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

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.

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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).

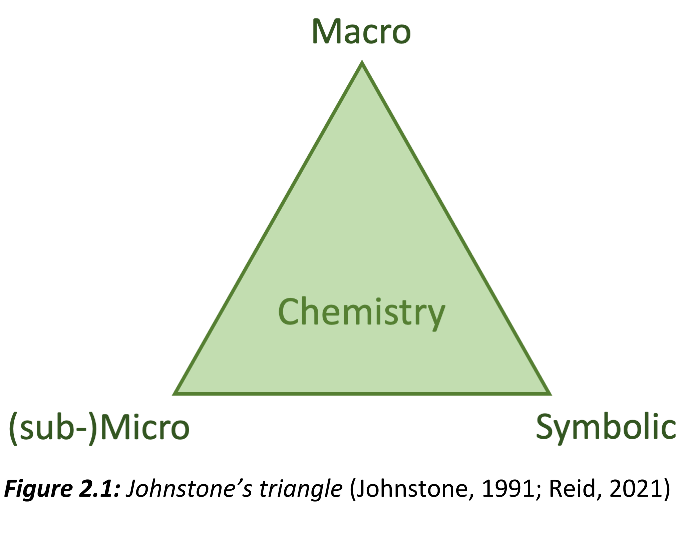

Figure 2.1: *Johnstone’s triangle* (Johnstone, 1991; Reid, 2021)

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.

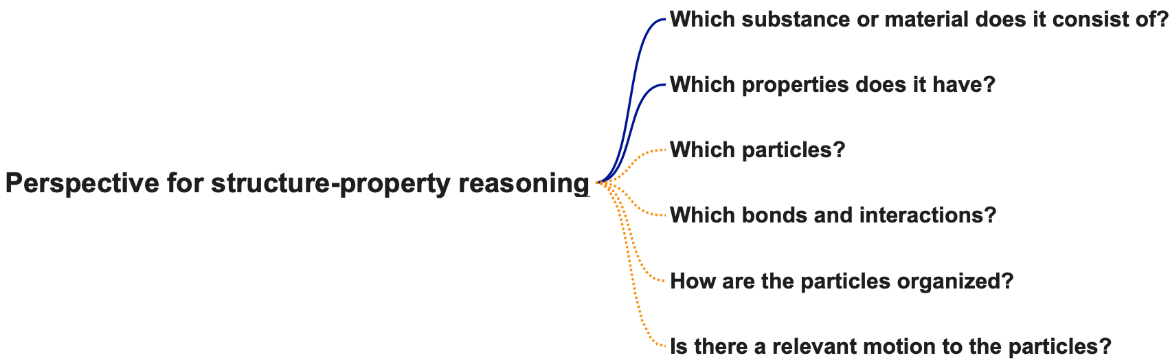

Figure 2.2: *The six main questions of the perspective for structure-property reasoning: dark blue lines for the macro-level questions, dotted orange lines for the micro-level questions.*

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).

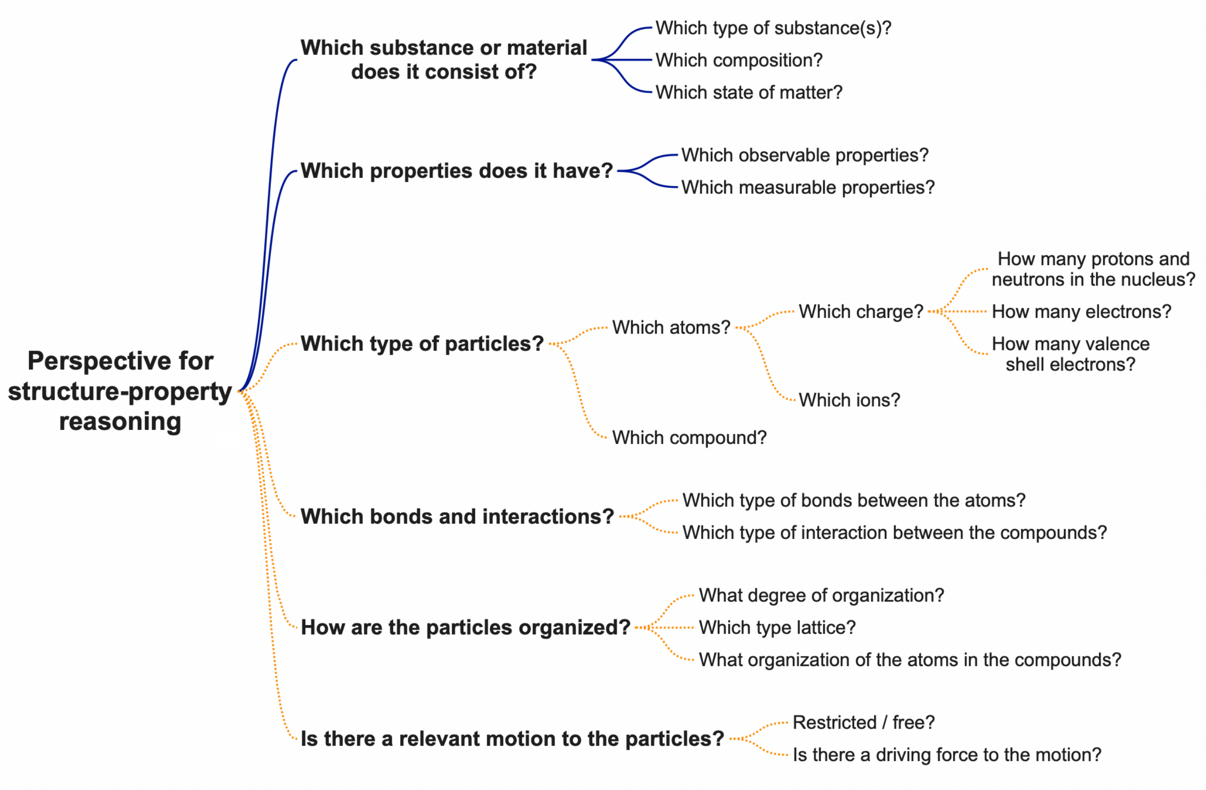

Figure 2.3: *The perspective for structure-property reasoning elaborated with several levels of questions: dark blue lines for the macro-level questions, dotted orange lines for the micro-level questions.*

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.

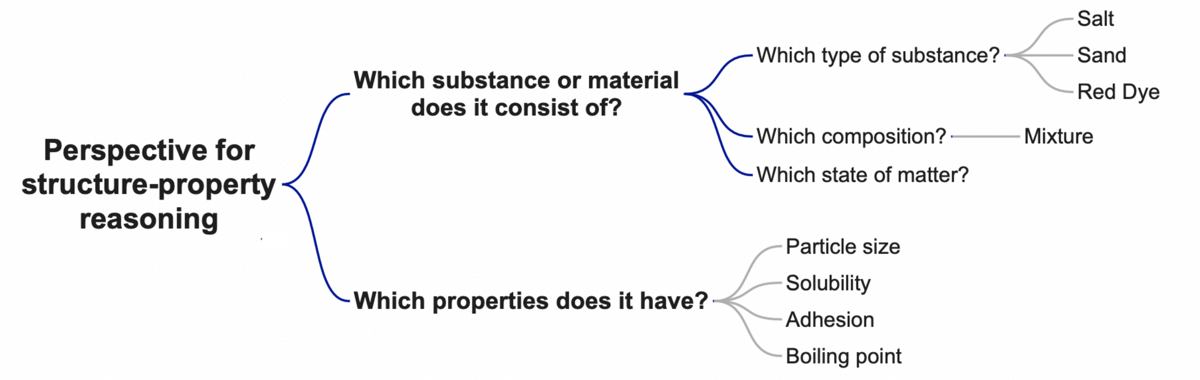

Figure 2.4: *Elaborated perspective for structure-property reasoning for the case of separation methods.*

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).

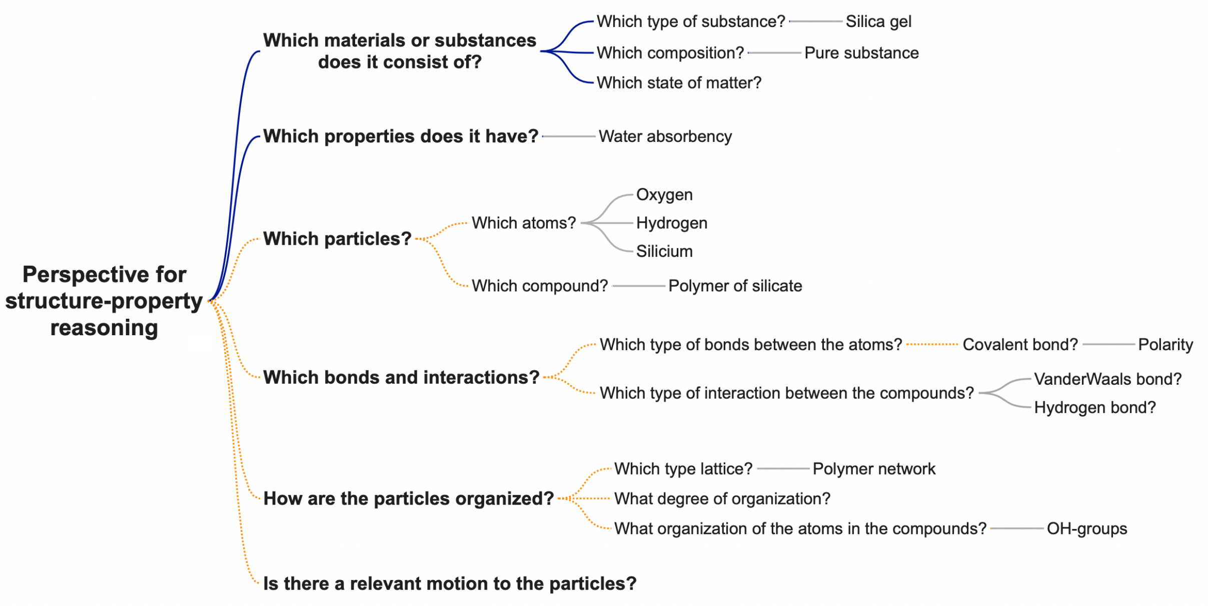

Figure 2.5: *Elaborated perspective for structure-property reasoning for the case of silica gel.*

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.

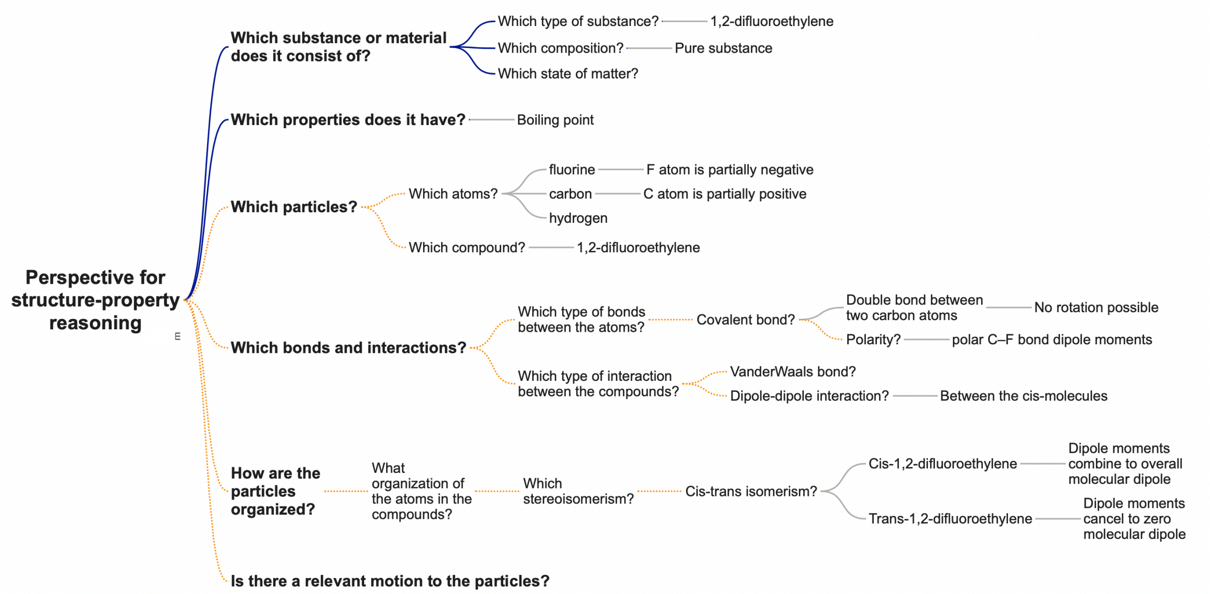

***Figure 2.6**: Elaborated perspective for structure-property reasoning for the case of cis-trans isomerism.*

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.

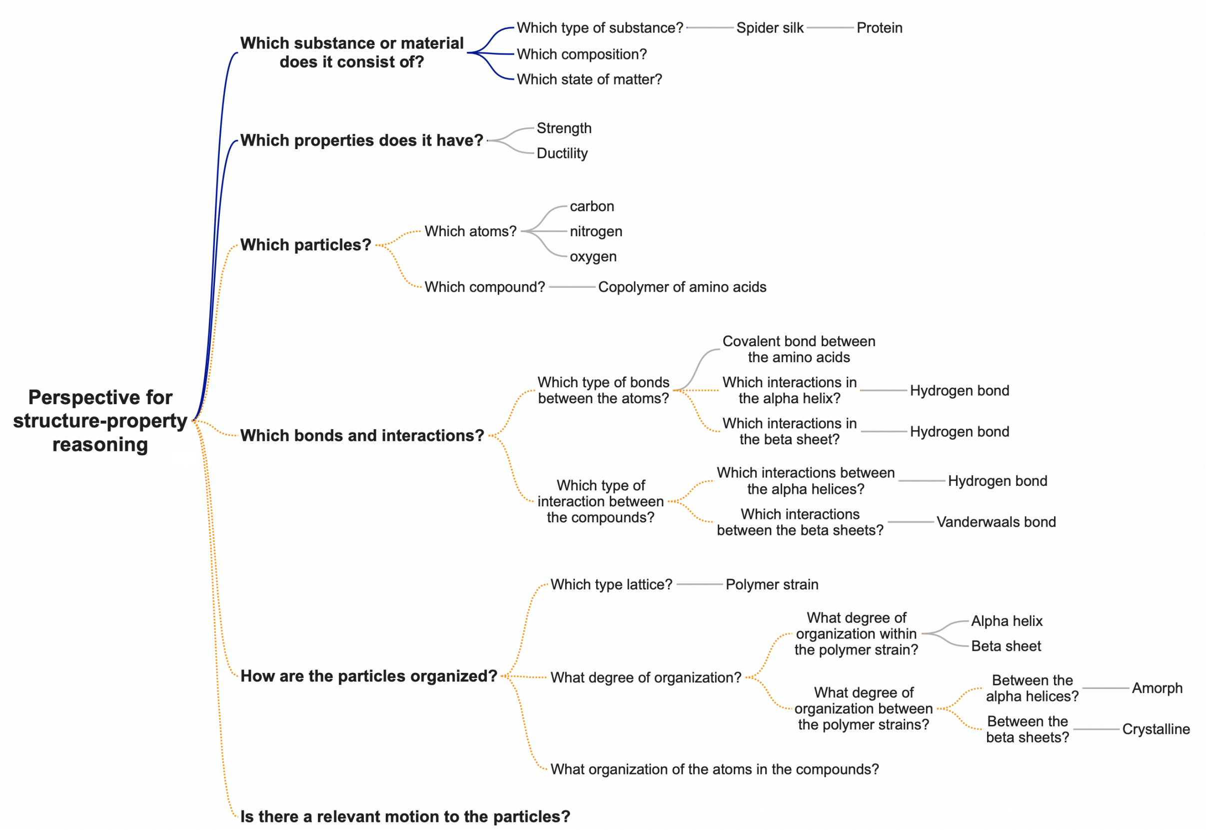

Figure 2.7: *Elaborated perspective for structure-property reasoning for the case of spider silk.*

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.