 2) het ondersteunen van POE-taak met het perspectief voor micro-macrodenken om de leerlingen te begeleiden bij het redeneren in de explain-fase. Bestaande demonstraties zijn herontworpen met behulp van deze twee ontwerpprincipes. De lessenserie is getest in twee leerjaren 4vwo om het effect van de twee ontwerpprincipes te bepalen. Het SPR-instrument is gebruikt om de voortgang in het micro-macrodenken van de klas als geheel te bepalen. Uit de resultaten van dit instrument bleek dat de lessenserie heeft bijgedragen aan de ontwikkeling van micro-macrodenken. De mapping taken van het SPR-instrument lieten zien dat leerlingen meer chemische concepten die ze nodig hebben voor micro-macro denken konden reproduceren en begrijpen. Daarnaast lieten de sorteertaken van het SPR-instrument zien dat leerlingen beter waren in het toepassen en evalueren van de kennis bij problemen die micro-macrodenken behoeven. Aan de hand van een student, genaamd Sally, en haar groepsgenoten is kwalitatief geanalyseerd hoe de progressie in het modelleren van micro-modellen verloopt.

De resultaten lieten zien dat de twee ontwerpprincipes het gewenste resultaat opleverden. Het gebruik van de POE-taak zorgde ervoor dat leerlingen meer actief betrokken waren bij het modelleren van de micro-modellen in de explain-fase. Hierdoor zullen de leerlingen meer kennis ontwikkelen over de benodigde micromodellen. Het SPR-instrument liet daarnaast zien dat het perspectief voor micro-macrodenken bij leerlingen was ontwikkeld. Dit maakt dat de waarde van het perspectief als ondersteuning bij het redeneren toeneemt. Beide ontwerpprincipes zullen de leerlingen helpen in het ontwikkelen van de vaardigheid van micro-macrodenken.

In **hoofdstuk 5** is de mate van praktische bruikbaarheid (Doyle & Ponder, 1977; Janssen et al., 2013) van de twee ontwerpprincipes van hoofdstuk 4 onderzocht. Hiervoor zijn acht scheikundedocenten geïnterviewd en gevraagd om de praktische bruikbaarheid van hun eigen aanpak te vergelijken met onze aanpak. De resultaten laten zien dat de docenten de praktische bruikbaarheid van de herontworpen demonstratie net zo hoog inschatten als die van 'normale' demonstratie. Als voordelen van het herontwerp werd genoemd dat leerlingen op deze manier in staat worden gesteld om voor zichzelf te denken en dat het perspectief voor micro-macrodenken kan fungeren als denkraam voor de leerlingen. Een veelgenoemd nadeel is dat het perspectief uit een groot aantal vragen bestond.

In het laatste hoofdstuk (hoofdstuk 6) worden alle opbrengsten van de deelstudies beschreven en bediscussieerd. De resultaten van de vier deelstudies hebben laten zien dat dat het perspectief voor micro-macrodenken geschikt is als model voor micro-macrodenken. Het perspectief bestaat uit vragen waarmee de macroscopische eigenschappen van een stof kunnen worden beschreven en verklaard met behulp van het microniveau. Docenten kunnen het perspectief gebruiken als ontwerpgereedschap bij het (her)ontwerpen van lessen of oor het ontwerp van evaluatie-instrumenten waarin het perspectief fungeert als basis van het instrument.

Daarnaast hebben de resultaten van de vier deelstudies laten zien dat de POE-taak de docent in staat stelt om leerlingen meer te activeren tijdens de demonstratie. De POE-demonstratie zorgt ervoor dat docenten bij de macroscopische oriëntatie van leerlingen kunnen beginnen. Door de predict-fase van de POE-taak zijn de leerlingen actief bezig met de demonstratie. De studentgerichte explain-fase van de POE-taak stelt studenten in staat om zelf na te denken en het micromodel te modelleren zodat het gedemonstreerde chemische fenomeen kan worden beschreven en verklaard. Het gebruik van het perspectief in de explain-fase ondersteunt de leerlingen bij het formuleren van verklaringen op microniveau. De vragen van het perspectief kunnen gebruikt worden om het fenomeen te beschrijven en te bevragen. De chemische concepten die als antwoord op de vragen naar bovenkomen kunnen de leerlingen helpen om een goed antwoord en micromodel te formuleren. De POE-demonstratie gecombineerd met het perspectief stellen de docent in staat om het micro-macrodenken expliciet te onderwijzen.

De twee ontwerpprincipes samen werden door docenten ook als praktisch bruikbaar ervaren. De praktische bruikbaarheid van de aanpak wordt verhoogd doordat er bestaande demonstraties gebruikt kunnen worden voor het herontwerp. De POE-taak voegt slechts een bouwsteen toe aan de aanpak. Het perspectief voor micro-macrodenken reorganiseert de chemische concepten die onderwezen moeten worden zodat er meer samenhang tussen de concepten ontstaat. De innovatie bestaat uit kleine aanpassingen aan de gebruikelijke lespraktijk. Hierdoor zal de innovatie als instrumenteel worden ervaren. De POE-taak geeft de leerling meer de gelegenheid om voor zichzelf te denken. Hierdoor zal de innovatie congruent zijn met de lesdoelen van de docent. Als laatste is de innovatie kosteneffectief door het gebruik van (bestaande) demonstraties die qua tijd, middelen en energie minder kosten met zich meebrengen in vergelijking met leerlingpractica.

Elk onderzoek kent zijn beperkingen, zo ook dit onderzoek. Allereerst was er een kleine groep leerlingen die als deelnemers meedeed in de studies van hoofdstuk 3 en 4. Het verdient dan ook de aanbeveling om dit onderzoek met grotere groepen te herhalen. Daarnaast is één lessenserie onvoldoende om het micro-macrodenken bij leerlingen te ontwikkelen. De lessenserie uit hoofdstuk 4 zal moeten dienen als startpunt voor een leerprogressie voor micro-macrodenken dat in vervolgonderzoek kan worden ontwikkeld. Een limitatie van hoofdstuk 5 is dat het ingeschatte praktische bruikbaarheid van docenten betreft. Vervolgonderzoek met daarin een professionele ontwikkeling zou kunnen onderzoeken hoe docenten de innovatie implementeren en hoe ze vervolgens de praktische bruikbaarheid van de aanpak waarderen. Als laatste is de geschiktheid van het perspectief voor micro-macrodenken alleen gedemonstreerd door een beperkt aantal voorbeelden. Dit maakt dat de reikwijdte van het perspectief gelimiteerd is tot het micro-macrodenken in het K-12 scheikundeonderwijs (PO en VO). Vervolgonderzoek zou duidelijk moeten maken of het perspectief voor micro-macrodenken kan worden uitgebreid om het gehele domein van micro-macrodenken en daarna ook alle andere onderwerpen van het K-12 scheikundeonderwijs te omvatten.

Uit dit onderzoek volgen diverse theoretische en praktische implicaties. Ten eerste lijkt het perspectief voor micro-macrodenken een bruikbare explicatie van micro-macrodenken. Dit maakt dat het perspectief gebruikt kan worden als denkkader, kennisorganisator en hulp-op-maat door de leerlingen. Docenten kunnen het perspectief gebruiken als ontwerpgereedschap voor het ontwerp van lessen, lessenseries en curricula. Daarnaast kan het perspectief gebruikt worden om evaluatie-instrumenten te ontwerpen. Het perspectief is onderdeel van het overkoepelend scheikundig perspectief voor het K-12 scheikundeonderwijs, waarmee de reikwijdte voor zowel leerlingen als docenten zal worden vergroot. De POE-taak maakt het mogelijk voor docenten om demonstraties effectiever in te zetten en daarmee micro-macrodenken explicieter te onderwijzen. Een dergelijke POE-taak is niet nieuw, maar de combinatie met het perspectief voor micro-macrodenken vergroot de waarde en de praktische bruikbaarheid van de demonstratie. Daarnaast zijn de twee ontwerpprincipes, de POE-taak en het perspectief ook toepasbaar in andere situaties waarin leerlingen micro-macrodenken moeten ontwikkelen zoals leerlingpractica en opdrachten.

Curriculum Vitae

Marie-Jetta den Otter was born on May 21st, 1977, in Groningen, the Netherlands. She attended secondary education at the Dollard College in Winschoten from which she graduated in 1995. Next, she obtained her Master of Science in Medicine and her Master of Science in Chemistry, both at the University of Groningen in 2003. Her master thesis focused on reactions in a model for cytoplasm. This is published in Organic & Biomolecular Chemistry. Next, she worked one year at the Nederlandse Voedsel- en Warenautoriteit (NVWA), where she investigated the safety of non-food products as toys.

In 2006, she obtained her Master of Science in Teaching Chemistry at the ICLON Leiden University Graduate School of Teaching. Her education specialization focused on the teacher job satisfaction at secondary education. During her internship, she worked at the Stanislas College Westplantsoen in Delft.

Marie-Jetta continued her teaching career at the Da Vinci College Kagerstraat in Leiden in 2006. Next to chemistry, she taught Science and NLT (Nature, Life and Technology). She was Science coordinator and she developed teaching materials for science. In 2016 she obtained a DUDOC-scholarship and she started her PhD-project "Bridging the Gap between Macro and Micro: Enhancing Students' Chemical Reasoning" at the ICLON. During her PhD trajectory, she presented at the ORD conference.

Currently, Marie-Jetta is employed as assistant professor "Vakdidactiek Scheikunde" at the TU Delft, where her work is mainly focused on teaching and mentoring preservice chemistry teachers.

Publications

Scientific publications

Articles in peer-reviewed Journals:

den Otter, M.-J., Dam, M., Juurlink, L. B. F., & Janssen, F. J. J. M. (2021). Two Design Principles for the Design of Demonstrations to Enhance Structure–Property Reasoning. *Education Sciences*, *11*(9), 504. https://doi.org/10.3390/educsci11090504

den Otter, M.-J., Juurlink, L. B. F., & Janssen, F. J. J. M. (2022). How to Assess Students' Structure–Property Reasoning? *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.2c00234

Manuscript submitted/under review:

den Otter, M.-J., Kuijpers, A. J., Dam, M., Juurlink, L. B. F., & Janssen, F. J. J. M. (under review) A Perspective for Structure-Property Reasoning to Explicate and Scaffold Thinking like a Chemist.

Presentations & Posters:

Juurlink, L.B.F., den Otter, M.-J., Janssen, F.J.J.M., Noteborn, M.H.M. (2018, 10-14 July). *Development of a Formative Assessment Instrument for Structure-Property Reasoning*. Poster presented at 25th International Conference on Chemistry Education (ICCE 2018), Sydney, Australia, 2018.

den Otter, M.-J. (2022, 6-8 July). *Scheikundig perspectief om scheikundig te leren denken*. Oral contribution to Onderwijs Research dagen, Hasselt, Belgium, 2022.

den Otter, M.-J., Juurlink, L. B. F., & Janssen, F. J. J. M. (2023, April 14). *How to Assess Students' Structure-Property Reasoning?* Poster presented at 2023 ECTN Annual Meeting and General Assembly, Amsterdam, the Netherlands, 2023.

Other output

Workshops:

den Otter, M.-J., (2018, November 15). *Onderwijzen en evalueren van het micro-macrodenken.* Masterclass for ONZ, Leiden, the Netherlands, 2018.

den Otter, M.-J., (2020, February 7). *Onderwijzen en evalueren van het micro-macrodenken.* Masterclass for ONZ bèta-symposium, Voorburg, the Netherlands, 2020.

den Otter, M.-J., Kuijpers, A. J., (2021, February 5). *POE-saus en denkkader voor je lespraktijk.* Workshop for ONZ bèta-symposium, online, the Netherlands, 2021.

den Otter, M.-J., Juurlink, L. B. F., (2022, February 4). *Sorteertaken voor domein-specifiek redeneren.* Workshop for ONZ bèta-symposium, Online, the Netherlands, 2022.

Dankwoord

Het doen van onderwijsonderzoek naar de didactiek van scheikunde naast je baan als docent is een behoorlijke uitdaging. Daarnaast is het doen van een promotieonderzoek best eenzaam, dus iedereen die daar iets van verlichting in heeft gebracht, ben ik veel dank verschuldigd.

Ludo, zonder jou was dit project nooit begonnen. Je telefoontje over deze beurs en dat je een idee had voor een onderzoek was zeer welkom. Sinds het Junior Science Lab kruisen onze paden regelmatig en dat heeft veel leuks en goeds opgeleverd. Hopelijk blijven die paden elkaar kruisen.

Michiel, fijn dat je bent ingestapt als begeleider om extra steun in het proces te geven. Dank voor al je feedback en het meedenken over diverse stappen in het onderzoeksproces.

Last, but not least, Fred, je speelde – wellicht onbewust – een belangrijke rol in mijn leven als docent en natuurlijk in dit project. Tijdens de leraaropleiding had je een inspirerende les over aandachtrichters, waarbij wij allemaal een stukje vijg te eten kregen. Het kraakte lekker tussen de tanden en na afloop vertelde je dat we allemaal een insectenkerkhof hadden opgegeten. Onze aandacht was gericht. Ook bracht je een hoop positiviteit door ons te dwingen in succeservaringen te denken en daar vuistregels uit te halen. Die positiviteit haalde ook dit project zo nu en dan uit het slob. Daarnaast heb je me veel geleerd over didactiek en onderwijsonderzoek.

Er zijn niet veel docenten die dit proces in gaan en dus ervaringen hebben met het doen van didactisch onderzoek. Daarom ben ik blij dat we samen optrokken in dit proces: Stefan, Koen en Eveline. Het sparren, de gekleurde planningen, de curve van Kubler-Ross, het gewoon samen werken zorgde steeds weer voor de motivatie om door te gaan. Laten we blijven optrekken samen. In dit kader wil ik ook mijn dank uitspreken aan mijn DUDOC-collega's van lichting 2016 en dan Jacqueline in het bijzonder.

Ook op het ICLON waren fijne collega's met steun en interesse zoals o.a. het actieonderzoek-groepje. Dank iedereen! En bijzondere dank aan Alma. Fijn dat we samen zo uitgebreid hebben nagedacht over het scheikunde perspectief en je woorden van steun in het promotietraject.

Dit onderzoek lukt niet zonder een fijne school met fijne collega's. Daisy, Tjerk, Filip, Mira, Ellen, Afke, William, Marie-José, Herman, Wytse, Marcel, Paula, Cédric, Nienke, Jelle en alle anderen: dank voor jullie steun, gezelligheid en samenwerking. Annick en Dorine, dank voor het mogelijk maken van dit project. En laat ik niet alle leerlingen van het Da Vinci College Kagerstraat vergeten die toch - al dan niet vrijwillig - hebben meegelopen aan dit onderzoek en allerlei andere didactische experimenten.

Ik wil woorden van dank uitspreken voor mijn nieuwe collega's van de TU Delft: Rutger, Tessa, Suzanne, Jan-Jaap, Marjan, Sanne, Sebastiaan, Laura, Freek, Gerben en alle anderen. Jullie interesse en steun maakten de laatste loodjes minder zwaar. Dank voor Bas, Jelmar en Arne-Jan voor het mogen uithuilen over mijn PWS.

Familie en vrienden, jullie steun was van groot belang! Susanne en Harry, Rianke, Lotte, Ivonne, Lynn, Robin-Roy, Lukas en Ineke, Bart, Thom, Mirthe, dank voor de broodnodige afleiding en gezelligheid, iets wat ik ook vond bij Thomas en Irna. Dank aan mijn ooms en tantes voor hun betrokkenheid. Speciale dank aan tante Marieke voor het maken van de prachtige omslag. Oom Jan, dank voor het suggereren dat een promotie een goed idee was. Jan en Janny, dank! En lieve pap en mam, dank voor alles, maar vooral voor het vertrouwen in mij gedurende al mijn onderwijsstappen! Julian, Olivier en Cathelijne, allemaal mijn lievelingskind. Het boek is af, dus we kunnen verder met ons leven. Lieve Gerlof, dank je wel.

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