Universiteit Utrecht

M.s.c. Science Education and Communication

Promoting secondary school student's understanding of the nature of science through quantum physics education

Master's thesis

Lisette Helder

Supervisor:

Dr. ir. K. (Kim) Krijtenburg-Lewerissa
Utrecht University

February 2025

Abstract

Prior research has suggested quantum physics may be a natural physical context to foster student understanding of the nature of science. However, it remains unclear whether students are able to translate their new profound views into profound arguments, although this skill is essential for scientific literacy. During and at the conclusion of a QP period, data was collected on the NOS understanding of two Dutch secondary school groups of 24 students each (ages between 16-18 years). The two groups had different teachers but followed the same textbook. Data was was analyzed within two different frameworks in order to investigate not only the declared NOS views, but also the argumentative resources of students. Data collection included lesson observations, written work throughout the period, and an open-ended questionnaire with supplementing semi-structured interviews at the end of the period. The results suggest that even though during the period of QP many students indeed declared profound views on the nature of science in the context of quantum physics, students still frequently resort to naive ways of arguing to justify these views. Furthermore, new and profound views on the nature of science appeared to be limited to the context of quantum physics.

Contents

1 Introduction

Currently, there exists a pressing need to improve the scientific literacy (SL) of European citizens. As stated in a 2019 report by the European Parliament's Committee on Culture and Education: "Considering the emerging threats relating to the spread of misinformation and disinformation and the influence of anti-scientific movements, fostering scientific literacy among the population has never been more essential. (p. 7)" . Past attempts at improving student's SL include the growing body of research on ways to improve student's understanding of the Nature Of Science (NOS) (Abd-El-Khalick & Lederman, 2000a; N. G. Lederman, 2007).

Whilst this prior NOS research has put forth a myriad of educational strategies that could promote NOS understanding, such as the use of a historical approach, inquiry-based learning and contemporary contexts (Allchin et al., 2014), fostering student's NOS views during science lessons still often fails to be realised because of several reasons. First off, teachers may consider spending time on lessons about NOS too time-consuming, especially when teachers feel like spending time on NOS limits them in teaching about scientific content (Höttecke & Silva, 2011). Furthermore, research has shown NOS should be presented in an explicit and contextualized way in order to create consistent and content-rich student understanding (Clough, 2006), requiring more expertise of teachers than their 'traditional' science lessons. Especially since science textbooks frequently do not meet the need of presenting students with explicit and contextualized NOS (Höttecke & Silva, 2011), expecting teachers to acquire the expertise of integrating NOS in the existing lessons by themselves may be largely unachievable and in turn a more realistic approach to fostering student's NOS is needed.

As a way of addressing the need for a way of teaching NOS which requires little additional time and expertise from teachers, a recent study (Stadermann & Goedhart, 2020) suggests quantum physics (QP) may be an excellent physical context to do so. The study found that students who have followed QP education show higher levels of understanding NOS than students in other contexts, even though the teachers in the study said not to have explicitly referred to NOS in their lessons.

However, it should be noted that although the findings of the discussed study suggest that students have well-informed NOS views in the context of quantum physics, it remains inconclusive whether QP is a more effective context to promote student NOS understanding than other physical contexts. Moreover, the study focused on students' declarative knowledge on NOS, but student ability to act upon this declarative knowledge through sound argumentation remains relatively unexplored. It therefore remains unclear whether the found NOS views in the study do indeed contribute to student abilities in critical discourse about scientific issues, whilst this is a skill that any scientific literate individual should posses. As stated in the EU report discussed in the first paragraph (2019): "Scientific literacy goes beyond the mere knowledge of scientific content. It should be understood as the ability to engage critically with and make informed decisions about science-related issues (p. 7)".

This research aims to investigate the effects of QP education on not only students' de-

clared NOS views, but also students' way of arguing about science, through the use of two different frameworks. By placing an additional focus on the argumentative resources of students, rather than solely on students' declared understanding of NOS, more information is gathered on student's ability to translate potential knowledge of NOS into critical discourse about scientific claims. Not only does such an approach address the urgent need expressed by the European parliament of helping individuals navigate and discuss scientific knowledge, it also allows for a thorough investigation of what happens to students NOS understanding throughout a period of QP education.

2 Theoretical background

This research explores how quantum physics (QP) can promote student understanding of NOS, with the larger aim of improving scientific literacy. The first three sections explore the interplay between Scientific Literacy (SL), the Nature Of Science (NOS) and Quantum Physics (QP) education. Then a summary of two different NOS frameworks is presented, concluding with a paragraph on how these frameworks can be combined in order to research student NOS understanding in a well-rounded manner.

2.1 NOS as a prerequisite for SL

This research is pinned on the notion that understanding NOS is essential for developing SL. In extensive frameworks of SL, such as (OECD, 2025) and (Siarova et al., 2019), understanding the scientific method and the epistemological principles it is based on, is considered an essential part of SL. This 'how and why science works' is generally referred to as the Nature Of Science (Jenkins, 2013). That NOS can be considered a prerequisite for SL is also evident in prior research (Abd-El-Khalick & Lederman, 2000a; N. G. Lederman, 2007), and curriculum development documents, e.g. the 2010 Dutch national curriculum renewal report (Commissie Vernieuwing Natuurkundeonderwijs, 2010) that states that in order to foster SL of Dutch students, students should gain insights in NOS.

2.2 The role of context in NOS views

Even though there is a rich tradition of approaching student NOS views as context-independent, see e.g. (Khishfe & Abd-El-Khalick, 2002; Khishfe & Lederman, 2007), a growing body of research has found that students often express different, and even contradicting, NOS views in different contexts, without being aware of the inconsistency of their own views (Brickhouse et al., 2000; Clough, 2006; Leach et al., 2000; Ryder et al., 1999). One way of explaining these found inconsistencies in NOS views is trough the use of the theory of conceptual change. In a 2006 paper, Clough uses the theory of conceptual change to account for results found in NOS research. Even if a lesson is designed to confront students with NOS, he argues, "humans, by their very nature, make sense of experience in light of what they already know. Towards this end, learners attend to aspects of phenomena and other information that fit prior ideas, often unconsciously ignore contrary information, and sometimes modify incoming information so that it also fits what is already known. (p.469)" Essentially this means students may not feel the need to change their existing ideas on NOS within contexts that are not explicitly discussed. As a result, isolated context-free NOS lessons seem to be of limited value. In stead, NOS should be ubiquitously and explicitly integrated within the context of science lessons in order to establish well-rounded NOS understanding, .

Another way of explaining the found inconsistencies is that expressed inconsistencies may be a product of an inability of supporting one's NOS claims in the appropriate manner (Deng et al., 2011; Ford, 2008), meaning that some students who hold desired NOS views, may fail to translate these views to consistent argumentation's when asked on their views on NOS.

2.3 Quantum physics and NOS

Recently added to the Dutch physics curriculum, QP is suggested to be designed in such a way, that NOS is fostered without the need of extra time or expertise from the teacher. A 2020 Dutch study (Stadermann & Goedhart, 2020) employed open-ended questionnaires and in-depth interviews in order to evaluate the quality of NOS views of 24 secondary school students who had just followed a period of QP. The quality of their researched NOS beliefs was evaluated through a framework consisting of five NOS features relevant for learning quantum physics, shown in Figure 1 This framework is based on an international comparison of curricula (Stadermann et al., 2019) that identified the five most relevant features of NOS in learning QP. Even though the teachers that taught QP in the 2020 study said to not have explicitly mentioned NOS principles during the lessons, the study found that all of the 24 interviewed students showed desired NOS views. This is an exceptional result because implicit NOS instruction has so far been found to be relatively ineffective in teaching NOS (Deng et al., 2011, p. 974). The 2020 study furthermore compared the findings to student's NOS views in other contexts (Abd-El-Khalick & Lederman, 2000b; Khishfe & Abd-El-Khalick, 2002; Khishfe & Lederman, 2007)[1] and concluded that the NOS views of the students who had just followed QP were exceptionally well-informed.

This conclusion may intuitively not be surprising, because a historical approach and the comparison of the boundaries of classical physics are embedded in QP education, which allows students to be introduced to aspects of the Nature of Science (NOS). Even though QP is taught differently in different countries, there seems to be an international consensus that QP allows for a natural way of introducing NOS. As pointed out by a 2022 Dutch study (Stadermann & Goedhart, 2020) "QP is science-in-the-making where fundamental aspects are still controversial in contrast to ready-made science as traditionally taught in school physics". Additionally, Norwegian researchers concluded QP facilitates discussions about the philosophical aspects of physics (Henriksen et al., 2014) and a textbook analysis on Chinese QP textbooks (Han & Wei, 2024) found QP to be "a unique resource for NOS representation in science textbooks (p.1)" where "QP naturally elicits philosophical questions that students can be urged to reflect on historical changes in the knowledge system, thus providing valuable chances to look into NOS (p.3)"

However, the original study by Stadermann and Goedhart (2020) differs significantly from the studies that are used for comparison in both theoretical foundations of NOS, and consequently in methodological approach. Firstly considering theoretical foundation, the original study views NOS views to be dependent on the context, meaning different NOS views may be expressed depending on the context the views are situated in. The paper thereupon researches students NOS views through the use of tenets about NOS that are adapted to the context of QP. Contrarily, all studies used for comparison measure NOS views in a context-independent way. If student views on NOS are indeed dependent on the context students are working in, comparing the findings of the original context-dependent study with context-independent studies is of limited value.

From the above it is evident that research on the effect of QP on student's NOS is limited in that it cannot be concluded that student NOS understanding is better than in other

[1]The article includes a fourth study the results are compared to(Herman et al., 2017), but this is not an empirical study and will therefore be left out of this analysis.

(physical) contexts, because the theoretical foundation, and with that the methodological approach, differ significantly from the studies used for comparison. Yet, also taking into account the didactic character of QP as discussed above, this research still considers the found well-informed views of students enough reason to further investigate the effect of QP on student's NOS.
Another point of improvement of the original study is that the students enacted NOS views remain relatively unexplored. As argued for in example (Deng et al., 2011) and (Smith & Scharmann, 1999), focusing on just declared NOS views of student may present an insufficient picture of their NOS understanding. In stead, an additional focus should be placed on student's ability to use NOS understanding to argue about scientific issues. In order to research both declared and enacted NOS views of students in the context of QP, two different frameworks are used.

2.4 Frameworks for evaluating NOS

In his review Deng et al. (2011) catagorizes NOS research into three frameworks, each with a distinct theoretical foundations and consequently methodological approaches. The frameworks include the uni-dimensional (UD) framework, the multi-dimensional (MD) framework and the argumentative recourse (AR) framework. The last two frameworks were used in this research and will be discussed in the next sections. This research does not consider the UD framework, because arguably this framework is a simplification of the MD framework that reveals a less detailed picture of student's NOS understanding.

The Multi-Dimensional framework
The multi-dimensional (MD) framework is pinned on the notion that understanding NOS is multi-dimensional understanding, where students can be ascribed a certain level of understanding for each NOS feature. NOS features include for example understanding the tentative nature of scientific knowledge and the socially and culturally embedded nature of science. Usually, level of understanding of a NOS feature is considered to range from a naive and empiricist view to a profound and constructivist view of science (Deng et al., 2011). Simply put, the empiricist beliefs there is an objective truth that exists independently from the individual and sooner-or-later, scientists can uncover this truth through experiments. The constructivist, on the other hand, presumes knowledge is constructed through social interactions and, with that, personal idiosyncrasies are not just a product of the scientists involved, but rather inherent to science (Deng et al., 2011).
The assumption of a continuum of student understanding of NOS, allows for quantitative data collection. As noted by Deng et al. (2011) in his review study, even when data is collected in a qualitative way, e.g. through interviews, data is often still analyzed in a quantitative way, by translating the findings to 'profoundness' of understanding for each of the NOS features. A popular methodological approach in this framework is the Views of the Nature Of Science (VNOS) questionnaire (N. G. Lederman et al., 2002a) where student views are coded as undesired views (i.e. empiricist), desired views (i.e. constructivist) or mixed views (i.e. a combination of empiricist and constructivist).
In the MD framework, student understanding of NOS has so far mostly been considered context-independent. As discussed in paragraph 2.2, this assumption is not supported by lit-

Figure 1: List of five NOS features relevant in in the context of QF. For each feature, an example of an undesired view and a desired view are given, as well as an illustration of the relevance of each feature for QP in secondary education. From: (Stadermann & Goedhart, 2020). N.B. The table is adapted to the vocabulary of this research such that it said NOS aspect in the original table where it says NOS feature now.

NOS Feature	**Example of an Undesired View**	**Example of a Desired View**	**Illustration of Relevance for QP in Secondary Education**
The role of scientific models	Scientific models represent reality as much as possible.	Scientific models and analogies show some aspects of phenomena in a simplified way.	Depending on the situation, either the wave model or the particle model is appropriate.
Tentativeness of scientific knowledge	Scientific methods yield absolute proof. Scientific knowledge is certain and unchangeable.	Scientific knowledge is always open to development, change and improvement.	It is not possible to understand quantum phenomena with Newtonian physics.
Creativity in science	Scientists always follow strict rules (the scientific method).	Scientists use their creativity and imagination.	The development of QP was only possible through out-of-the-box thinking and creative (thought) experiments.
Subjectivity in science	Science is universal, and scientists are objective; therefore, only one correct interpretation of phenomena is possible.	Science is influenced by non-scientific aspects like personal preferences or historical, cultural, social and economic conditions.	In contrast to other scientists, Einstein was convinced that QP is not a complete description of nature because he could not accept the randomness of QP as fundamental.
Controversies in science	Acceptance of new scientific knowledge is straightforward. Only one interpretation can be correct.	Discussions and disagreements about scientific ideas are essential in scientific development. Different interpretations may exist.	The discussions between Einstein and Bohr show how different philosophical positions result in contrasting interpretations. There is still no consensus about the interpretations of QP. An open atmosphere without strict ideologies makes new developments in QP possible.

erature, and consequently this assumption has received notable criticism (Deng et al., 2011; Rudge & Howe, 2013). A way of addressing this criticism is by doing context-dependent research in the MD framework. This is for example done by the discussed 2020 study on QP and NOS (Stadermann & Goedhart, 2020), where questions of the VNOS questionnaire are adapted to the context of quantum physics. A significant disadvantage of this approach however, is that, in order to assure context-dependent measurement, a different measuring device has to be designed for each context. As a result, measuring devices are hardly generalized. Moreover, further criticism of the MD framework is that well-informed declarative views of students do not assure students are also able to argue about scientific issues in a scientific way. The argumentative resource framework addresses this criticism and is discussed in the next paragraph.

The Argumentative Resource framework

In contrast to the UD and MD frameworks, studies in the AR framework focus on *how* students argue about science, rather than *what* the contents of the arguments are. Studies in this framework generally reject the idea that discourse is a neutral reflection of internal (NOS) views, making it meaningless to treat expressed NOS views as a measure of what students really think about NOS. In stead, studies may focus on how studies construct and criticize claims about (the nature of) science, as for example done by Roth and Lucas (1996b). In their longitudinal study on NOS in physics, the authors identified nine types of interpretative repertoires (IR) that the students in the study used to motivate and criticize claims about the nature of science. The choice of repertoire essentially reflects what students deem an appropriate epistemology in the context they are working in to justify the argument they are making.

A full list of attempted summaries of the descriptions presented in (Roth & Lucas, 1996b, p.157 - p. 161) is presented below:

1. Historical repertoire:

This repertoire appeals to specific events or advancements in the evolution of scientific knowledge.

2. Empiricist repertoire:

This repertoire appeals to the classical scientific method (existing of e.g. observation, experimentation, and hypothesis testing) as the path to reliable knowledge, successfully filtering out the influence of human idiosyncrasies and/or mistakes.

3. Rational repertoire:

This repertoire appeals to exercising clear reasoning, making valid inferences, and establishing logical relationships between events. Students may either stress the importance of logical reasoning, or exercise logical reasoning themselves. Consequently, within this repertoire, perceived irrationality of a claim is reason to reject the claim.

4. Cultural repertoire:

This repertoire appeals to the notion that societal norms, beliefs, and values shape individual and collective understanding, including scientific knowledge.

5. Perceptual repertoire:

This repertoire appeals to the individual and/or relative nature of human perception and how human understanding is fundamentally limited by the limitations of human senses.

6. Representational repertoire:
This repertoire appeals to the role of language in scientific theorizing. Within this repertoire, it is established that language does not constitute truth, but rather describes it.
7. Authoritative repertoire:
This repertoire appeals to the impact of established scientific paradigms, peer influence among scientists, commonly accepted beliefs, or the opinions of acknowledged experts, on scientific development.
8. Intuitive repertoire:
This repertoire appeals to intuitive knowledge, common sense and (shared) experiences. Statements in this repertoire can e.g. start with "I feel like", "it is obvious that" or "from my experience".
9. Religious repertoire:
This repertoire appeals to belief in a supernatural being, e.g. by resourcing to religious texts and teachings.

IRs should not be confused with themes. Rather, only comments that are in line with the epistemology of the repertoire described above, should be considered part of the respective repertoire. For example, both comments: "Experiments can be misleading" and "This is true because it is what we have seen in many experiments", are about experiments, but only the latter is considered to be part of the empiricist repertoire, because it aligns with the epistemology described above.

2.5 Combining frameworks

Researching both student's declared and enacted NOS views, through the use of the MD and the AR frameworks respectively, can introduce a more comprehensive picture of student NOS understanding in light of SL. Students' profound declared NOS views, do not automatically guarantee the student can discuss scientific claims in a profound manner (see .e.g Zeidler et al. (2002)). And, visa versa, students who are be able to argue about science in an appropriate way, may declare poorly informed NOS views (see e.g. Ford (2008)). In this research, both the MD and the AR frameworks were taken into account to answer the research question:

RQ: How does quantum physics education support secondary students to learn about the nature of science?

3 Data collection

3.1 Procedure

During and at the conclusion of the QP period, data on student NOS understanding in the context of QP was collected and analyzed within the two different frameworks. Data collection took place in two groups. In both groups data collection included an open-ended questionnaire about QP in the context of NOS with supplementing semi-structured interviews at the end of the period. On top of this, in one group written work was collected throughout the period and the lessons were observed. Due to limited time, lesson observations and the collection of written work was limited to one of the two groups. Data collection is depicted schematically in Figure 2

	GROUP 1 (N=24)	GROUP 2 (N=24)
WEEK 1	▪ Lesson observations	
WEEK 2	▪ Lesson observations ▪ Written work: controversy (N=19)	
WEEK 3	▪ Lesson observations ▪ Written work : scientific models (N=17)	
WEEK 4	▪ Lesson observations ▪ Written work: tentativeness (N=15)	
WEEK 5	▪ Lesson observations ▪ Written work: subjectivity & creativity (N=19)	
WEEK 6	Questionnaire (N=20)	Questionnaire (N=16)
WEEK 7	Interviews (N=4)	Interviews (N=4)

Figure 2: Schematic depiction of data collection. A questionnaire with semi-structured interviews was carried out in both groups. Due to limited time, written work and lesson observations were carried out in only one of the two groups.

3.2 Setting

Data collection was carried out in two *vwo* 6 groups (students are 16-18 years old) at a Dutch secondary school. Both groups consisted of 23 students. Both teacher had studied physics and one teacher had 9 years of teaching experience, the other 15. The students in this study

followed a period of QP education. The QP period lasted approximately 8 weeks and each week included 150 minutes of lesson time. Both groups used the same textbook, but were taught by different teachers.

The textbook
The used textbook, *Systematische Natuurkunde* (SysNat), is widely used in Dutch education and includes all QP learning aims prescribed in the Dutch national syllabus. Similar to the other QP Dutch textbooks, it does not include any learning aims on NOS in QP. However, whilst all other Dutch QP textbooks still explicitly refer to some or all NOS features shown in Figure 1, SysNat does not (Smeets, 2019).

The lessons
Following the structure of the textbook, the majority, though not all, of the QP concepts were introduced through the use of a historical approach, and none of the lessons included inquiry-based learning or contemporary contexts. The discussed QP concepts, as well as the employed educational strategies, of each paragraph are shown in Figure 8.

3.3 Target NOS features

Even though a more extensive list, of approximately ten NOS features, has been widely researched in NOS research (Deng et al., 2011), this study focuses on five NOS features that prior research has put forth to be of particular relevance in QP education (Stadermann et al., 2019). These features, along with examples of desired and undesired views, both general and in the context of QP, are presented in Figure 1.

3.4 Questionnaire and interviews

Questionnaire
At the end of the QP period, students were asked to fill in an open-ended questionnaire about NOS in the context of QP. Students were asked to respond to each of the three statements shown in Figure 3, explaining which parts of the statements the student (dis)agreed with and why. Students were asked to formulate their response to each statement in at least six sentences, motivating their ideas and using examples where possible. The questionnaire was administered in a controlled classed setting: students were working individually and in silence. Each student completed the questionnaire within the set time limit, which was 30 minutes.
Important criticism of NOS evaluation methods is that forced-choice data collection is often based on the problematic assumption that students (dis)agree with statements because of the same reason the researcher does (N. G. Lederman et al., 2002b). For this reason, this study employed an open-ended questionnaire, because open-ended items allow students to elucidate on their own views on the targeted NOS features, without being constrained to forced-choice options given by the researcher.
The interview scheme of Stadermann and Goedhart (2020) was used as the basis for the

questionnaire in this study, though it was adapted to fit the contents of the QP lessons of this study. The contents of the questionnaire can be found in Figure 3.

Interviews
Eight students (±22%) were interviewed about their questionnaire responses. All interviews lasted between 20 and 35 minutes. Furthermore, all interviews were audio-recorded and transcribed verbatim. The interview scheme is shown in Figure 4.
Because student NOS views are considered context-dependent, administering a pretest at the start of the instructional period is meaningless, as most students have little to no prior knowledge of (QP) at that stage. Consequently, assessing changes in NOS views becomes more challenging. To address this, questions specifically targeting changes in students' views were incorporated into the interview process. The interview thus served two purposes. First off, the interviews were used to check if the researcher correctly interpreted students' questionnaire responses. Secondly, the interviews were used to ask students if their NOS views had potentially changed throughout the period, and if so, what lessons and/or topics made them change their views. Students were only asked about the features tentativeness, scientific models and creativity, because only a small part of the interviewees wrote about the other two features (subjectivity and controversy) in response to the questionnaire
For the selection procedure, both teachers were asked to select four students with varying levels of motivation and performance in physics. The eight selected students were asked to partake in interviews. Some students declined, and in those cases another student who fit the same category was asked.

3.5 Written work

Throughout the QP period, students were asked write down their answers to questions about NOS in the context of QP. Students were given the explicit instruction to do so individually and to be elaborate in their answers. Starting in the second week of the period, four sets of questions were covered; one each week. Questions were linked to the content of the lessons. In each set of questions, the first question was designed with the aim of testing if students had the minimal conceptual knowledge needed to answer the one or two questions that followed. Each of the following questions were turn related to one of the five NOS-features discussed in section 2.3. As an illustration, the first set of questions is presented below:

> **1.** Can you describe in one or two sentences the difference between Newton's and Huygens' theories about light? Tip: Check page 110 in the book.
> **2.** Do you think it's problematic that Huygens and Newton had different theories about light? Why or why not? Try to give a detailed response and support your answer

All questions can be found in Appendix A.
The questions were meant to be designed in such a way that they do not make explicit references to NOS, because if questions refer too directly to NOS, the questions themselves may influence student thinking and the effect of the QP curriculum on the students' NOS views

becomes less visible.

Figure 3: The three statements in the questionnaire and the respective NOS features each statement relates to. Students were asked to respond to each statement, explain why they (dis)agree with different parts of each statement.The questionnaire is based on (Stadermann & Goedhart, 2020), but is adapted to fit the contents of the QP lessons from this study.

Statement (translated from Dutch)	Related NOS features
Statement 1. Different physicists may have different ideas about the experiments that were important in developing quantum theory. This is because people make mistakes. But when we remain objective by continuing to follow the scientific method, sooner or later we will find out the truth about how the quantum world works. Then the quantum theory is complete and we no longer have to change the theory.	Subjectivity in science, Tentativeness of scientific knowledge, Controversy in science
Statement 2. Physicists should agree what model is the best one: the particle model or the wave model. After all a model is an exact representation of reality and only one model can be true. Switching between models is therefore unnecessary and confusing. Agreeing on one model would make it a lot easier for students in school.	Role of scientific models
Statement 3. Right now we cannot explain why electrons behave the way they do. But if physicists want to discover that, they need a lot of creativity to find an explanation. That is how new interpretations are developed. That is a part of science.	Creativity in science

Goal	Example questions
1. Warm-up	Did you like learning about QP? Did you think this chapter was different than other chapters?
2. Check interpretations	(For each of three NOS features) - What do you mean by 'theory'? - Can you explain what you mean by [quote]? What kind of errors do you mean? Can you give an example? - You're saying here that we may still need to tweak quantum theory when we think it's ready. Why do you think this?
3. Inquire about difference between QP and other physics	- Do you think [students' response on tentativeness] is different for quantum theory and other physical theories?
4. Inquire about change in views	I hear you say [students' response on tentativeness]. - Is that correct? - Did you already think this before this chapter? If no: - how did you think about this at the start of the chapter? - What made you think differently about this? Can you name topics/lessons/others?

Figure 4: A schematic overview of the interview scheme used in this study.

3.6 Lesson observations

In the 2014 paper, Allchin et al. (2014) points out that NOS research should focus on how lessons may affect student NOS understanding in regards to different NOS features, rather than expecting that all features are promoted in the same way. In order to address this need, the QP lessons in this study were observed to provide insight in the relevance of the five different NOS features in the QP lessons. Specifically, lessons were observed for the QP concepts introduced, the relevant NOS features, and the IRs used by the teacher. For the latter two cases, the respective coding schemes shown in Figure 5 and Figure 7 were used.

4 Data analysis

4.1 Analysis of written work and questionnaire responses

Student responses to both the written work and the questionnaire were first coded for the NOS feature(s) each response related to, using the coding scheme shown in Figure 5. Subsequently, the responses were coded as desired or undesired, using the coding scheme in Figure 6 The distinction between desired and undesired is based on (Stadermann & Goedhart, 2020), but to make it more concrete, each category (desired and undesired) is further specified in accordance to the responses collected in this study. Finally, the responses were coded for the IRs that students used to motivate their views on NOS features, using the coding scheme shown in Figure 7.

In both the written work and the questionnaire, some responses were not coded because of several reasons: because a response did not relate to any of the NOS features, because it

was not clear to the researcher what NOS view the student expressed or because the student did not (clearly) use an IR in their response. Furthermore, direct responses the questions and/or statements, such as "I agree with this statement" were not taken into account when determining student's NOS views. Rather, only NOS views that were explicitly formulated by students were considered. Finally, only one student formulated a response to the questionnaire that related to subjectivity in science, and similarly, in week 5 no students formulated a response that related to creativity in science. Therefore the NOS features are left out of the analysis in the respective weeks.
Some students referred to the same NOS feature in response to different statements in the questionnaire. Only when a student expressed desired views in each of the responses, was the student's NOS view labeled as desired for the respective feature.
Whilst in the original paper, Roth and Lucas (1996b) only identified nine IRs, in this study a new repertoire was added: the technological repertoire. Although the interplay between technology and scientific knowledge could arguably be scaled under the perceptual repertoire, a more detailed picture of student repertoires is presented by adding the repertoire separately -especially considering the repertoire was appealed to as frequently as some of the other repertoires. Furthermore, the notion of models as a representation of reality, rather than just language as a representation of reality, was added to the representational repertoire.
Lastly, all responses were first coded individually by the first researcher. To check for internal consistency 20% of the written work and 10% of the questionnaire was thereafter coded by a second researcher. There was 100% and 97,3% overlap in the coding of NOS features and desired/undesired respectively. In coding for IRs however, there was only 65% overlap. It was therefore concluded the coding scheme should be improved. In order to do so, ambiguities in the coding scheme were discussed by the first and second researcher. Based on this discussion, the coding scheme was adjusted and the same responses were coded again by the second researcher. After this second round the overlap was still only 75%. The first and second researcher then discussed their coding for each of the responses that caused disagreement and together agreement was reached . In doing this it became clear that 8 out of the 12 disagreements were caused by the researchers still deviating in the way they thought about the authoritative repertoire and the coding scheme was accordingly adjusted to more clearly define the bounds of the authoritative repertoire.

4.2 Analysis of interviews

After the interviews were conducted, the example of Abd-El-Khalick and Lederman (2000b) was followed in order to confirm internal consistency between the questionnaire and the interviews. Specifically, the interview transcripts were used to profile each student as desired/undesired for each of the NOS features that the student had discussed during the interview. Next a comparison was made to the profile that had prior been made based on the student's response to the questionnaire. No inconsistency was found between the profiles determined by the interviews and questionnaires. This confirmed that the questionnaire accurately reflected participants' NOS views, enabling further analysis to be undertaken.

NOS Feature	Examples of general views	Example of view in the context of QP
The role of scientific models (SM)	Scientific models represent reality as much as possible. Scientific models and analogies show some aspects of phenomena in a simplified way.	Depending on the situation, either the wave model or the particle model is appropriate.
Tentativeness of scientific knowledge (T)	Scientific methods yield absolute proof. Scientific knowledge is certain and unchangeable. Scientific knowledge is always open to development, change, and improvement.	It is not possible to understand quantum phenomena with Newtonian physics.
Creativity in science (CR)	Scientists always follow strict rules (the scientific method). Scientists use their creativity and imagination.	The development of QP was only possible through out-of-the-box thinking and creative (thought) experiments.
Subjectivity in science (SUB)	Science is universal, and scientists are objective; therefore, only one correct interpretation of phenomena is possible. Science is influenced by non-scientific aspects like personal preferences or historical, cultural, social, and economic conditions.	In contrast to other scientists, Einstein was convinced that QP is not a complete description of nature because he could not accept the randomness of QP as fundamental.
Controversies in science (CO)	Acceptance of new scientific knowledge is straightforward. Only one interpretation can be correct. Discussions and disagreements about scientific ideas are essential in scientific development. Different interpretations may exist.	The discussions between Einstein and Bohr show how different philosophical positions result in contrasting interpretations. There is still no consensus about the interpretations of QP. An open atmosphere without strict ideologies makes new developments in QP possible.

NOS feature	Desired view	Examples from this study	Undesired view	Examples from this study
Scientific models	Both models* should be used.	• Both models are partially true. A combination of the two should be used, though neither one is completely true. • The two models should be used because both are/can be true. • Both models should be used because both models are appropriate/representative, (depending on the situation). Models are a way of representing reality, rather than a constitution of reality.	One model should be used.	• Only one of the two models is true.
Tentativeness of scientific knowledge	QP theory is tentative.	• QP is open for change. But it is impossible to know if the theory is finished or not. • QP will never be complete.	QP theory is not tentative.	• QP will be different in the future, but it will be finished at some point. • QP is finished now.
Creativity in science	Creativity is essential in science.	• (Parts of) the scientific approach demands - among other things- creativity.	Creativity does not belong to science.	• Creativity has no place in science. • Creativity can be helpful, but it is not essential in science.
Controversy in science	Different interpretations of QP may exist.	• Developing new interpretations is part of science. • Different interpretations of QP exist now. This is good because this difference drives scientific progress. • Different interpretations of QP exist now. This is not because scientists make mistakes.	There should not exist different interpretations of QP.	• Multiple interpretations do not belong to science. • Multiple interpretations are problematic because the aim (of science) is to find the one definitive explanation.
Subjectivity in science	Social, cultural and paradigmatic influences affect the interpretations that scientists make.	• Scientific interpretations are subject to the established scientific paradigm they are made in. • Scientific interpretations are subject to social and cultural aspects.	Science is always objective.	

*two models in this case refers to the wave model and the particle model.

Figure 6: Coding scheme for coding the quality of student's declared NOS views. The scheme is largely based on the way Stadermann and Goedhart (2020) distinguish between desired and undesired views to allow for comparison later on. Both categories (desired and undesired) are further specified according to the responses found in this study.

Figure 7: Coding scheme for interpretative repertoires. The repertoires and their descriptions are adapted from (Roth & Lucas, 1996b). The technological repertoire was added by this author. The religious repertoire was not used by the students in this study.

Interpretative repertoire	Description	Examples from this study	Notes by author
Historical (his)	This repertoire appeals to specific events or advancements in the evolution of scientific knowledge.	*"So that Newton and Huygens did not agree caused a lot of developments in phsycics"*	
Empiricist (emp)	This repertoire appeals to the classical scientific method (existing of e.g. observation, experimentation, and hypothesis testing) as the way of successfully filtering out the influence of human idiosyncrasies and/or mistakes, making it the path to reliable knowledge.	*"We have seen an experiment in the lessons with all those dots with an interference pattern, there you can see that the wave model and the particle model are correct."*	Arguments appealing to things being proven (through experiments) belong to this repertoire. Arguments about needing different interpretations to find the right answer, are about using the scientific approach to filter out personal idiosyncrasies and should therefore be labelled as empiricist repertoire.
Rational (rat)	This repertoire appeals to finding logical explanations of phenomena, exercising clear reasoning and making valid inferences. Students may either stress the importance of logical reasoning, or exercise logical reasoning themselves. Consequently, within this repertoire, perceived irrationality of a claim is reason to reject the claim.	*"I do not think it problematic because they both had good arguments"* *"I think the term 'creativity' is weird here. Physicists should in fact come to their arguments in a logical manner."*	Arguments about finding logical explanations of experiments belong to the rational repertoire.
Cultural (cult)	This repertoire appeals to the notion that societal norms, beliefs, and values inherently shape individual and collective understanding, including scientific knowledge. True objectivity is considered impossible in this repertoire.	*"Because this [QP] is a subject that is pretty complicated and where you can think of different theories. Things that cause this are that physicist do not believe some subjects like these because they are about chance. "*	Different from the authoritative repertoire in that only socio-cultural influences on scientific thinking are considered.
Perceptual (perc)	This repertoire appeals to the individual and/or relative nature of human perception and how human understanding is fundamentally limited by the limitations of human senses and human imagination.	*"No, because we can't track it [quantum particles], new things will always continue to be discovered, I think"*	After doing the interviews it became clear that the notion that 'it is impossible for us humans to completely understand QP' was not a rational argument, but rather a perceptual argument, referring to our inability of observing all things needed to explain QP completely.
Representational (repr)	This repertoire appeals to the role of language and models in scientific theorizing. Within this repertoire, it is established that language and models[1] do not constitute truth, but rather describe it.	*"I also think we should use the best possible representation of reality, but that is not one of these two models. The way reality is best described now is by using both models and the switching between them, so until we have found a better model we should continue like this and not pick one of the two."*	Keep in mind that not any argument that is about models is representational, only when the student talks about models as a way of *describing* reality -not a constitution of reality.
Authoritative (auth)	This repertoire appeals to the impact of established scientific paradigms, peer influence among scientists, commonly accepted beliefs, or the opinions of acknowledged experts, on scientific development	*"I think that because it [QP theory] was new and a lot of physicist were not used to ascribing effects to chance, the results of the experiments were interpreted differently."*	Different from cultural repertoire in that only the influences of established paradigms on scientific thinking are considered here.
Intuitive (int)	This repertoire appeals to intuitive knowledge, common sense and (shared) experiences. Statements in this repertoire can e.g. start with ``I feel like'', ``it is obvious that'' or ``from my experience''.	*"I think it is hard to think what 'complete' would mean. I would not be surprised if in between a new discovery is made that shows there are more layers."*	Not all comments that start with "I think" or "I believe" are intuitive. Also take into account the formulation of the question (are students asked what they think?)
Religious (rel)	This repertoire appeals to belief in a supernatural being, e.g. by resourcing to religious texts and teachings.		
[2]Technological (tech)	This repertoire appeals to scientific knowledge being dependent on, and at the same time limited by, the technology that allows scientist to make relevant observations.	*"No, I think technology will always continue developing. Because of that discovering will continue."*	

[1] `` and models'' was added by this author.

[2]The technological repertoire was added by this author

5 Results

5.1 Lesson observations

Figure 8 shows the QP concepts covered each week. The concepts were introduced though lectures, after which students got time to practice with the exercises in the book, and occasionally discuss the exercises in class.
The figure furthermore shows the observed IRs used by the teacher. In order to illustrate this, several quotes are presented here.

To start off with, the teacher often used the empiricist repertoire:

> "If we use experiments to show that diffraction and refraction are visible, we know we are dealing with a wave." (teacher, lesson 1)

Furthermore, the teacher used the rational repertoire each lesson, usually when using formulas to discuss the relation between two or more variables:

> "Because of the sinus you can't just do that, because the relationship is not directly proportional" (teacher, lesson 3)

The teacher used the representational repertoire to explain the use of the wave function:

> "It's about the energy of a particle and we describe that with a frequency of a wave" (teacher, lesson 5)

Or to stress the distinction between describing reality though the use of classical theory versus quantum theory:

> "Classically they [alpha particles] don't have the energy to get out, so classically you wouldn't have radioactive decay. But, quantum mechanically speaking, there is a chance of being in the forbidden region." (teacher, lesson 9)

Additionally, figure 8 shows the NOS features that were relevant for each lesson. Notably, references to the NOS features were mostly made implicitly. For example, in week 3 the teacher discussed how the role of creativity in science was different in QP than in the physics the students had seen so far, without explicitly talking about the role of creativity in science:

> "That is not how you learned that science normally works: first think carefully and then derive a formula and then see whether the formula is correct. Planck just messed around a bit until he had a formula with which he could describe the measured curve very accurately. [..] He knew that this is the formula he had to arrive at. Then he worked for another 2 years to find the derivation of the formula. To find the derivation he had to assume this [E=hf]." (teacher, lesson 3)

In addition to this, the teacher implicitly discussed the nature and the role of scientific models when talking about different atomic models, as can be seen in the following quotes:

> "The classical image of an electron orbiting the nucleus like a planet orbits the sun is too primitive. And the shell model in chemistry is also a gross simplification." (teacher, lesson 8)

"The Bohr model is of course very primitive, but it is easy to use." (teacher, lesson 8)

Week	Lesson	Introduced QP concepts	(Implicitely) referenced NOS features	IR of teacher
1	1	Diffraction, refraction, interference, Young's experiment	CR, T	emp, his, rat, repr, int
	2	Photoelectric effect, wave-particle duality, probability, two slit experiment, observer dependence, classical theory versus quantum theory	CO, SM, SUB, T	emp, his, perc, rat, repr
2	3	Einstein Bohr debates, Bohr atomic model,	CO, CR, SM, T	emp, his, rat, repr
	4	*(repetition of a different chapter)*	-	-
3	5	Wave function, Davisson-Germer experiment, Debroglie wavelength	SM	his, tech, rat
	6	*(repetition of a different chapter)*	-	-
4	7	(one-dimensional) potential well, non-deterministic position of a quantum particle	SM	rat, repr
	8	Tunnelling	SM	rat, repr
5	9	Pauli exclusion principle, band gap, (semi)conductors, isolators, spin	none	rat, repr
	10	Doping, pn-junctions	none	his, rat

Figure 8: The introduced QP concepts, relevant NOS features and used interpretative repertoires (IRs) of the first 10 lessons of the QP period. Lesson activities included lectures, time to practice with the exercises in the book, and discussing exercises in class. NOS features were generally referred to implicitly.

5.2 NOS views during and at the end of the period

Figure 9 shows the number of students who expressed desired and undesired in each week and the questionnaire. In all weeks, the students seem to have quite well-informed views.

	Desired	Undesired
Week 2 (N=19)		
Controversy in science	12	2
Week 3 (N=17)		
Role of scientific models	11	2
Week 4 (N=15)		
Tentativeness of scientific knowledge	9	2
Week 5 (N=19)		
Subjectvity in science	13	0
Creativity in science	-	-
Week 6 : Questionnaire (N=36)		
Controversy in science	12	3
Role of scientific models	26	1
Tentativeness of scientific knowledge	26	2
Subjectivity in science	-	-
Creativity in science	28	3

Figure 9: Amount of desired and undesired NOS views in the written work (week 2-5) and the questionnaire (week 6). The features creativity in science, and subjectivity in science were left out in week 5 and 6 respectively, because in these weeks little or no students formulated a response that related to these features.

Even within the same category (i.e. desired or undesired), students often talked about NOS in different ways. To illustrate the different ways students talked about each NOS feature, some comments of special interest are highlighted below.

Controversy

Not all students shared the same views on the nature of different interpretations. Some students claimed that different interpretations are a result of scientist making mistakes:

> If we continue in this way, we will probably find out many times that things that we previously thought were not correct and then we will eventually arrive at a complete theory.(student 3, questionnaire)

other students claimed different interpretations are not (necessarily) the result of scientists making mistakes:

> I think that different physicists can think differently about experiments, regardless of people making mistakes or not. People have different perspectives and because of this they can formulate different theories. (student 13, questionnaire)

In line with this, it was not always clear whether students considered multiple interpretations to be a good temporary solution until scientists have found the one true interpretation, or whether students considered controversy a fundamental and perpetual part of science:

> Personally I find it important that different ideas about a subject can lead to an answer. It is important that you look together to who is right or which data are we missing, rather than it becoming a debate about who is right. (student 35 questionnaire).

Scientific models

In week 3, students were asked whether they found the wave and particle model good models. In response to this some students related the quality of the models to their comprehensibility, other students related the quality of the models to their explanatory power and other students related the quality to both the comprehensibility and the explanatory power of the model. Not all students wrote the same about the relation between models and reality. On one hand, a part of the students talked about models as constitutions of reality, referring to models as being "true":

> Of course only one model can be true, but that does not mean that one model is better than the other. It can be that the truth is in between the models, making neither of the models the truth. Now, that does not have to be a problem, because the models work well to explain things. For example, the wave model and the particle model both have their advantages in explaining phenomena. So I don't think we should teach one model [to students]. (student 16, questionnaire)

On the other hand, other students talked about models as being representations of reality: students in this group talked about the two models as being "appropriate" and/or "representative", rather than true, and the majority of these students explicitly stated that models are a representation of reality.

> I also think that we should use the best possible representation of reality, but that is not one of the two models. The way that describes reality best now is through the use of both models and switching between them, so until we have found a better model, we should continue like this and not pick one of the two. (student 3, questionnaire)

Moreover, students were not always consistent in the way they spoke about the relation between models and reality, as can be seen in the following comments:

> They are both models so I would not say that they are true or untrue, they are ways of perceiving that you can apply to reality, but I would say that the particle model is more true than the wave model. (student 7, week 3)

> They are both true it is a duality sometimes it is one sometimes it is the other so they are not always right. But each one has their own function. (student 12, week 3)

Tentativeness
Interestingly, some students ascribed the impossibility of completing QP theory to the QP concept uncertainty:

> No, it seems impossible to me to finish quantum theory, because you cannot exactly predict the trajectory of quantum particles. (student 11, week 4)

Furthermore, a popular view was the idea that the more scientists discover about QP, the more they realize what they do not know yet:

> When we discover more and more I think that a consequence of that is that we will also see more and more what we don't know and that it will therefore become difficult to finish quantum theory. I think we will always find smaller particles, systems and branches. (student 17, questionnaire)

Remarkably, not all students seemed to understand what the scientific method is, as reflected in the following comment:

> I don't agree that we can only understand the quantum-world through scientific methods. I cannot exactly explain why, but I think that the quantum world is so complicated that is is made up of something that the scientific method does not understand yet. (student 27, questionnaire)

In line with this, some students mentioned that the scientific method was not sufficient to completely understand QP and scientist should try other methods.

Subjectivity
In week 5 students were asked if it is possible for scientists to interpret QP experiments in different ways and all 19 students agreed. When asked what may cause different physicists to interpret the same experiments in different ways. 11 students ascribed this difference to the influence of an established scientific paradigm (in this case Newton's wave theory or Huygens' particle theory) on scientific thinking, 1 student ascribed this to social and/or cultural influence on scientific thinking, and 2 students ascribed it to both:

> I think that because it [QP theory] was new and many physicists were not used to ascribe effects to chance, the results of experiments were interpreted differently. Like Einstein who refused to accept that a chance effect existed on the most fundamental level. (student 3, week 5)

Creativity
Many students who said creativity is an essential part of science, also stated that creativity alone was not sufficient for scientific progress, thorough experimenting and logical reasoning were also considered essential:

> Creativity to find an explanation is definitely part of science. For example with gravity on earth, you don't just know by looking how long the apple would take to reach the ground. For that, you have to do experiments where no one has every thought about. If that is not creative, I don't know what that word means. To understand electrons, there is therefore only one option: being creative. (student 26, questionnaire).

Other students disagreed and proposed that in stead of being creative, scientists should follow the scientific method:

> Discovering something like that [electron behaviour] does not require creativity, but a lot of research. Saying that an explanation requires creativity, implies that it is made up. Interpretations are developed through research and in this way improving a model until it is accurate enough. The method discussed in the statement therefore is not a part of the scientific process. (student 18, questionnaire)

However, during the interviews it became clear that not all students work with the same definition of creativity, possibly explaining the difference in views described above. Whereas all but one students loosely defined creativity as doing or thinking of something that has not been done or thought of before, one student equated creativity with not being bound to valid reasoning.

> Yes, I just don't think it [creativity] really fits with science, because I think creativity fits more with art subjects or something like that. Yes, you may be open to things, but I also have the idea that there are actually no limits to creativity, you know, so you don't necessarily follow everything. That you come up with really crazy things that don't actually make sense. (student 4, interviews)

5.3 Interpretative repertoires during and at the end of the period

Figure 10 and Figure 10 show the IRs used in response to the written work and the questionnaire respectively. Students used the IRs shown in the figure to motivate their expressed NOS views. Additionally, students sometimes used multiple repertoires to support their claims.
In both the written work and the questionnaire, the empiricist repertoire was used most frequently. Furthermore, the figure shows the repertoires were used in a different frequency when justifying arguments about different NOS features.

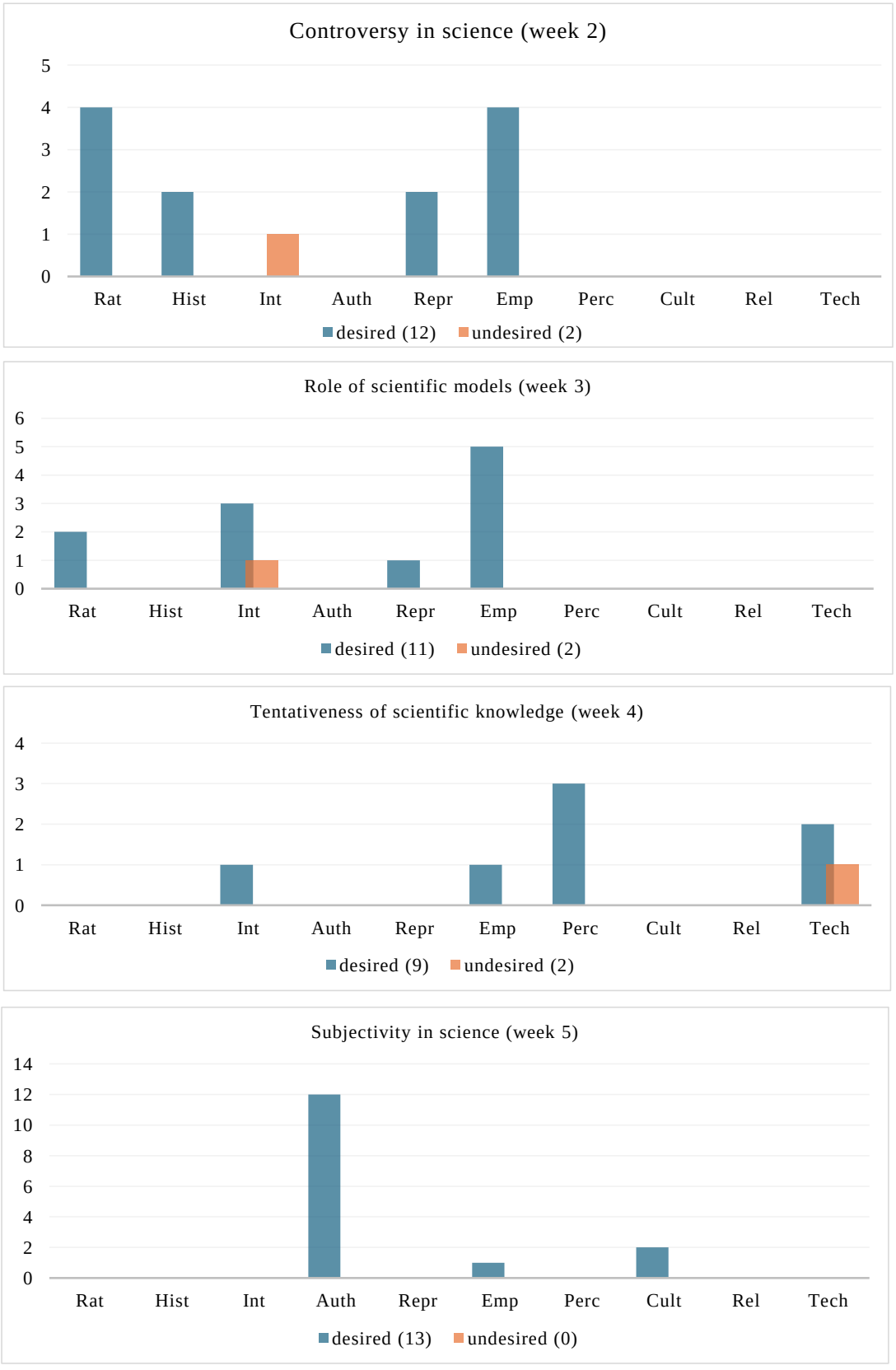

Figure 10: IRs used by students in response to the written work in week 2-5. Students used the IRs to justify their view on the NOS features shown here.

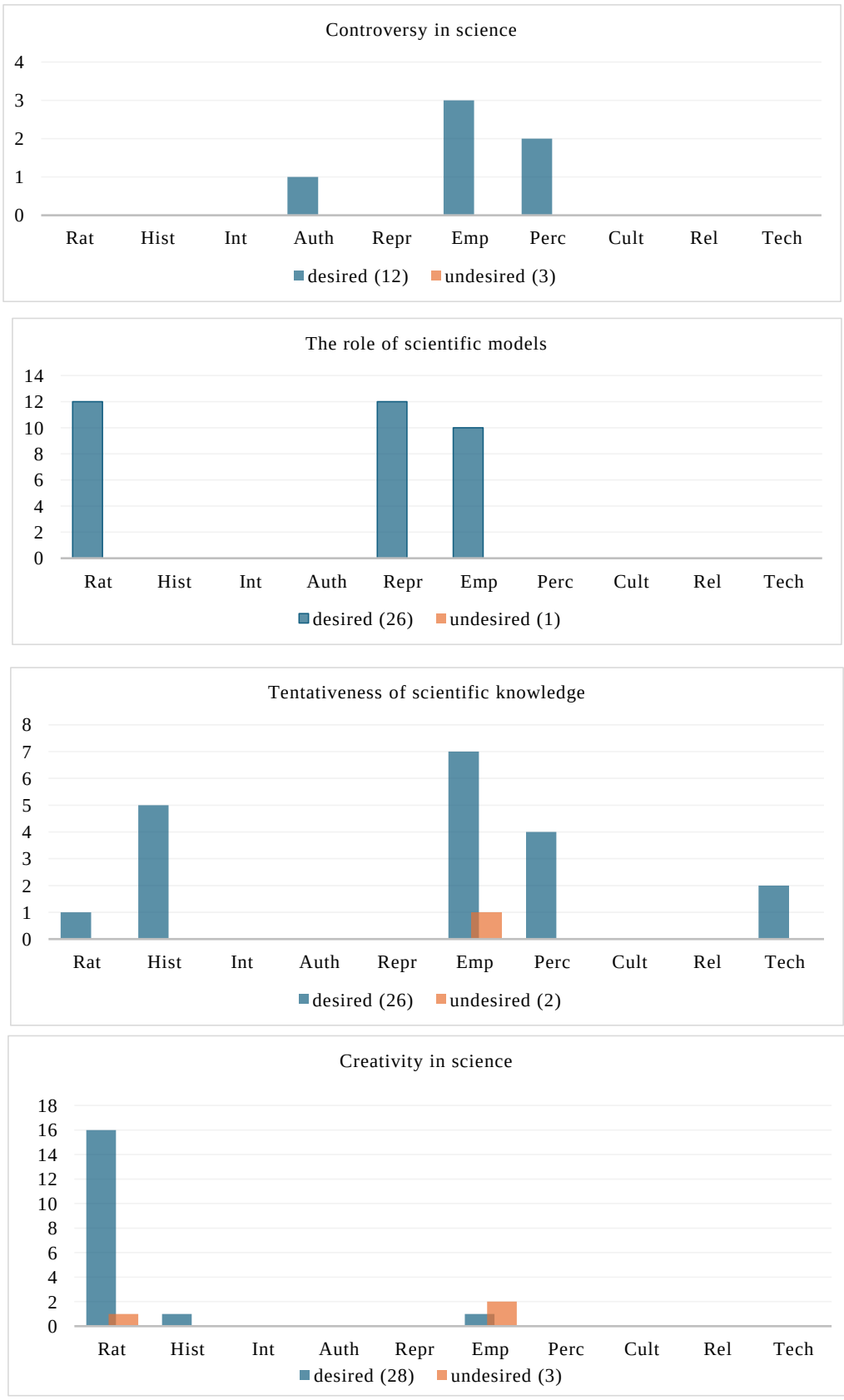

Figure 11: IRs used by students in response to the questionnaire in week 6. Students used the IRs to justify their view on the NOS features shown here.

5.4 Interviews

Figure 12 presents an overview of the part of the interview where students were asked about potential changes in their views and if their views differed for QP and other physics. In the figure students' motivation and performance are labeled: P- indicates poor performance, P+ indicates good performance, M- indicates poor motivation and M+ indicates high motivation. The figure shows that many students thought QP was different from other physics in regards to one or more NOS features. For example, one student said, relating to tentativeness of scientific knowledge, that whereas QP is unfinished, we fully know how some of the other physics works:

> **Researcher:** Other topics you have discussed include for example electricity, electromagnetism even, mechanics, so everything with forces and such. Would you say that we already fully understand that or not?
> **Student:** Yes, I think so.
> **Researcher:** And what about quantum?
> **Student:** You don't know that. We literally don't know. We still get the simplified version of what we know. We also get, say, the biggest question that Einstein was also working on: does light have wave behavior or light behavior? We get that question too. And with mechanics we get easy formulas about centripetal force of which we actually know exactly how it works.

From the group of students that did not distinguish between QP and other physics in regards to a feature, all of the students said they thought the same about the NOS feature at the start of the period. Moreover, from the group of students that did distinguish between QP and other physics in regards to a NOS feature, none of these students said their existing NOS views were challenged during the period. In stead most of these students commented that they did not know anything about QP at the start of the period yet and were therefore not able to change their NOS view on this feature.

5.5 Ambiguity in student NOS arguments

When talking about NOS in the context of QP, students were not always able to find the right language to explain or motivate their claim. The majority of the 8 interviewed students struggled to properly define one or more of the terms they used in their arguments. When asked to give their definition of a term they used, e.g. the terms 'model' and 'interpretation', students seemed to lack the vocabulary or knowledge to do so, and in stead often resorted to repeating their arguments or naming examples.
Furthermore, students sometimes expressed conflicting views, especially in regards to the tentative nature of scientific knowledge. For example, one student wrote:

> "I think one day we will have found out everything about the quantum theory. But I don't think we can ever say with certainty that we have indeed discovered everything. In my opinion, there is no experiment with which you can test that. You only have experiments that support your theory or not, but if we ultimately no longer find new situations in which the quantum theory is incorrect, I don't think that means that those situations do not exist." (student 7, questionnaire)

The student seems to first draw on an intuitive repertoire in the first sentence, but then continues to rely on the rational repertoire for the rest of the argument. As a result, the student claims both that one can never be sure we have discovered everything, and contrarily, also that they think that one day "we will have found out everything about the quantum theory".

Student	NOS feature	Difference between QP and physics	Topics that made students think about NOS feature
1	[1]T	Yes	
[2](P+ M-)	SM	No	
	CR	No	Two slit experiment
2	T	No	
(P- M-)	SM	No	
	CR	-	
3	T	Yes	Two slit exp. with observer
(P- M-)	SM	-	
	CR	No	
4	T	Yes	
(P- M+)	SM	No	
	CR	Yes	Particle in a well
5	T	No	
(P+ M+)	SM	No	
	CR	No	
6	T	Yes	
(P+ M+)	SM	No	
	CR	No	
7	T	-	
(P- M-)	SM	-	
	CR	No	
8	T	Yes	Wave particle duality
(P- M+)	SM	No	
	CR	No	

[1]T = tentativeness of scientific knowledge, SM = the role of scientific knowledge, CR = the role of creativity in science
[2]P+ = well-performing, P- = poorly performing, M+ = well-motivated, M- = poorly motivated

Figure 12: A summary of the interview results. The middle column shows whether students distinguished between QP and other physics for the respective NOS feature. The right column shows whether students said to have changed views on this NOS feature. '-' indicates a student was unsure or inconsistent.

6 Conclusions and discussion

6.1 QP and NOS

In this study it was found that after a period of QP, students generally declare a range of desired NOS views in the context of QP. The numbers of desired/undesired NOS views found in this study are comparable to previous findings. Table 1 shows the percentage of students that expressed desired and undesired views, in this study (right), and in the study by Stadermann and Goedhart (2020) (left). It seems that in both studies a large portion of the students expressed desired NOS views on the role of scientific models, creativity in science and the tentative nature of scientific knowledge, though more students expressed undesired views in this study than in the 2020 study.

	Stadermann (2020)		**Helder (2025)**	
NOS feature	**Undesired view**	**Desired view**	**Undesired view**	**Desired view**
The role of scientific models	0 %	100%	3%	72%
Tentativeness of scientific knowledge	0 %	100%	6%	72%
Creativity in science	4%	96%	9%	78%
Subjectivity in science	0%	100%	-	-
Controversies in science	0	100%	8%	33%

Table 1: Percentage of students who expressed undesired and desired view on five different NOS features, comparing the results from the interviews by Stadermann and Goedhart (2020) on the left (N=24), to the results from the questionnaire from this study on the right (N=36). Both studies investigate the NOS views in the context of QP of Dutch secondary school students (age 16-18) after they follow a period of QP lessons.

However, even though the majority of students generally seemed to express desired NOS views in the context QP, student NOS understanding was still limited in two ways.

First off, in this study, undesired views were defined in such a way that they are generally in line with the empiricist philosophy. Within these views, scientific progress is straightforward and does not require creativity and the scientific method is considered a way of filtering out human mistakes and idiosyncrasies, leading us to the one right interpretation in the end. From this it may seem like students who declare desired NOS views therefore successfully reject empiricist ideas about NOS, at least in the NOS feature in question. However, Figure **??** shows that many students declared a desired NOS view by relying on the empiricist repertoire. Essentially, these students are declaring a constructivist view, but still appeal to an empiricist way of thinking to justify this view. For example, the following student declares that multiple QP interpretations exist and are not the result of mistakes -a desired statement on controversy in science in the MD framework- but uses the empiricist repertoire to support their view, appealing to experiments as the path to reliable and objective knowledge:

> Different physicists may indeed have different ideas about experiments, but that is not because people make mistakes. In some experiments there is simply not enough knowledge to prove that one opinion is correct and the other is not. The

> two different opinions mean that more experiments need to be done to ensure that we have enough knowledge to determine a definitive outcome from an experiment. So by remaining objective we will sooner or later find out the truth about how the quantum world works. (student 28, questionnaire)

This result suggests that even though after a period of QP many students had accepted new profound ideas about NOS in the context of QP, students still frequently resorted to their more naive (i.e. empiricist) ways of arguing about science.
Likewise, previous research Baily and Finkelstein (2009) found that students often switched between the quantum perspective and the realist perspective to talk about QP, even though the realist perspective is insufficient to properly understand QP. Similarly to this study, students failed to completely adjust their discourse in line with their new QP knowledge, and in stead often relied on their traditional perspectives to justify their claims.

Secondly, from the interviews it could be concluded that students consider their NOS views in other physical contexts separately from their NOS views in the context of QP. Even when their NOS views were different in case of QP and other physics, students did not feel like their existing NOS views were challenged when learning about QP. The results suggest students may experience NOS works differently in QP than in other physics. This finding is in line with Clough (2006) who uses the theory of conceptual change to underscore that students usually only change their NOS views within the context that is explicitly discussed. Looking through the lens of conceptual change, this finding could indicate that a period of QP may encourage students to accept new and constructivist ideas about NOS in the context of QP, but not in other contexts.

Summarizing the above, even though a period of QP education seems to promote students NOS views in the context of QP, this effect seems to be limited to only declared -not enacted- NOS views and to NOS views only in the context of QP

Significance for SL
As mentioned before, this research serves the bigger purpose of researching student NOS understanding in light of their SL, broadening the focus from just students' declared NOS views, to also students' enacted views. In this study it was found that students often fail to form clear and internally-consistent arguments, even when their declared NOS views seem profound. Moreover, when students do succeed to formulate clear and consistent arguments, many students still relied on the empiricist repertoire to justify their views, even when their NOS views appeared constructivist. Hence, it appears students' SL after a period of QP education is still limited as students are often unable to translate their profound views into profound arguments.

6.2 Implications

In the remainder of this section, implications for future research will be discussed. The first paragraph discusses implications for research on NOS in the context of QP. Next, implications are discussed for NOS research in general and the last paragraph discusses how NOS research can better address the need of improving student SL. Finally, the implications for education are discussed in the last section.

Broadening the scope to more NOS features
The five NOS features that were investigated are put forth to be most relevant in QP by Stadermann et al. (2019). However, following the historical approach of the lessons, often experiments were discussed together with the theories that are based on the experiments. Therefore the nature of and distinction between observation and inference and the empiric nature of science could also be considered as relevant NOS features. Future research on NOS in QP could also take these features into account to research the effects of QP on NOS more extensively.

Systematic combination of frameworks
Within the large body of NOS literature that works within the MD framework, it is not always clear whether students' argumentation is taken into account when categorizing claims into desired and undesired. For example, N. G. Lederman et al. (2002b) writes that the examples that students use to back their NOS views should be "carefully examined and factored in when assessing respondents' views. (p.513)", but it is not clear how exactly this should be done. This research shows how the AR framework can be used to investigate expressed views and arguments separately, allowing for a more systematic way of investigating students' NOS understanding.

More focus on context-dependent data collection
This study shows a way of comparing student NOS views that are measured in the same context, which is in line with the growing body of literature that suggests student NOS views are context-dependent. As context-dependence implies the context students are working in affects their expressed views, comparisons of NOS views are only meaningful when they are compared to other views in the same context. By conducting more context-dependent data collection, as done in this study, more meaningful same-context comparisons can be drawn in the future.
However, conducting context-dependent research on a larger scale demands valid data collection methods in many different contexts. To allow for context-dependent data collection, future research should therefore first focus on designing and evaluating these methods.
The importance of developing valid context-dependent methods is highlighted in this study. Because there was no tried-and-tested way of evaluating student NOS views in the context of QP during a period, the written work questions had to be designed from the ground up. As a result, the questions were often structured in a suggestive manner, even though they were designed not to effect students NOS ideas. In fact, during the interviews said not to have thought about certain NOS features. This underscores designing valid context-dependent methods is an iterative process that demands several rounds of testing and evaluating.

More attention to the AR framework
When placing an additional focus on the argumentative resources of students through the AR framework, rather than solely on students' declared understanding of NOS through the MD framework, more information was gathered on student's ability to translate potential knowledge of NOS into critical discourse about scientific claims. It became clear students' argumentation did not automatically change when their declared NOS views did. This result highlights the MD framework is not sufficient to get a complete picture of students' NOS understand in light of SL, In stead, the AR framework should also be included to addresses the need expressed by the EU to improve student ability to critically engage with science.
However, the AR framework has received relatively little attention so far and as a result, there are few tried-and-tested ways of investigating students' NOS arguments.(Deng et al., 2011) Moreover, IRs have been critiqued for their complexity as an analytical tool, because analyzing IRs often demands a deep familiarity with the data and often involves an iterative process of developing and refining the interpretative frameworks (Deng et al., 2011). In this study, too, many arguments could not be coded for a repertoire, and the coding scheme had to be adapted to better fit the arguments in this study. This underscores a need for an AR evaluation method that is better adapted to investigating student arguments about NOS.
Furthermore, even though IRs allow for a systematic way of describing the type of arguments, it remains unclear how the model can be used as a way of evaluating the quality of an argumentation. For example, it has been argued that a bigger range of IRs may suggest the development of a critical stance (Roth & Lucas, 1996b, p.175), but it can be questioned whether a wider range of IRs also assures students are able to use the appropriate IR in the appropriate context. Unlike the NOS views in the MD framework, there are no agreements on which repertoire is most profound given a context. Future research should focus on using IRs in a way that allows for evaluating the quality of NOS arguments.

6.3 Implications for education

Within MD NOS research, internally inconsistent claims are often disregarded as 'mixed views', but the AR framework allows for another way of looking at these claims. The following student seems to first draw on an intuitive repertoire in the first sentence, but then continues to rely on the rational repertoire for the rest of the argument.

> "I think one day we will have found out everything about the quantum theory. But I don't think we can ever say with certainty that we have indeed discovered everything. In my opinion, there is no experiment with which you can test that. You only have experiments that support your theory or not, but if we ultimately no longer find new situations in which the quantum theory is incorrect, I don't think that means that those situations do not exist." (student 7, questionnaire)

As a result, the student claims both that one can never be sure we have discovered everything, and contrarily, also that they think that one day "we will have found out everything about the quantum theory".
By taking into account students' arguments, and not just their isolated declared NOS views, the above suggests it may be fruitful to not just expose students to NOS during instruction,

but to also scaffold students in using appropriate terms and interpretative repertoires to explain and motivate their NOS views.

Furthermore, the interviews in this study suggest students do not automatically translate their new NOS views to other physical contexts, but rather consider NOS in QP separately from NOS in other physics. This result confirms the need for context-rich NOS instruction that confronts students with profound NOS views in a wide range of contexts.

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A Written work questions

Week 2 Below are a few questions about what you have learned in physics so far. There are no right or wrong answers to these questions.

- Can you describe in one or two sentences the difference between Newton's and Huygens' theories about light? *Tip: Check page 110 in the book.*
- Do you think it's problematic that Huygens and Newton had different theories about light? Why or why not? Try to give a detailed response and support your answer.

Week 3 Below are a few questions about what you have learned in physics so far. There are no right or wrong answers to these questions.

Two models are described below. Read the descriptions carefully.

The particle model: Light consists of a stream of particles. A light source continuously emits light particles, and light rays are the paths of those particles.

The wave model: Light consists of vibrations that propagate very quickly. Light is a wave phenomenon, similar to sound or water waves.

- Do you think the particle model is a good model? Explain why you think so.
- Do you think the wave model is a good model? Explain why you think so.
- Is the wave model true? Is the particle model true? Explain for both models why you think that.

Week 4 Below are a few questions about what you have learned in physics so far. There are no right or wrong answers to these questions.

- Can you describe some differences between classical physics and quantum theory? *Tip: Check page 136 in the book.*
- Do you think the scientific knowledge we have about quantum theory will change in the future?
  - **If no:** Why do you think the scientific knowledge we have about quantum theory will not change in the future? Try to give a detailed answer!
  - **If yes:** Do you think quantum theory can ever be "complete"? Why or why not? Try to give a detailed answer!

Week 5 Below are a few questions about what you have learned in physics so far. There are no right or wrong answers to these questions.

- Can you name some experiments that have been important for quantum theory? *Tip: See, for example, pages 123, 125, and 133.*

- Do you think it's possible for different physicists to interpret these experiments in different ways?
  - **If no:** Why do you think it's not possible for different physicists to interpret these experiments in different ways? Try to answer in multiple sentences.
  - **If yes:** What do you think might cause different physicists to interpret the same experiments in different ways? Try to write down everything you can think of and respond in multiple sentences.