Chapter 14
Perspectives for Teaching About How Science Works

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An integrative, perspective-directed, and practical approach to teaching the nature of science is elaborated in this contribution. The approach is *integrative* in the sense that students reflect on general and domain-specific aspects of knowledge development. In order to do this, students contribute to knowledge development using domain-specific *perspectives* that guide them in formulating questions as well as answers and criteria to assess those answers. The approach is *practical* in the sense that three heuristics were developed that offer teachers practical design support for redesigning their regular lessons into integrative, perspective-based lessons.

14.1 Introduction

There is a long-standing tradition that advocates the implementation of nature of science (NOS) aspects in science education (Lederman and Lederman 2014; Hodson 2014; Allchin 2013; Niaz 2011). Roughly two influential visions on the teaching and learning of NOS can be distinguished: a *general aspects* approach and a *domain-specific* approach (Kampourakis 2016; Duschl and Grandy 2013).

The "general aspects" approach suggests that a limited set of NOS aspects that are common to all the natural sciences should be explicitly taught in science education. Examples are "science produces, demands, and relies on empirical evidence" and "scientific knowledge is tentative, durable and self-correcting." Although different versions of the "general aspects" approach exist, some important aspects are

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common in all lists (see Kampourakis 2016 for an overview). Students often have misconceptions about these general aspects of NOS (Lederman and Lederman 2014). To address students' conceptions, teachers are advised to explicitly reflect with students on general NOS aspects, on the basis of both lesson situations (e.g., when students make observations through a microscope, the teacher can emphasize the difference between observation and inference) and historical cases of scientific research (see McComas and Kampourakis 2015 and in this volume as Chapter 30 for many historical cases to illustrate general aspects of NOS).

The domain-specific approach to teaching NOS takes a somewhat different stance. In this approach, students, with support from their teachers, participate in scientific practices such as formulation of research questions, and to the development and critical testing of models and constructing arguments (Duschl and Grandy 2013). The premise is that students, by participating in scientific practices and by reflecting on process and product, develop not only scientific knowledge but also insight in domain-specific aspects of knowledge development. If, for example, students are stimulated to develop particle model explanations for certain properties of substances and to reflect on explanations and process afterwards, they learn not only about specific aspects of particles, such as different types of particles giving rise to different types of bonds, but also about the type of questions that become relevant in the process of searching for a particle explanation, the nature of particle models and their limitations, and what are valid arguments for evaluating such models.

The approach to teaching NOS that we elaborate in this chapter builds on both the general aspects and the domain-specific approach, but differs in three ways: it is an integrative, perspective-directed, and practical approach to teaching NOS. We will briefly discuss each of these three aspects.

Integrative We agree with Kampourakis that both general and domain-specific approaches have valuable elements and that students need to be offered opportunities to gain experiences with both. Kampourakis (2016) proposes that students are first taught a general aspects approach, before they are taught a domain-specific approach. In our approach we integrate both in the opposite order. Students are stimulated to contribute themselves to knowledge development, supported by the teacher. Reflection on the product and the process of knowledge development contributes to insight in the scientific models that are used and developed and in domain-specific ways of thinking. After participating in this type of knowledge development processes in the context of different domains, the teacher can reflect with the students on their experiences and on more general aspects of NOS.

Perspective-Directed There is broad consensus among philosophers of science that knowledge development is directed by more general ideas (Kuipers 2007). Ideas such as "substances consist of particles" and "properties of organisms fulfil a function" are not the outcome of research but rather the starting point. Such ideas direct what are relevant type of questions, which type of models are developed, and what are important criteria for evaluating these models (see, for an overview, Kuipers 2007). Different terms are used to refer to these general ideas, such as paradigms

(Kuhn), research programs (Lakatos), and perspectives (Giere). In our approach we prefer the term "perspective" because it covers the function of the general ideas. A perspective lights up certain aspects of the "real world" and directs the research on those aspects. At the same time a perspective blinds you for other aspects. Therefore, many complex problems ask for a multiperspective approach (Wimsatt 2007). A researcher's background and goals determine to a large extent the perspective or perspectives he or she adopts in the process of knowledge development (Giere 2010b). Philosophers of sciences broadly subscribe the significance of perspectives as epistemic scaffolds. In spite of this, perspectives are rarely elaborated in the domain-specific approach to NOS in science education, as scaffolds for supporting students with knowledge development. Perspective-directed knowledge development is central to our approach. It provides opportunities for students to reflect on possibilities and limitations of perspectives, and subsequently on the nature, the strengths, and the weaknesses of specific domain-specific ways of thinking.

Practical Many proposals for teaching NOS, and especially those that are developed within the domain-specific tradition, are considered unpractical by teachers (Janssen and Van Berkel 2015; Janssen et al. 2013). The reason is that teachers are not provided with tools that enable them within the available time and resources to redesign their regular lessons in a relatively simple way to lessons that support students with contributing to knowledge development, without undermining other important goals such as cover content in time and create work order. This is one of the most important reasons of the lack of impact on practice of ambitious educational change proposals from the domain-specific tradition (Janssen and Van Berkel 2015). To meet the criterion of practicality, we therefore developed practical tools for teachers that enable them to implement our approach to NOS in their regular teaching practice.

In sum, in this chapter we propose a practical and integrative approach to teaching NOS that starts with engaging students in contributing to perspective-directed knowledge development. By reflecting on these experiences, students develop insight in domain-specific ways of thinking. After students have experienced different domain-specific ways of thinking this way, they can reflect with the teacher on general aspects of NOS. For this purpose we reformulated the NOS aspects that McComas (2008) proposes as questions.

This chapter is structured as follows. To illustrate the idea of a perspective and how perspectives function in domain-specific knowledge development processes, we first discuss the historical case of the chemist Pauling and the biologist Burnet. Both wanted to understand how a diversity of antibodies can be produced, but approached the problem from very different perspectives. This led to two different models for explaining the problem of diversity of antibodies. Next, we introduce the practical tools that teachers are offered to redesign their regular lessons into lessons that support students with perspective-directed domain-specific knowledge development, and with reflection on more general aspects of product and process. The type of learning processes that emerge are illustrated with two examples: a functional perspective in biology and a particle perspective in chemistry. Finally, we discuss how teachers can support students with reflecting on their experiences with perspective-based domain specific knowledge development to learn about general aspects of NOS.

14.2 An Illustration of the Role of Perspectives in Knowledge Development

The field of immunology had a period of rather stormy developments in the 1940s and 1950s (Silverstein 2009). One of the central questions at the time related to the mechanism by which the human body produces a variety of structures (antibodies) that are able to specifically recognize other structures (antigens) within the enormous diversity of those antigens found on invading pathogens and particles that might enter the body. Several models were developed to explain this specificity problem. The chemist Linus Pauling and the biologist Frank MacFarlane Burnet each approached the problem from their own scientific field in order to explain the phenomenon. This nicely illustrates the extensive influence of their scientific background on the modeling process.

In 1940, Pauling began his work on the unrevealed mechanism behind the specificity of antibodies from the perspective of his knowledge regarding inter- and intramolecular forces. He asked the question: "what is the simplest suggestible structure for a molecule with the properties observed for antibodies, based on the extensive information now available about inter- and intramolecular forces, and what is the simplest reasonable formation process of such a molecule?" (Pauling 1940, p. 2643). The model he designed came to be known as a direct template model for antibody formation. First the antigen "instructs" that an amino acid chain be formed, and then the protein is folded into the appropriate 3D structure, using the antigen as template. This direct template model was criticized by the biologist Burnet in part because he applied a functional biological perspective to the problem. Burnet argued that Pauling's model did not explain various aspects of the specificity problem that are functionally important for the survival and reproduction of the organism. Burnet's models, and those developed by other biologists in that period, "…were devised primarily to account for two sets of phenomena for which the direct template theory seems quite irrelevant. The first is the absence of immunological response to 'self' constituents and the related phenomena of immunological tolerance; the second is the evidence that antibody production can continue in the absence of antigen" (Burnet 1957*, p. 68).*

Thus, instead of clarifying the specificity of antibodies by the chemical structure and bonding of the molecules involved, Burnet wanted to explain the functional adaptations of antibody forming. He developed two alternatives. New insights in DNA function and protein synthesis resulted in both models being evaluated as rather unlikely. Burnet finally replaced the instruction-type models with a clonal selection model (Burnet 1957). This clonal model not only fitted neatly with the new insights in DNA and protein synthesis, but it also explained the functional adaptations of the immune response rather well. In Burnet's clonal selection model, the antigen does not "instruct" which antibody needs to be formed, but—analogous to the evolution theory—random cells first are produced with receptors that each can bind only one type of antigen. After binding the antigen (selection), the respective cell is produced rapidly, and its "offspring" will produce the specific antibodies.

This case shows that the chosen perspective not only determines how the research question is formulated, but what type of models are developed and which specific criteria are considered to be important when testing those models. In this case the chemical structure and bonding perspective and the functional biology perspective are complementary. Although Burnet's clonal selection model prevailed, Pauling's underlying molecular key-lock principle of biological specificity has inspired a variety of new research subfields, such as drug design.

14.3 Perspective-Based Knowledge Development in Science Classrooms

In traditional science lessons, students generally do not contribute to knowledge development, and perspectives hardly play a role. Schwab (1962) characterized these types of lessons as "rhetoric of conclusions." Knowledge is provided ready-made and subsequently mastered through practice with solving standard problems. Students do not learn what domain-specific ways of thinking and reasoning are that can be used to develop knowledge. How to convert traditional ready-made science lessons into science-in-the making lessons? For this, we developed practical tools (also referred to as heuristics) that enable teachers to redesign their regular lessons in a cost-effective way into lessons that support students with perspective directed knowledge development and with reflection on the nature of this process and its products (Fig. 14.1).

1. Reverse the usual sequence of lesson parts or lesson segments (reverse-heuristic).
2. Remove certain lesson parts or segments selectively, and offer these to students when needed (selective omission heuristic).
3. Formulate general ideas that underlie the topic and content at hand as questions (reformulation heuristic).

Below we will illustrate and explain these three heuristics by means of a biology lesson for grade 9 students about spiders making a web using the biological functional perspective. In addition, we discuss an example of knowledge development from the chemical particle perspective.

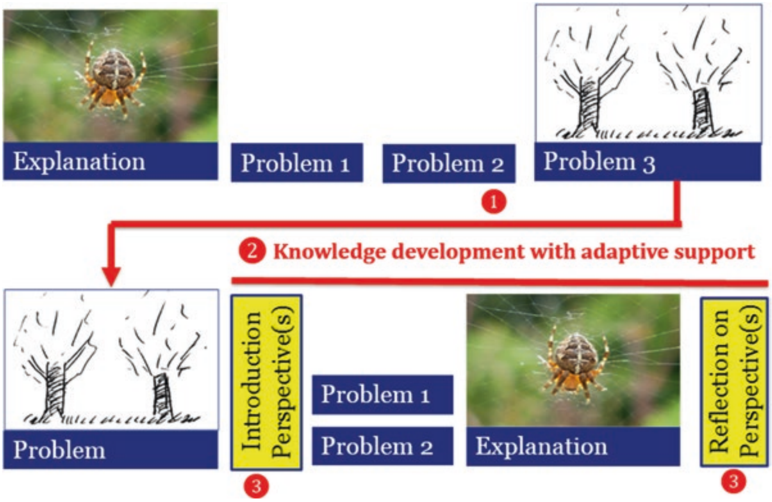


Fig. 14.1 Three heuristics for converting regular science lessons into perspective-based knowledge development. Exemplified for teaching about how spiders make their webs

14.3.1 Perspective-Directed Knowledge Development in Biology Education: Using a Functional Perspective

The regular lesson of the teacher in this case had the typical pattern of many science lessons (Janssen and Van Berkel 2015): First, the teacher explains the new subject matter, after which students work on problems in order to check whether they understood the new theory. In this case the teacher showed his students a video that showed a spider making a web. Next, students worked on a series of relatively easy and more complex problems, such as the following: students were asked how a spider secures that his prey does not fly away again after getting caught in the web (problem 1), and how do spiders tune their web to catch prey? (problem 2). And students were asked to draw a web between two trees and explain how a spider can make such a web (problem 3). Next we show how a teacher can redesign his or her lesson to a lesson that supports perspective-directed knowledge development using the three heuristics.

Reverse Heuristic In traditional lessons, knowledge is presented ready-made, whereas in perspective-based teaching, lessons start—similar to scientific research—with the formulation of the problem. First the teacher chooses a problem that covers the learning goals as much as possible and places the problem at the start of the lesson. The problem does not need to be the same problem as the original research problem that led to the knowledge development in the first place. It is important, however, that both the perspective and the knowledge that are taught in the particular lesson are needed for solving the problem. The teacher might want to adapt the problem to make it more suitable, relevant, and motivating for the students (see Janssen and Van Berkel (2015) for additional guidelines for problem formulation and problem introduction). In this particular case, the teacher chooses the problem "draw a spider web between the trees and explain how a spider can make such a web" (problem 3). This is a complex problem. Students will need support with solving it.

Selective-Omission Heuristic Lesson parts or segments can be used as an adaptive support for students. This implies that everything that students are offered in a regular lesson, such as "explanation of new subject matter" or "practice applying the new knowledge," can be considered support for solving the complex problem that is introduced at the start of the lesson. All these normal lesson segments are omitted and only offered to students when they indicate that they need the lesson segment. In this case, the teacher, for example, let his students think about the spider web problem for the first 10 minutes. If they got stuck, they were offered problem 1. Problem 1 contained a hint for the solution (a spider should at least make sure that a prey does not fly away again). After another 10 minutes, the teacher offered the video that shows a spider making a web and students were given the assignment to evaluate and to adjust and/or complete their theory of how a spider makes a web, using the information in the video.

Reformulation Heuristic The regular lesson is now redesigned into a lesson that supports students with contributing to knowledge development. A perspective that is fundamental to the subject matter at hand and that directs this process is still missing. An important idea that is fundamental to many properties of organisms is the idea of functionality: a property seems to be adjusted in such a way that it fulfils one or more functions in a certain environment with the least possible disadvantages for the survival and reproduction of the organism. This idea is well-known among biology teachers. For this idea to function as a perspective in a knowledge development process, it needs to be reformulated as a question or a set of questions (Fig. 14.2). The functional perspective enables students to develop knowledge concerning biological systems by means of redesigning the system at hand. The teacher introduces this way of thinking by modeling redesign of another biological system. Students use the biological functional perspective for developing knowledge about a property (structure or behavior) of an organism (in this case: making a web), by using the questions that belong to the biological functional perspective for guidance in redesigning and evaluating the property they are investigating (see below) in several subsequent cycles (see also Janssen and Waarlo 2010 for applications of this strategy in biology education; Green et al. 2015 for applications of this strategy in biological research).

In the fragment of student discourse presented here, Kim tried to come up with the simplest possible design for a spider web, whereas Marc tried to formulate what disadvantages Kim's redesign proposal had for the organism. This can lead to adjustment of the "solution" or to the formulation of a new problem.

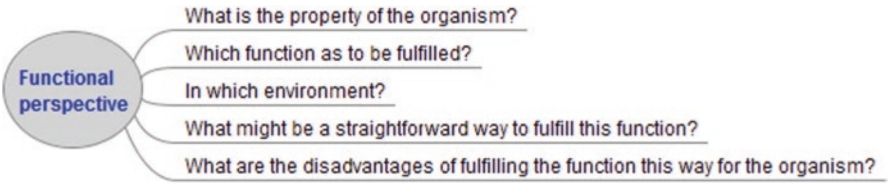


Fig. 14.2 Aspects of the biological functional perspective

Kim: Well that is simple. He [*the spider*] sticks the thread to the tree and walks down across the ground to the other tree.
Marc: Yes, but that certainly has a disadvantage. Then the thread would rip apart when he walks to the other tree.
Kim: I have a better idea. A sort of kite. He sticks the thread to the kite and the wind blows it to the other tree.
Marc: Well then the wind has to blow in the right direction by accident. But okay.
Kim: Okay, then he does it a few times so that he has a few threads and can go make the circles.
Marc: Yes but then a fly will walk away if he catches a fly. That is a disadvantage.
Kim: Than we have to make the threads sticky.
Eric: But then the spider will stick to his own web.
Marc: Eh, how do we do this. Shall we look at the whiteboard?

This fragment of student discourse shows how the functional perspective directs the knowledge development of the students about how spiders make a web. At a certain point they made use of problem 2 that the teacher had put on the whiteboard. After 10 min the students were given the assignment to compare their theories to the video that shows how a spider makes a web.

We described how students can learn to use a certain perspective for thinking about complex problems. However, to develop an understanding of the possibilities and limitations of a domain-specific perspective or way of thinking, reflection on the perspective used is necessary. Insight in the assumptions that underlie a perspective can be developed by using examples that the assumption does not apply to. In this case the teacher can, for example, ask the students what the function is of our chin, or the noise that our heart makes. The properties in these examples do not fulfil a function. Some properties are side effects of properties that do have a function. The cross on the back of the spider, for example, does not have a function in itself (Fig. 14.1). A spider secretes waste through little tubes and this becomes visible in the form of a cross. By means of this kind of examples, students become more aware of assumptions underlying a perspective and subsequently in which case it is useful to use the perspective and in which case not.

14.3.2 Perspective-Directed Knowledge Development in Chemistry Education: Using a Particle Perspective

Students need to understand that to explain behavior of matter, you need knowledge not only concerning particle types and types of chemical bonding (and their strengths) but also concerning organization of particles. A regular chemistry lesson to 16- to 17-year-old A-level students would typically start with an explanation of how particles of different types of matter are typically organized, given the chemical bonds between the particles (Fig. 14.3). A logical connection would be made with what they already learned: how organization and movement of particles explain the behavior of substances in different phases. This knowledge is used to explain about how chemical bonds and their strengths determine how particles of molecular substances, salts, and metals are organized at room temperature. To explain how the organization of particles, as an emerged property of particles and bonding between those particles, influences behavior, models of organized particles can be used. Next students work on part tasks such as: explain why ice floats on water or explain how water molecules are organized around sodium chloride ions when sodium chloride is solved. The lesson ends with a more complex task (this might be homework): both graphite and diamond consist of carbon atoms. However, both substances behave totally different: diamond is, for example, one of the hardest substances that we know, whereas graphite, which is used in pencils, is very "soft." You can easily

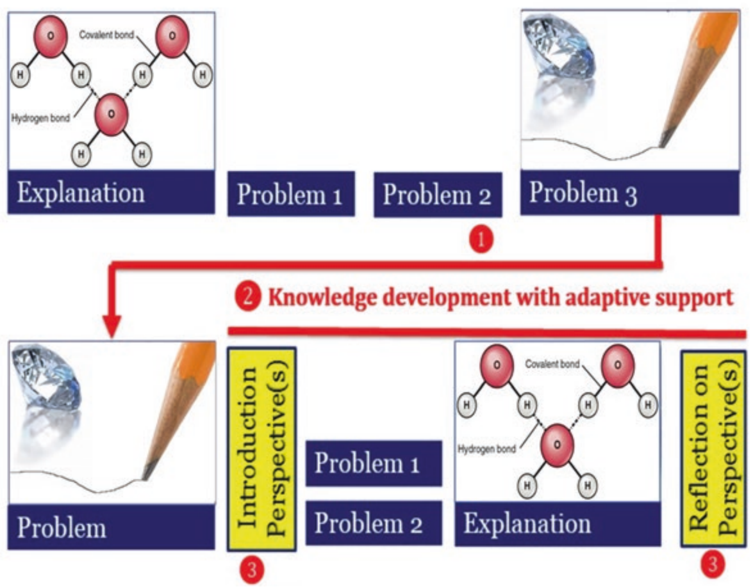


Fig. 14.3 Three heuristics for converting regular science lessons into perspective-based knowledge development. Exemplified for teaching about the organization of particles

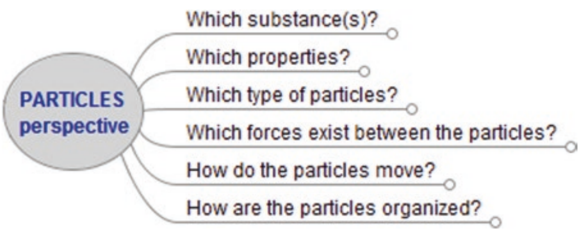
wipe off ultrathin layers from graphite. How can you explain this difference? To solve this latter problem, all branches of the particle perspective are needed both to understand the problem (the differences) and to find an answer.

In the reversed lesson, the diamond-graphite problem is brought to the fore (Fig. 14.3). By emphasizing the strangeness of the case (why are these substances *so* different), students are stimulated to solve the problem. The particle perspective is offered as a tool for thinking about it: what type of bonding is possible between carbon atoms and what are relative strengths of these chemical bonds? And of course, how are the carbon particles possibly organized in both substances? If students need support, the teacher can offer them the part tasks about water and ice and the difference in boiling point between 2,2,-dimethylpropane and *n*-pentane.

A simple version (we call it an entry version) of the particle perspective was provided by the teacher to support knowledge development (see Fig. 14.4). Below is a fragment of the discussion that emerged in a group of three students (16 years old, A level) working on the diamond-graphite problem (T = teacher/S = student):

S1: The nature of the particles is the same: all C-atoms.
S2: The bonds should be different, so there should be another structure too.
S1: Diamond is harder, so the bonds are stronger. Graphite has weaker bonds; the material breaks off more easily.
S3: Which bonds are strong? Ionic bonds? O no, that's stupid, both materials are molecular. There can't be ionic or metal bonds.
S1: Can you melt diamond?
S2: Perhaps it's like coal: one big molecule.
S3: Diamond doesn't look like carbon.
S1: Okay, let's focus on the bonds.
S2: Graphite could be more like in rows, like a metal, you can shove off a layer, not like with a salt.
S3: Diamond can be a lattice, a crystal lattice; that's why, it is so strong.
S2: But does that mean a different bond or a different organization?
S1: How could there be different bonds?
S2: Single bonds or double atomic bonds?
S2: So, in diamond, all atoms are linked with double bonds.
T: Could you draw that option?
S2: [Draws]
S1: No, that's not good, you only make a very long molecule, no crystal. I don't think triple bonds would work either.

Fig. 14.4 Particle perspective: entry version



S3: I think there should be more symmetry.
It should have something to do with differences in bond strength.
T: Why didn't you consider Van der Waals forces?
S1: I didn't think carbon atoms could form molecules.

In this example, students reasoned that the differences between diamond and graphite might be explained by the strengths of the bonds between the particles and by the organization of those particles. As the type of particles (C-atoms) and the property of the substances (hardness) were already given, certain bonds and movement were ruled out. Students used the particle perspective to explore options, focusing on the questions "what forces exist between particles?" and "how are the particles organized?" They extended these branches of the particle perspective with different options they knew exist, i.e., differences in organization of particles in diamond (crystal lattice) and graphite (rows), and the possibility of double and triple bonds between the C-atoms in diamond (see Fig. 14.5). However, they considered different covalent bonds, but did not consider the possibility of Van der Waals forces between large particles, which would imply big molecules of carbon as an option. Although differences in organization of the particles are suggested to explain the different properties between graphite and diamond, this train of thought is not pursued further in this fragment (but might have led to the idea of "big molecules").

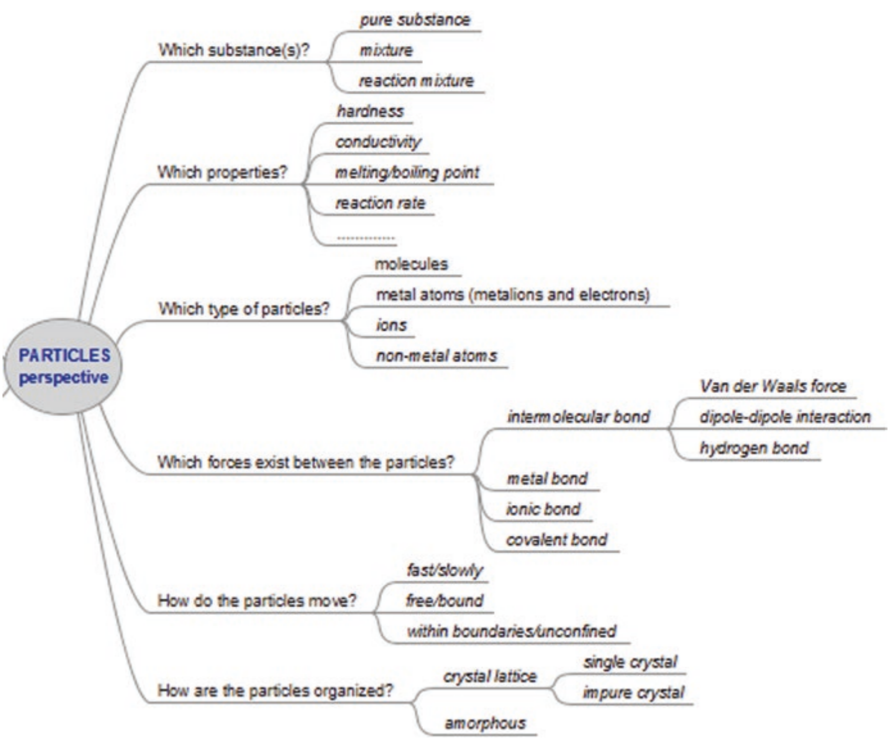


Fig. 14.5 Particle perspective: more advanced version

14.4 How Can Perspective-Based Knowledge Development Contribute to Understanding of General Aspects of Nature of Science?

The examples of the spider web and the diamond/graphite problem show how teachers can redesign their regular lessons into lessons that support perspective-directed knowledge development relatively easy. They show how perspectives can support students in developing scientific knowledge. At the same time, students become familiar with domain-specific ways of reasoning that belong to specific perspectives, the assumptions that underlie these perspectives, the questions that are connected to specific perspectives, and how answers can be constructed and tested. After participating in this type of knowledge development processes in the context of different domains, the teacher can reflect with the students on their experiences and on more general aspects of NOS (Table 14.1). In this final section we elaborate the relation between the perspective approach to knowledge development and general aspects of NOS (McComas and Kampourakis 2015).

Therefore we rephrased the NOS core aspects as questions (Table 14.1). Students can be stimulated to think about these questions drawing on their experiences with knowledge development about topics, using multiple perspectives. Reflection on general aspects of NOS can also be stimulated using historical cases, such as the case of Pauling and Burnet discussed in a previous section (Allchin et al. 2014; for an overview of historical case studies that are already available, see Allchin 2012). We will discuss how the NOS core questions can be addressed. For this we draw on widely shared ideas in the philosophy of science on the role of general searchlights for knowledge development (Kuipers 2007). More specifically, we draw on scien-

Table 14.1 Core aspects of NOS rephrased as questions

Core aspects of the nature of science associated in three domains	Questions
Human elements in science	What aspects of science are subjective?
	Is creativity vital to progress in science?
	Does science depend on social and cultural factors?
Tools and products of science	Is evidence required in science? What counts as evidence?
	Does science follow a stepwise plan?
	What is the nature of laws and theories?
Special nature of scientific knowledge	How does science differ from technology and engineering?
	Is science tentative, durable, and self-correcting?
	Does science have limits?

tific perspectivism as a recent and advanced approach on knowledge development that emphasizes the important role of perspectives for knowledge development. Important representatives of scientific perspectivism are Giere (2010a, b), Wimsatt (2007), and Callebaut (2012). For an overview, see Janssen and Van Berkel (2015).

14.4.1 Domain #1: Human Elements in Science

Subjectivity Is a Factor Scientific perspectivists assume that there is a reality that is independent from human knowledge construction (Giere 2010a; Wimsatt 2007). However, our knowledge of reality is always constrained by our perspectives and incomplete. We cannot achieve a "view from nowhere" (Wimsatt 2007). Our mind does not function as a bucket that fills itself with "true knowledge" by unprejudiced observation. Instead, our mind is more like a searchlight; our interests and perspectives determine what kind of questions we ask and what kind of knowledge we will develop. This "orientation" aspect can come to life when students reflect on their own experiences and how they use multiple perspectives as search lights. Also historical cases can be used to make insightful how multiple perspectives functioned as search lights that illuminate different aspects of the situation. Take, for example, the case of Pauling and Burnet that shows that two perspectives were needed to solve the antibody formation problem. But this does not mean that "anything goes." Scientific perspectivists argue that although perspectives are not empirically testable themselves, the knowledge developed within a perspective can and should be critically tested (Giere 2010a).

Creativity Is Vital Knowledge does not pour in our minds when we use our senses well; instead, knowledge development requires a creative leap. This applies to knowledge development within a perspective, as well as to the development of new perspectives. The development of the evolutionary perspective or the perspective of classical mechanics demanded enormous creative thinking, as it required the adjustment of, or even letting go of common assumptions and ideas (Thagard 2012).

There Are Social and Cultural Influences Because we are human, social and cultural factors do always play important roles in the choice of perspective (Thagard 2012). We can illustrate this with the case of Pauling that we discussed earlier. Pauling's research, for example, was not directed by biomedical problems at all at first. Shifts in the type of research funded at the time forced Pauling to do so (Nakamura and Csikszentmihalyi 2001). Since inter- and intramolecular forces were his expertise, he approached the new research area from this perspective.

14.4.2 Domain #2: Tools and Products of Science

Evidence Is Required Although social and cultural factors play important roles in our choice of perspective and the formulation of our expectations, we always need to critically assess our expectations by conducting experiments (Giere 2010a; Callebaut 2012). The case of Burnet and Pauling additionally shows that a perspective determines for a great part what data seem as relevant in order to test specific expectations. Pauling tested his direct template model with data on chemical bonding. Burnet collected data that followed from the biological functional perspective to test his model.

Science Shares Methods But No Shared Step-By-Step Plan Scientific knowledge development has three aspects: formulation of a question or problem, formulation of a tentative answer, critical testing of these answers (Popper 1973). As we have seen in the example of Pauling and Burnet, all three aspects are biased by the chosen perspective (Wimsatt 2007). As a result, there is no uniform protocol for conducting science that we can teach students. Instead, students need to develop different perspectives, such as the biological functional perspective and the chemical particle perspective, and learn how different perspectives might lead to different questions, possible (parts of) answers and ways to test those answers. In this way, perspectives can become thinking tools for investigating certain situations (Janssen and van Berkel 2015).

Nature of Laws and Theories Scientific perspectivism argues that knowledge has a hierarchical structure (Giere 2010b). At the top of the hierarchy are the assumptions that are fundamental to the perspective at hand. When descending in the hierarchy, knowledge becomes increasingly concrete. Figure 14.4 represents a fragment of the knowledge hierarchy within the chemical particle perspective. A knowledge hierarchy implies that knowledge development within a perspective starts with a general idea (properties of substances can be explained by properties of particles), which is then gradually elaborated in detail through the process of science (different possible properties of substances and particles). This can be seen as progressive differentiation of the perspective. When students develop knowledge using perspectives, such as the chemical particle perspective, this will result in increasing branching of the perspective (see Fig. 14.5). By comparing multiple perspective "trees," the hierarchical structure of perspectives can be made insightful. Besides differentiation, it is also possible to further generalize a perspective. The evolutionary perspective is a good example of this. Initially, three conditions for evolution by selection (variation, heredity, and differential fitness) were only applied for explaining the evolution of new functional properties of organisms and new species. This perspective was generalized by different authors. It may now be applied to explain a variety of phenomena that include a form of adaptation, e.g., in neurology, immunology (clonal selection model), human sciences, chemistry, and epistemology (Bickhardt and Campbell 2003). Students can also be stimulated to verify to what extent a particular perspective that they used in one domain (e.g., biology) can be applied in another domain (e.g., technology). The biological functional perspective that we discussed using the spider web example has many communalities but also differences with a technological structure-function perspective. By exploring the communalities and differences, students develop insight in which aspects can be generalized, and which aspects cannot. In both cases, it is, for example, assumed that a structure has multiple functions. However, from the biological perspective, those functions are always connected to survival and reproduction, whereas from a technology perspective, different types of functions are possible.

14.4.3 Domain #3: The Special Nature of Scientific Knowledge

Science Is Distinct from Technology and Engineering Technology and engineering are essentially about the question how a current situation can be transformed to a desired situation. In science, the core questions are "what is the case?" (description of the situation) and "why is this the case?" (explanation of the situation). Although the questions and methods differ, scientists make use of technology in their investigations. Technology can even deeply influence science. It produces tools that enable us to create observations that greatly extend our limited possibilities as human beings (e.g., MRI scans, telescopes, electromicroscopes). New discoveries by new technologies can lead to whole new research fields (e.g., the discovery of bacteria by van Leeuwenhoek) (Giere 2010a).

Science Is Tentative, Durable, and Self-Correcting Both absolutism and relativism are avoided within perspectivism. Scientific perspectivists and relativists agree that knowledge is not absolute, but is a human construct (Bunge 2006). However, as we remarked before, scientific perspectivists argue that though perspectives are not empirically testable themselves, development of perspective-based knowledge is and should be testable (Callebaut 2012). Therefore, knowledge can be improved so that it fits the real world better than before, but knowledge is always fallible and connected to a perspective (Wimsatt 2007; Giere 2010a). To clarify this general aspect for students, a series of historical cases that concern the same topic can be elaborated (see, for immunology, Silverstein 2009).

Science Has Limits We are only able to perceive limited aspects of reality (Giere 2010a). Scientific perspectivism acknowledges the perspectival character of our knowledge. A perspective always provides a partial and incomplete picture of the world. There are some problems that can be solved without bringing information from outside the perspective. Many problems, however, require a coordination of information from multiple perspectives (Wimsatt 2007). The need for multiple perspectives can be illustrated by many historical and topical cases. Also ethical and social aspects can come to the fore, for example, genetic testing, plastic soup, and climate change.

In this contribution we discussed an approach to teaching NOS that differs in three aspects from other dominant approaches to teaching NOS. First of all, our approach integrates a "general aspects" approach to teaching NOS and a domain-specific approach to teaching NOS. Additionally, we acknowledge in our approach the central role of perspectives in knowledge development, as epistemic and directive scaffolds for articulating questions, and assessing tentative solutions. Finally, we explicitly acknowledge that teachers have limited time, resources, and capacity in their regular practices for developing NOS teaching approaches. To meet the criterion of practicality, we developed three *practical* tools for redesigning regular lessons into lessons that support teaching NOS this way.

References

Allchin, D. (2012). The Minnesota case study collection: New historical inquiry cases for nature of science education. *Science & Education, 21*, 1263–1282.

Allchin, D. (2013). *Teaching the Nature of Science: Perspectives and Resources*. St Paul: SHiPS Education Press.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: Integrating student inquiry, contemporary cases and historical cases in classroom practice. *Science Education, 98*, 461–486.

Bickhard, M. H., & Campbell, D. T. (2003). Variations in variation and selection: The ubiquity of the variation-and-selective-retention ratchet in emergent organizational complexity. *Foundations of Science, 8*(3), 215–282.

Bunge, M. (2006). *Chasing reality: Strife over realism*. Toronto: University of Toronto Press.

Burnet, F. M. (1957). A modification of Jerne's theory of antibody production using the concept of clonal selection. *The Australian Journal of Science, 20*(3), 67–69.

Callebaut, W. (2012). Scientific perspectivism: A philosopher of science's response to the challenge of big data biology. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences, 43*(1), 69–80.

Duschl, R. A., & Grandy, R. (2013). Two views about explicitly teaching nature of science. *Science & Education, 22*(9), 2109–2139.

Giere, R. N. (2010a). *Scientific perspectivism*. Chicago: University of Chicago Press.

Giere, R. N. (2010b). An agent-based conception of models and scientific representation. *Synthese, 172*(2), 269–281.

Green, S., Levy, A., & Bechtel, W. (2015). Design sans adaptation. *European Journal for Philosophy of Science, 5*(1), 15–29.

Hodson, D. (2014). Nature of science in the science curriculum: Origin, development, implications and shifting emphases. In *International handbook of research in history, philosophy and science teaching* (pp. 911–970). Dordrecht: Springer.

Janssen, F. J. J. M., & van Berkel, B. (2015). Making philosophy of science education practical for science teachers. *Science & Education, 24*(3), 229–258.

Janssen, F. J. J. M., & Waarlo, A. J. (2010). Learning biology by designing. *Journal of Biological Education, 44*(2), 88–92.

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), 1–43.

Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching, 53*(5), 667–682.

Kuipers, T. A. (2007). Laws, theories and research programs. In D. M. Gabbay, P. Thagard, J. Woods, & T. A. Kuipers (Eds.), *General philosophy of science: Focal issues* (pp. 1–97). Amsterdam: Elsevier.
Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education, Vol 2 (30)* (pp. 600–620). New York: Routledge.
McComas, W. F., & Kampourakis, K. (2015). Using the history of biology, chemistry, geology, and physics to illustrate general aspects of nature of science. *Review of Science, Mathematics and ICT Education, 9*(1), 47–76.
McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17*(2–3), 249–263.
Nakamura, J., & Csikszentmihalyi, M. (2001). Catalytic creativity: The case of Linus Pauling. *American Psychologist, 56*(4), 337.
Niaz, M. (2011). *From 'Science in the Making' to Understanding the Nature of Science*. An Overview for Science Educators. Routledge.
Pauling, L. (1940). A theory of the structure and process of formation of antibodies. *Journal of the American Chemical Society, 62*(10), 2643–2657.
Popper, K. (1973). *Objective knowledge*. Oxford: Clarendon.
Schwab, J. J. (1962). The teaching of science as enquiry. In J. J. Schwab & P. F. Brandwein (Eds.), *The teaching of science*. Cambridge, MA: Harvard University Press.
Silverstein, A. M. (2009). *A history of immunology*. Academic Press.
Thagard, P. (2012). *The cognitive science of science: Explanation, discovery and conceptual change*. Cambridge, MA: MIT Press.
Wimsatt, W. C. (2007). *Re-engineering philosophy for limited beings: Piecewise approximations to reality*. Cambridge: Harvard University Press.