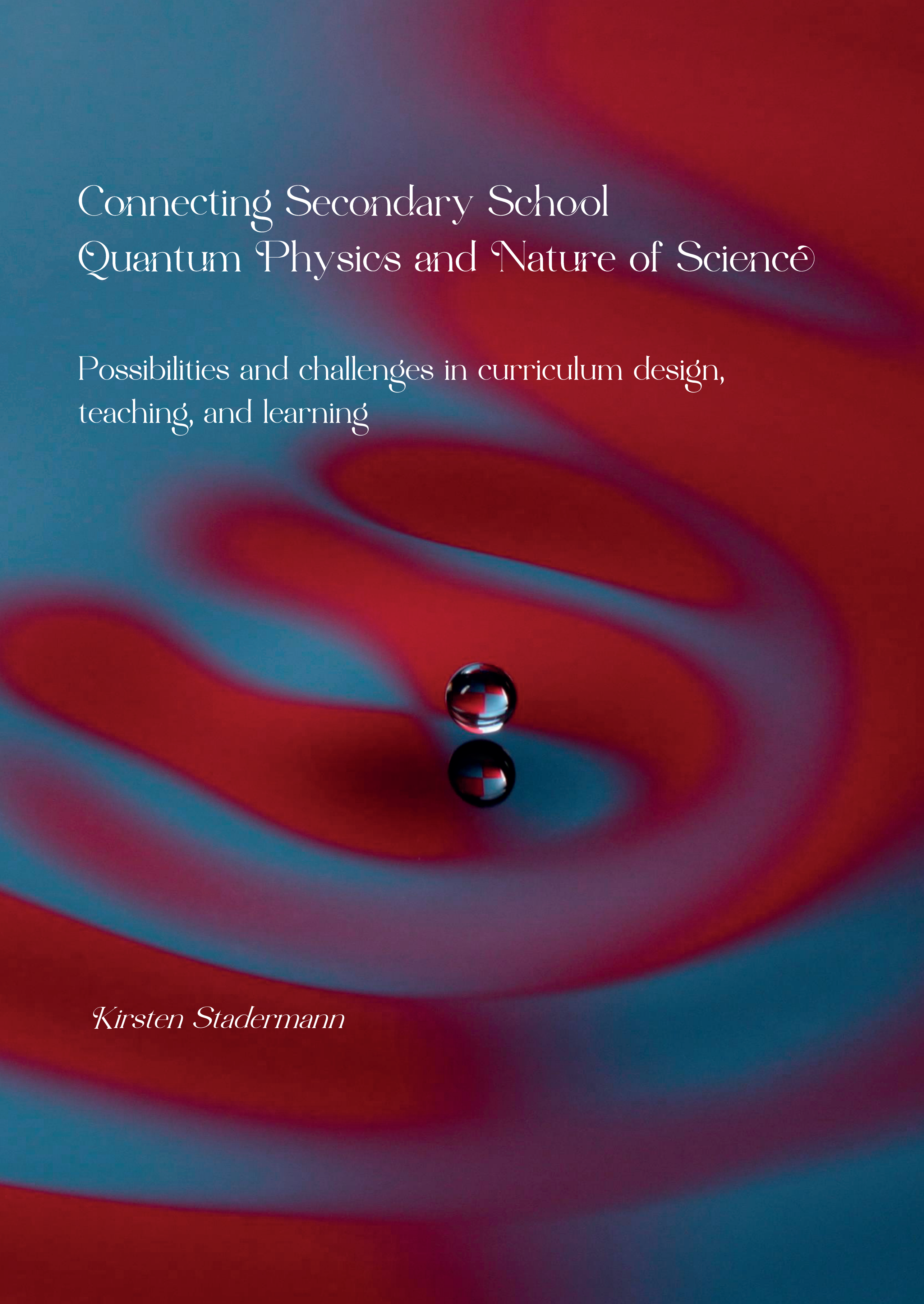

Connecting Secondary School Quantum Physics and Nature of Science

Possibilities and challenges in curriculum design, teaching, and learning

Kirsten Stadermann

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The Research Ethics Committee (CETO) of the University of Groningen has reviewed the research proposal under number 62688502 and has established that the research protocol is in conformance with internationally recognised standards for the protection of the research participants.

Cover: Photo of a walking millimetric silicon oil droplet, bouncing on a vibrating Petri dish, filled with silicon oil. Such walking oil droplets have been used by Bush (2015) to perform astonishing fluid dynamics experiments which resemble quantum physics phenomena. With ingenious lighting, Daniel Harris (2017) captured these hydrodynamic pilot-wave phenomena in aesthetic photographs. Photo credit: Daniel M. Harris.

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Connecting Secondary School Quantum Physics and Nature of Science

Possibilities and challenges in curriculum design, teaching, and learning

Proefschrift

ter verkrijging van de graad van doctor aan de
Rijksuniversiteit Groningen
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rector magnificus prof. dr. C. Wijmenga
en volgens besluit van het College voor Promoties.

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Heike Kirsten Elisabeth Stadermann

geboren op 4 april 1966
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Prof. dr. W.R. van Joolingen

Contents

Graphical overview of thesis

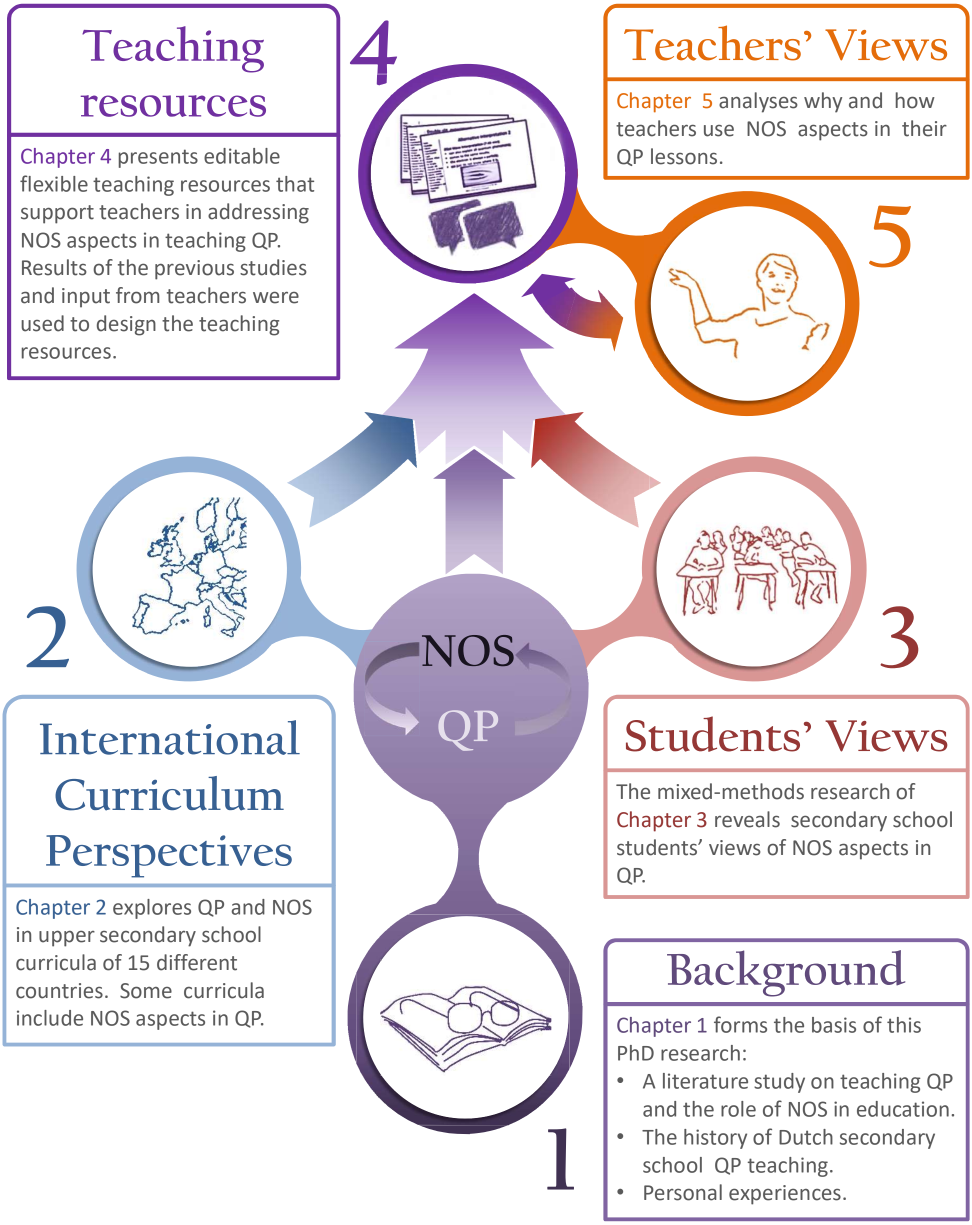


Figure 0-0 Graphical overview of Chapters 1 to 5 of this thesis.

Figures and Tables

Personal introduction

Each PhD research is a project that develops over several years and not only reflects scientific insights but is also a personal journey of the researcher. As with every journey in my life, in the beginning, there was not much more than a rough plan, a big amount of curiosity, and the hope – or actually the deep belief – that on the way, I would meet people who would inspire me and help me when necessary. In the following, I will explain why and how I connect my personal and my scientific evolution.

My research is about quantum physics (QP) and the Nature of Science (NOS), how these two constructs are intertwined, and how this connection can be fruitful for teaching and learning physics in high schools. My fascination for QP has a long history. I had a great physics teacher at school (Figure 0-1) who was enthusiastic about QP, and that was indeed the reason why I decided to study physics at the University of Münster in 1985. NOS, on the other hand, was an unknown term for me until 2016, when I started my PhD research. I had been unaware that the term NOS existed and that, over the years, a whole area of educational research about NOS teaching had developed. I was not unaware of what the term stands for: the way science works as a human enterprise.

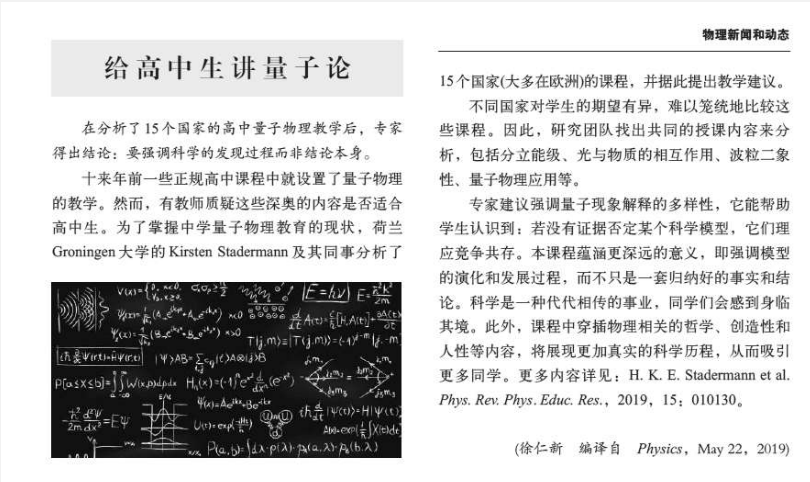
Figure 0-1 My high school physics class, with teacher Camen, at the Theodor-Heuss-Gymnasium in Hagen, 1985. Notice the Schrödinger equation on the blackboard

NOS teaching aims to dispel common myths such as “scientific knowledge is unchangeable and universal”, “scientists are 100% objective”, and “scientific research is a structured procedure that does not allow creativity” (Hodson, 1998; McComas, William F., 1998). These myths are created and supported not only by teachers and textbooks but also by the way scientific research is presented in research papers, conference contributions, and PhD theses (Glasson & Bentley, 2000). Especially in a PhD thesis about NOS, I feel that I should be as open and honest as possible about the fact that personal and social circumstances influence scientific research in a concrete local and historical setting (in physicists’ language: a point in space-time).

To make the NOS aspect of “science as a human endeavour” visible in my own research in this thesis, I do not keep all non-scientific influences for a limited acknowledgement until the end of the thesis. Once in a while, I will instead explicitly mention relations between my scientific research and other events of my life – as far as I am aware of them. Obviously, from my limited point of view, I cannot see everything that influenced my work. However, I hope to give an impression of how fellow travellers, incidental acquaintances, mentors, and supporters shaped and guided my research.

Another point I want to address is the grammatical choice of voice in this thesis. Science is human work, and this should be visible in a report on the work. Therefore, I will try to use the words “we” and “I” consciously. This project has been created in cooperation with co-authors and advisors, making the we-voice a natural style to describe our shared efforts in the joint projects of Chapters 2 to 5. However, I do not want to shift the responsibility for my ideas and decisions to anybody else. Therefore, other parts of this thesis are written in the I-voice. A third option is using the passive voice; however, I try to minimise its use because it creates a distance to the topic discussed, which does not reflect my research situation. I will reflect on my role as a researcher in Chapter 6.

One of the fantastic things about doing research and publishing articles is that people all over the world get to know the research. To my surprise, my first published article in this thesis even received a comment in a Chinese magazine for popularising university science:



物理新闻和动态

给高中生讲量子论

在分析了15个国家的高中量子物理教学后，专家得出结论：要强调科学的发现过程而非结论本身。

十来年前一些正规高中课程中就设置了量子物理的教学。然而，有教师质疑这些深奥的内容是否适合高中生。为了掌握中学量子物理教育的现状，荷兰Groningen大学的Kirsten Stadermann及其同事分析了15个国家(大多在欧洲)的课程，并据此提出教学建议。

不同国家对学生的期望有异，难以笼统地比较这些课程。因此，研究团队找出共同的授课内容来分析，包括分立能级、光与物质的相互作用、波粒二象性、量子物理应用等。

专家建议强调量子现象解释的多样性，它能帮助学生认识到：若没有证据否定某个科学模型，它们理应竞争共存。本课程蕴涵更深远的意义，即强调模型的演化和发展过程，而不只是一套归纳好的事实和结论。科学是一种代代相传的事业，同学们会感到身临其境。此外，课程中穿插物理相关的哲学、创造性和人性等内容，将展现更加真实的科学历程，从而吸引更多同学。更多内容详见：H. K. E. Stadermann et al. *Phys. Rev. Phys. Educ. Res.*，2019，15：010130。

(徐仁新　编译自　*Physics*，May 22，2019)

Figure 0-2 Chinese comment in a magazine for popularising university science (Source: DOI : 10.7693/wl20191109

Translation of the text shown in *Figure 0-2* (by Google translate)

Teaching high school students about quantum theory

After analysing high school quantum physics teaching in 15 countries, experts came to the conclusion that the scientific discovery process should be emphasised rather than the conclusion itself. In the past decade, some formal high school curricula started to include quantum physics. However, some educators question whether these complex contents are suitable for high school students. In order to grasp the current status of quantum physics education in secondary schools, Kirsten Stadermann of Groningen University in the Netherlands and her colleagues analysed courses in 15 countries (mostly in Europe) and made teaching recommendations accordingly.

Different countries have different expectations of students, and it is difficult to compare these courses in general. Therefore, the research team found typical teaching content in their analysis, including discrete energy levels, the interaction of light and matter, wave-particle duality, and quantum physics applications.

Experts recommend emphasising the diversity of interpretations of quantum phenomena, which can help students realise that if there is no evidence to deny a scientific model, they should compete and coexist. This course contains a more far-reaching goal, that is emphasising the evolution and development process of models, not just a set of summarised facts and conclusions. Science is an endeavour passed down from generation to generation, and students will feel immersed in it. In addition, physics-related philosophy, creativity, and humanity are interspersed in the curriculum, which will show a more real scientific journey and attract more students. For more details, see *H. K. E. Stadermann et al. Phys. Rev. Phys. Educ. Res., 2019, 15, 010130*

Chapter 1:
Background

General introduction

1.1 Why Quantum Physics in secondary education?

Quantum physics (QP), or quantum mechanics as it is often called, has a reputation for being fascinating, weird and incomprehensible at the same time. The label "quantum" is popular and seems to give everything a powerful mystical status, from quantum dishwasher tabs to quantum dating. It is easy to find a QP solution on the internet for every problem in life, and even world peace is claimed to be explained through QP. Accordingly, the theoretical physicist Lawrence Krauss writes, "No area of physics stimulates more nonsense in the public area than quantum mechanics" (Krauss, 2010, p.36). Combating pervasive quantum quackery (Stenger, 1997) and showing students what QP really is, was one of three reasons the Dutch physicist, physics teacher and teacher educator Van Bemmel (2011b) gave to support the introduction of QP into high school physics in the Netherlands; he calls it the "cultural relevance" of teaching QP. The other two reasons are the importance of QP within current physics research and its significance for technical applications. Additionally, in the last few years, there has been a growing awareness of the future economic relevance of quantum-based industry, and worldwide educational initiatives have been developed to deliver a growing "quantum workforce" (Plunkett et al., 2020).

In this thesis, I argue that teaching quantum physics in secondary school is also worthwhile because of the unique role of Nature of Science (NOS) in learning conceptual QP. This reason goes beyond the – certainly relevant – potential of QP-related technology. To understand how and why science works, that is, to obtain an adequate view of NOS (see 1.4), is relevant for all students, not only for those who will become part of a future quantum workforce. If students could develop an informed understanding of NOS, this would arguably help inspire a more diverse population of students to study science (Erduran & Dagher, 2014; Hong & Lin-Siegler, 2012). NOS is also an essential component of scientific literacy for all citizens, which is the basis for understanding science-related issues, such as climate change and the COVID-19 pandemic. Additionally, it is argued that a general informed understanding of NOS helps citizens participate in socioscientific public debates and make personal decisions in situations when science is involved (Driver et al., 1996; Holbrook & Rannikmae, 2007). The concept of NOS is explored in more detail in 1.3.

1.2 A short history of teaching quantum physics in Dutch secondary schools

Compared to the history of QP, which is more than 100 years long now, the history of teaching QP in Dutch schools is short, and there was a period in which it was not clear if secondary students would get the chance to learn about QP in their physics courses. The background of van Bemmel's plea (2011b) for QP in secondary education has been the controversial introduction of this subject into the compulsory part of the *voorbereidend wetenschappelijk onderwijs*[1] (vwo) physics curriculum. Physics is a three-year elective course for upper secondary vwo students in the Netherlands with a three-hour national written final examination.

[1] Dutch pre-university secondary education, currently attended by approx. 20% of the secondary students (Nederlands Jeugdinstituut, 2021).

Currently, between 50 % and 60 %[2] of all vwo students choose physics as one of their eight or nine subjects for the written national final exam. The first national physics exam with questions about QP was held in 2016. It goes beyond the scope of this thesis to explain why QP was not incorporated earlier into the Dutch curriculum. In general, it has to do with different interests, different powers and different internal dynamics—or lack of it—of the many stakeholders involved in curriculum reforms (Abdurrahmani, 2013; Zohar & Cohen, 2016).

Nevertheless, initiatives had been taken before to renew the physics curriculum. In the context of a major educational reform (Tweede Fase) in 1996, a pioneering group of physics teachers, teacher trainers and university physicists expressed the desire to include more modern physics in the Dutch secondary school physics curriculum and started the Project Moderne Natuurkunde (PMN) (Hoekzema et al., 2004; Hoekzema et al., 2009; Meijer, 2005). In this educational reform project, teaching material for the last year of pre-university upper secondary schools (vwo) was developed, which covered modern areas of physics, such as elementary particle physics and QP. The idea was that students should get a picture of contemporary physics in conceptually interesting and challenging contexts without confronting them with complicated mathematics (Hoekzema et al., 2004). Additionally, PMN material aimed to convey that there are many unanswered questions in physics (de Vries, 2008). At that time, students could choose between two levels of physics courses: a basic course (na1) and a more advanced course (na1,2) for the last three years of vwo. The na1,2 course was an admission requirement (and to some extent a preparation) for a technical or physics-related university study. It was not a very popular course; in 2005, for example, 28% of all vwo pupils took their final exam in na1 and only 18% in na1,2 (Huijts et al., 2007). Teachers of a na1,2 course could choose to participate with their class in the PMN. Approximately 400 students participated in PMN each year from 2001 to 2009 (Hoekzema et al., 2009), which were approximately 2 % of all vwo students who took a physics course. The students who followed the PMN course got an adapted version of the national final exam. Many of them participated in specially organised field trips to famous research institutes such as CERN in Geneva (Zwitserland) or JET in Oxford (UK).

When I started to work as a physics teacher at the *Praedinius Gymnasium* in Groningen in 2002, my predecessor already used PMN material with his na1,2 class, and I continued with it. I found it a very valuable programme that helped to inspire many students to study physics. However, the successful PMN ended when a major reform of upper secondary education *Herziening Tweede Fase,*[3] led to introducing a new physics curriculum in which physics was no longer offered at two different levels. The last possibility for a final exam with PMN questions was held in 2009.

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[2] In 2017, e.g., 56 % of all vwo students passed the physics exam (CBS, 2019).

[3] Translated: Revision upper secondary education

The above mentioned major reform of upper secondary education was a response to many complaints – including those of thousands of tomato tossing secondary school students in the Hague – about the high academic pressure and the fragmented and overloaded curriculum experienced by students (Valk, 2003). As a result of the easing of the curriculum, especially the science subjects lost lesson time. Representatives from business, higher education and physics education were concerned that physics would be marginalised in the new curriculum. Several interested parties formed the *Nederlands Platform voor Natuurkunde*[4] (NPN) to give physics education a voice. This organisation advocated establishing an expert group to renew the Dutch physics curriculum for all upper secondary students. Indeed, in 2004, the Ministry of Culture, Education and Sciences (OCW) gave the *Commissie Vernieuwing Natuurkunde-onderwijs*[5] the task to conceptualise a modern vision on a new Dutch physics curriculum for upper secondary schools. Based on the vision document *Natuurkunde leeft*[6] (van Weert et al., 2006), this commission developed an experimental version of a new physics curriculum *Nieuwe Natuurkunde*[7] (NiNa), which was informed by the experiences from PMN and recent developments in science education in Great Britain, *Twenty-First Century Science* (Millar, 2006), and in Germany *Physik im Kontext*[8] (Duit et al., 2005; Mikelskis & Duit, 2007). Important goals of the new curriculum were (1) presenting concepts of modern physics in authentic contexts, (2) showing the connection between different science disciplines, and (3) enhancing students' scientific literacy (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo, 2010). Several author teams developed context-based NiNa modules that covered the complete three-year physics curriculum of upper secondary schools (see Figure 1-1). In 2008 the Praedinius Gymnasium started together with 11 other vwo schools to test the new teaching materials. For the participating pilot schools, an experimental exam syllabus was developed, including a module about conceptual QP (van Bemmel, 2010). However, during the NiNa pilot, QP was an optional theme that was not part of the national written final exam (Pieters et al., 2007).

In order to stress that this school QP is not the same as quantum mechanics of most university courses, which would require an academic level of mathematics, the particular domain in the exam syllabus has been called *Quantumwereld*[9] (see Table 1-1). In short, the following ideas formed the basis for the content of the module: (1) both photons and electrons have wave and particle properties, (2) using these properties, quantum tunnelling can be explained qualitatively, and (3) through the model of a "quantum particle in a box" simple spectra could be understood quantitatively and qualitatively (van Bemmel, 2011a). The pilot school teachers were regularly invited for professional training to learn about the contents and the ideas behind each NiNa module. In these training meetings, teachers discussed their experiences

[4] Translated: Dutch Platform for Physics
[5] Translated: Commission for Physics Education Renewal
[6] Translated: Physics is alive
[7] Translated: New Physics
[8] Translated: Physics in context
[9] Translated: Quantum World

with the new material, and physicists gave lectures on contemporary developments in physics. The test phase of pilot exams lasted from 2010 to 2015. In an evaluation report, the organising commission advised the Minister of Education, Culture, and Sciences to introduce the experimental curriculum, with some adjustments, for the whole country (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo, 2010). The advice for a new national physics curriculum was, among others, based on an external evaluation of the experiences of students and teachers during the NiNa pilot project (Bruning et al., 2011). The most notable change was that QP became part of the compulsory part of the final exam. Van Bemmel writes in a note: "Pilot school teachers indicated they consider 'Quantum World' more suitable for all students [.....] On their initiative, the subjects were exchanged [...] 'Quantum World' is in the final exam, and 'Elementary Particles' [...] is now an optional topic." (van Bemmel, 2011a, p.94). The decision to make QP a compulsory part of the Dutch vwo physics curriculum had far-reaching consequences; it is intriguing to see to what extent coincidence played a role in this outcome (see *Figure 1-2*).

In 2014 the Minister for Education accepted the advice, and the renewed national curriculum was introduced across the country. Soon afterwards, the first syllabus with a list of specified QP topics was published for the national final exam (Groen et al., 2014). This syllabus is almost identical to the one that is still valid today (2021); a translation of the QP chapter of the current syllabus is provided in Table 1-1.

For many teachers who had not been involved in the NiNa pilot phase, the introduction of QP in the mandatory curriculum came as a surprise and was consequently controversial for some of them. There were proponents and opponents amongst physics teachers, teacher trainers and textbook authors. The opponents of the introduction of QP had concerns about the level of understanding possible for students (and even teachers) with limited mathematical backgrounds (Biezeveld, 2009; Biezeveld et al., 2011; Brouwer & Peerdeman, 2011). They argued that teaching QP on a conceptual level would bear the risk that students would not deeply understand the underlying principles. Students would just repeat some tricks" to solve test problems. Proponents of QP, like van Bemmel, recognised QP as an opportunity to make physics lessons more up-to-date and more attractive for secondary students. They also advocated the more general educational role of QP as part of culture, which is related to NOS.

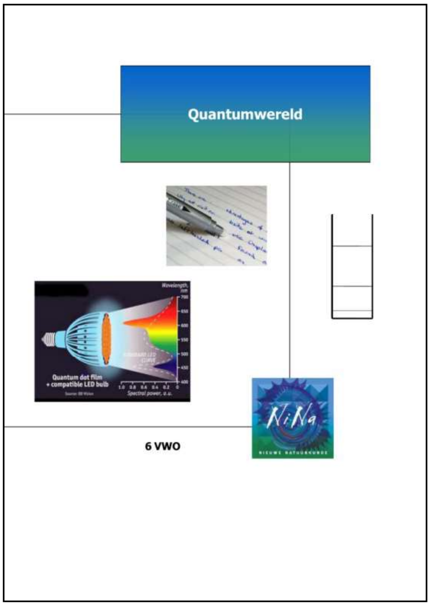

Figure 1-1 Cover page of the NiNa module Quantumwereld

Figure 1-2 Woudschoten 2010. At the end of January, during the final meeting of NiNa

Pilot teachers, members of the Commissie Vernieuwing Natuurkundeonderwijs and experts of the Dutch examination board came together to provide input for the definite advice to the minister. Due to winter weather and illnesses, a few invitees did not attend. Discussions were held in groups, sorted by topics; I had chosen the topic of Quantum World. When all groups gathered their results for the final report, I said that I saw QP as more fundamental than the topic of elementary particles, for which QP is the basis. Therefore, I expressed to prefer ' Quantum World' in the general compulsory part of the curriculum and the ' Elementary Particles' as an elective topic. Some other participants supported this plea for introducing all students to QP. It was one of the last discussion topics, and not everyone was paying attention anymore. So it turned out that the idea was accepted into the final report without much discussion. Few of the participants realised that this would mean a significant change for physics education in the Netherlands. In the end, the minutes were approved by all present. This was surprising because QP had not been tested in the pilot exam, and many teachers themselves had never taken QP during their university study. I expected this decision to be reversed because as long as QP was only an elective subject, it would be unproblematic for teachers with little QP knowledge; they could easily bypass it. However, QP has been an accepted part of the national final exam for six years now, and every teacher in upper pre-university classes has to teach it. The history of teaching QP in the Netherlands would probably be different if all invitees had been at the winter meeting in 2010, if the attendees had checked the minutes with their full attention and if I had not been educated in Germany, where QP already is in the curriculum for a long time, or if the Dutch students had never thrown tomatoes in the Hague. All alternative histories, though, might exist in parallel universes. (Photo credit: Ch.G. van Weert)

Table 1-1 QP in the Dutch exam syllabus 2021 vwo examen 2021 (College voor Toetsen en Examens, 2019)

Learning outcomes
Candidates can apply Heisenberg's wave-particle duality and uncertainty relation in contexts and can explain the quantisation of energy levels in a few examples using a simple quantum physics model. The candidate is able to: 1. explain light as a wave phenomenon, • explain in which situations diffraction of light waves occurs; • explain a pattern of intensity in terms of constructive and destructive interference;
2. apply wave-particle duality to explain interference phenomena in electromagnetic radiation and matter particles, • perform calculations using the de Broglie wavelength; • describe the double-slit experiment and explain its significance; • technical terms: probability, probability distribution; • at least in the context of electron microscope;
3. use the photoelectric effect to show that electromagnetic radiation is quantised (used terms: photon, energy extracted, energy quantum);
4. describe quantum phenomena in terms of the confinement of a particle, • apply Heisenberg's Indeterminacy Relation; • describe the quantum model of the hydrogen atom and calculate the possible energies of the hydrogen atom; • describe the quantum model of a particle in a one-dimensional energy well and calculate the possible energies of the particle; • technical terms: Bohr radius, zero-point energy;
5. describe the quantum tunnelling effect by means of a simple model and indicate how the probability of tunnelling depends on the mass of the particle and the height and width of the energy barrier, • at least in the contexts: Scanning Tunnelling Microscope (STM), alpha decay.
The following formulas belong to these specifications: $p = mv$ $\lambda = \frac{h}{p}$ $\Delta x \Delta p \geq \frac{h}{4\pi}$ $E_n = -\frac{13{,}6}{n^2}$ (in eV) $E_n = n^2 \frac{h^2}{8mL^2}$

1.2.1 Textbooks

Figure 1-3 Dutch pre-university physics textbooks containing a chapter on QP in 2020

To meet the new final exam requirements, publishers invited authors for new textbooks to develop materials according to the new syllabus. Because this syllabus covers the subject content of the last three years of Dutch secondary schools (4,5,6 vwo), most publishers divide the entire content between three different volumes in a series, one volume for each year. Figure 1-3 shows the Dutch commercial physics textbooks that were available in 2020. Traditionally, textbook authors in the Netherlands are often teachers. Publishers invited especially physics teachers who participated in the NiNa pilot to write a chapter about QP. Although this authorship enhances the chance that innovative ideas from the NiNa project enter the books (Ververs, 2016), research on the development of commercial textbooks shows that, in the interplay between authors, editors and publishers, author intentions are not always visible in the final product (DiGiuseppe, 2014). Indeed, all textbooks cover all the aspects mentioned in the final exam syllabus for physics (see 1.3.3), but there are distinct differences in how the authors of different textbooks approach QP. Dutch physics textbooks nowadays are written by author teams, varying from three to 13 authors who all contribute to the final product, and it is not documented how the authors made decisions about what or how to present QP. Rolf Smeets (2019) analysed how QP is presented in six Dutch textbooks (see *Figure 1-3*): *Systematische Natuurkunde* (van Dalen et al., 2015), *Newton* (Flokstra et al., 2015), *Nova* (van Bemmel et al., 2015), *Pulsar* (te Brinke et al., 2015), *Stevin* (Biezeveld et al., 2016) and *Overal natuurk*unde (Sonneveld et al., 2015). He found that most analysed textbooks present QP concepts within additional contexts that are not mentioned in the exam syllabus. These topics vary from advanced scientific examples (*Overal natuurkunde* addresses black body radiation, entanglement and the EPR experiment) to more practical examples in which QP is used to explain phenomena (for example, *Pulsar, Nova* and *Newto*n explain colour pigments and quantum dots). Only *Systematische Natuurkunde* does not offer additional topics and stays very close to the syllabus content. According to Smeets, all books present real-life contexts in the introduction of the chapters and sometimes in exercises; the most popular topics are solar cells, LEDs and lasers. Additionally, all books, except *Systematische Natuurkunde,* show experiments or simulations of experiments that can be done in class. Concerning the representation of NOS, Smeets found significant differences between the textbooks. For example, *Systematische Natuurkunde* does not explicitly address the role of models in QP, whereas other books devote at least some sentences on the development of atomic models. *Pulsar*, *Nova* and *Newton* also emphasise that all scientific models have limitations. *Overal* and *Stevin* pay attention to societal aspects and controversies in the development of quantum theory; these are also the only two textbooks that mention QP interpretations (see 1.3.3) and state that the *Copenhagen interpretation* is currently the most accepted one. Smeets concludes that Dutch physics textbooks offer a broad choice of how much attention is paid to real-life applications, research, history and the future of QP. Additionally, he ranks the textbooks on how much attention they pay to NOS aspects such as tentativeness of scientific knowledge, controversies in science and limitations of science, and science as a human endeavour. In this ranking, *Systematische Natuurkunde* is at the lower end with a 'pragmatic approach' that emphasises calculations and problem solving and does not mention NOS aspects. In contrast, *Stevin* and *Nova* are at the higher end of the NOS ranking with a 'more philosophical approach' in which explicit attention is paid to the history of QP and NOS aspects. The other three textbooks are ranked between these two extremes (Smeets, 2019, p.24).

In another study, Borin (2021) compared the representation of six NOS-related concepts in QP in textbooks in Italy, the UK and the Netherlands. From each country, he analysed the two most frequently used upper secondary school physics textbooks, which are *Systematische Natuurkunde* and *Newton* for the Netherlands. In his detailed analysis, he found several misrepresentations of historical facts that convey undesired NOS views in both Dutch books. The comparison of the six textbooks from different countries revealed that overall the British books presented a broader view on various NOS aspects than the Dutch and Italian ones. Especially in *Systematische Natuurkunde*, Borin found examples of "quasi-historical misconceptions" with "no intention to describe the real dynamics of the scientific endeavour" (Borin, 2021, p.72).

Dutch physics teachers typically do not develop their own teaching material. Especially when teaching topics for which their own expertise is low, teachers generally rely on the textbook (Chiappetta et al., 2006; Stern & Roseman, 2004). Therefore, the pedagogical approach and structure of the textbook is usually the basis of physics lessons. Teachers of a school are responsible for choosing the textbook series they want to use for at least four or five years. In the case of QP, there seems to be a broad choice in how it is represented in different textbooks. However, when the new curriculum was introduced, many teachers were unfamiliar with how their textbook would represent QP because they had to choose a textbook series before the volume, which includes the QP chapter, was published. It is very unfortunate that the textbook *Systematische Natuurkunde* with the largest market share in the Netherlands is precisely the one in which NOS aspects are presented in an undesirable way.

Like in other countries where QP was introduced in secondary schools recently, not all teachers were familiar with QP (Giliberti et al., 2004; Michelini et al., 2004). Therefore, many Dutch universities developed special QP teacher courses for in-service or pre-service teachers who needed more background information. Participating in such professional development courses is voluntary in the Netherlands, and only a minority of teachers participated. In a recent meeting of different stakeholders (see 1.1.1) about faulty questions in the Dutch exams, participants were concerned that teachers lack the necessary knowledge about QP and that professional development courses do not attract enough participants (de Graaf, 2018). For many teachers, especially in the first years after introducing the new curriculum, QP lessons were probably guided by the textbook content.

1.2.2 Exams

Since 2016, each Dutch final exam in physics at the pre-university level (vwo) contains some questions related to QP. The quality of some of these questions has been criticised regularly (de Vries-Uiterweerd, 2018; Hoekzema, 2017; van Joolingen, 2016). The authors found questionable formulations in the given problems and errors in the grading guidelines. Van Joolingen (2016) concludes that it is extremely difficult to make good exam questions for conceptual quantum physics at secondary school level. Due to the concerns about QP questions in the final exams, the *Nederlandse Natuurkunde Vereniging*[10] (NNV) offered support to the Dutch exam authority *College voor Toetsen en Examens*[11] (CvTE) for constructing QP-related questions.

Additionally, a meeting was held between physics educators, members of NNV and members of CvTE. They, among others, mention the gap between "real" quantum mechanics and the quantum world as taught at schools. Although all attendees felt QP should be a part of the mandatory part of the curriculum, they advised that the content of the exam syllabus needed to be revised (de Graaf, 2018).

1.3 The nature of Quantum Physics

The development of quantum theory started at the beginning of the twentieth century — the so-called "first quantum revolution". Now, it is one of the essential pillars of physics. While the development of quantum physics (QP) theories has not been straightforward, QP is now routinely used to explain the most varied phenomena: superconductivity, quantum entanglement, photosynthesis in plants, the stability of atoms, the fusion of hydrogen atoms in the sun, and how migratory birds sense magnetic fields. Because QP can make precise predictions about the behaviour of light and matter, it has become the basis for all modern semiconductor-based information technology used in computers and smartphones. Additionally, many other devices we use in everyday life, science, industry, and medicine are technical applications of quantum phenomena: LEDs, lasers, photovoltaic solar panels, quantum dot displays, magnetic resonance imaging (MRI), electron microscopy and scanning tunnelling microscopy (STM). Max Tegmark even states in a popular documentary, "If quantum mechanics suddenly went on strike, every single machine that we have in the US, almost, would stop functioning." (Tegmark, in Cort & Rosen, 2011).

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[10] Translated: Dutch Physical Society
[11] Translated: Board of Tests and Examinations

Certainly, the development of QP was not linear. After a period of post-war, pragmatic physics research in the US, a group of eccentric young physicists had “the faith that deep philosophical questions, such as the implications of Bell’s theorem and quantum entanglement, were worth asking” (Kaiser, 2011, p.75); they caused a “quantum revival” in the 1970s. With their interest in quantum entanglement, they initiated the “second quantum revolution” (Dowling & Milburn, 2003), in which QP is not only used as a tool to explain natural phenomena but to create new man-made quantum states. Experiments with entangled quantum objects and developments in quantum information led to new research on the scientific frontier. Sincethen, even more, quantum phenomena have been used in new technical applications. Now, for example, many high-tech companies are involved in building quantum computers. If we look into the future, a quantum internet could be envisaged to enable messages with special, information-theoretically secure quantum encryption.

However, not only the exact predictions or the versatile technical applications make QP fascinating. Arguably, it is the fact that QP phenomena — and the consequences of the theory that describes them — do not resemble anything in the visible world and classical physics. Such ‘weird’ quantum phenomena challenge even the imagination of great physicists and led, for example, Richard Feynman to remark: “I think I can safely say that nobody understands quantum mechanics.“ (Feynman, 1965, p. 123). Every teacher should ask what *understanding* exactly means and to what extent physics describes nature. To my understanding, theories in physics merely entail models to describe nature; however, the development of such models is seldom communicated in school physics (Schwartz, 2019). Nevertheless, we cannot escape addressing epistemological questions when teaching QP because students will ask whether QP describes reality.

Indeed, all predictions from QP have been verified experimentally, and new technology can be developed by applying the QP formalism. Therefore, many physicists consider the current state of knowledge about quantum physics to be sufficient. Others, however, are challenged by the lack of clarity about how to interpret the situation before and during a quantum measurement. If we want to know what exactly happens in these situations, we have to draw on one of the different, more or less, paradoxical interpretations of QP (see 1.3.3). This unsolved problem of interpreting QP inspires creative physicists to develop new research, but it also intrigues people outside science. Many popular physics books describe the seemingly incomprehensible and fascinating character of QP for lay persons (e.g. Zeilinger, 2003). The different interpretations of QP not only engage physicists but are also fertile ground for imaginative speculation and various science fiction books (Mellor, 2003; Niven & Scott, 1971; Pohl, 1986). Even more spectacular are various — more or less scientific — videos on the internet, which bring students into contact with QP, even before the subject has been introduced in class.

1.3.1 Quantum physics formalism and the question of what it means for reality

Traditionally, introductory quantum mechanics has been a course for second- or third-year university physics students. The combination of challenging physics concepts and complex maths makes these QP courses difficult (Marshman & Singh, 2015). To handle the mathematical formalism of QP, students first have to learn about partial differential equations, operators and complex numbers in Hilbert space.

The time-dependent Schrödinger equation for a one-dimensional quantum object in a potential V is given by (1).

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V\Psi \tag{1}$$

It is a linear partial differential equation that describes the space- and time-dependence of the wave function Ψ of the quantum object. $i\hbar\frac{\partial}{\partial t}$ is the energy operator which acts on the wave function Ψ and corresponds to the total energy of a system in classical physics, whereas $-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V$ on the right side of the equation is called the Hamiltonian, corresponding to the kinetic and the potential energy.

Traditional introductory university QP courses are often taught in a “minimal instrumentalist” way. This approach is also referred to as the “shut up and calculate” method in which a quantum particle is described by the wave function $\Psi(x,t)$ but there is no interpretation of what Ψ might be (Johansson et al., 2018; Svozil, 2018). The only explicit connection to the real world is the Born rule which states that $|\Psi(x,t)|^2$ represents the “probability density” of the quantum particle. This is a rather strange term because, in any measurement, a quantum particle is always detected as a single point with no spatial distribution, or in other words: in measurement, the probability density of a quantum particle is always 100% in one point and 0% in all other points. To circumvent the missing connection between formalism and reality, the so-called ensemble interpretation can be used. In this interpretation, the probability density is a relative frequency distribution for a group of particles with the same properties, or better formulated: $|\Psi(x,t)|^2\,\Delta x$ is the chance to detect the particle within the interval Δx around the position x.

In traditional university courses, students often feel that many of their questions are not addressed in the lectures; students are mainly occupied with solving the Schrödinger equation with different boundary conditions (Johansson, 2018; Johansson et al., 2018). This solution usually consists of distinct possible wave functions, the so-called eigenstates of a system. Without measurement, the quantum object is said to be in a superposition of all possible eigenstates. Any conceptual interpretation of wave functions or their superposition is usually avoided, making it difficult for students to develop a conceptual understanding of QP (Baily et al., 2010; Greca & Freire, 2014a). This problem has a long history. According to Bloch

(1976), a student of Erwin Schrödinger at the University of Zürich wrote the following poem about his professor in the 1920s:

Gar Manches rechnet Erwin schon
Mit seiner Wellenfunktion.
Nur wissen möcht' man gerne wohl
Was man sich dabei vorstell'n soll.

Which Bloch freely translated as:
Erwin, with his psi, can do
Calculations quite a few.
But one thing has not been seen:
Just what does psi really mean?

1.3.2 **The double-slit experiment**

Since solving the Schrödinger equation is beyond the mathematical capacity of most Dutch secondary school students, concentrating on mathematical formalism is not an option for teaching QP at this level. However, even without performing any calculations, questions about the meaning and interpretation of the wave function can be illustrated. The enigmatic double-slit experiment is a perfect way to do so. In educational contexts, the double-slit experiment is usually first presented as the experimental evidence for the wave nature of light. It is attributed to the physicist Thomas Young, who challenged Isaac Newton's established corpuscular theory of light in the early 1800s. The basic idea is to create a simple interference pattern with light, which is only explainable if light is considered as a wave.

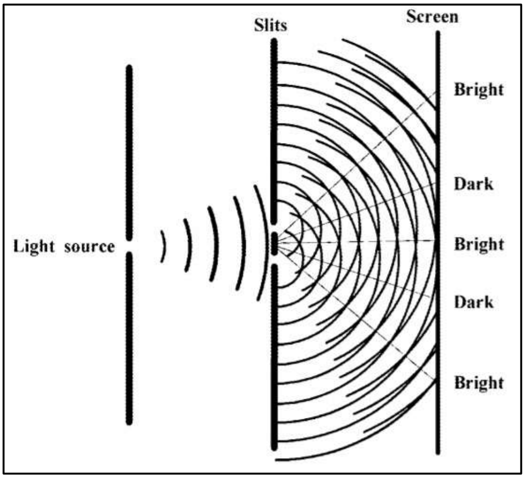

Figure 1-4 Double-slit experiment [illustration form Beal, A. (2000). *Structural Engineer, 78*(14), 27-32]

Figure 1-4 provides an illustration of a wave split into two, which later come together on a screen. The different lengths that both waves travel to each point on the screen result in a phase shift. Therefore, the two waves create an interference pattern on the screen: places where the two waves alternately extinguish and amplify each other. From a historical viewpoint, the role of the double-slit experiment for Thomas Young's theory is questionable (Michelle Mercier. 2021). However, its conceptual simplicity is unsurpassed and became therefore a popular setup (in thought experiments and actual experiments alike) to investigate the nature of the phenomena.

The seemingly straightforward argument that anything that produces an interference pattern in the double-slit experiment must be a wave (and not a localisable particle) proves to be fallacious in QP. Not only photons but also electrons (Jönsson, 1961; Merli et al., 1976) and even large molecules (Juffmann et al., 2012) produce interference patterns. Moreover, this pattern builds up over time, even if there is only one particle at any one time in the experimental setup and each particle is detected at the screen one by one. This is, in essence, the incomprehensible feature of QP; it illustrates, without maths, the problem of the suddenly disappearing superposition of possible eigenstates. Therefore, in an educational setting, the double-slit experiment is ideal for illustrating terms like superposition, probability density, and wave-particle duality of quantum particles.

In 2002, readers of Physics World voted the double-slit experiment with single electrons as the most beautiful experiment in physics (Crease, 2002). Richard Feynman held that the double-slit experiment embodies "all of the mystery of quantum mechanics, to put you up against the paradoxes and mysteries and peculiarities of nature one hundred per cent." (1965, p.130). Until now, the double-slit experiment has been used in every popular science video, interactive simulation, introductory quantum mechanics lecture, physics textbook and philosophy of science papers to work out and discuss the specific properties of QP (see, for example, Aharonov et al., 2017; Ananthaswamy, 2019; Sayer et al., 2017).

1.3.3 Interpretations of QP

What is the meaning of the wave function? Does it describe a real entity? What is a particle? Does it exist before we detect it? Is it created through the act of measurement? If quantum particles make up matter, then is there an objective reality at all? Why does QP only give us a superposition of all possible outcomes, but we measure only one? What happened to all other possibilities? Do we lack information that would enable us to predict which outcome we will measure precisely? Do other possible outcomes of measurement exist, but not in the reality we can see?

Since the early days of QP, these questions have arisen, and many interpretations of the quantum theory have been developed. Some have been proven wrong[12], but there are still several interpretations or different quantum theories that "work" (see for an overview Filho, 2014). These interpretations differ conceptually, and some also differ in their mathematical presentation. They often represent a peculiar philosophical perspective on the reality we live in (the so-called worldview), yet each one makes identical predictions for all known experimental results. Up to now, no experiment, in principle or in practice, has been able to distinguish various interpretations (Allori, 2015; Cheong & Song, 2014; Maudlin, 2019). If physics was only concerned with describing processes to predict the results of experiments,

[12] For example, through a Bell test (such as Aspect et al., 1981) all local hidden variable theories can be rejected.

then the debates that revolve around the foundations of QP were meaningless. Should the lack of falsification not be enough to stop any argumentation?

Some scientists are indeed happy with the mathematical formalism of QP without any interpretation (Fuchs & Peres, 2000; van Kampen, 2008). These physicists are satisfied because the mathematical formalism is extraordinarily productive, and the theoretical predictions of QP are very precise. It is also possible to teach QP concepts without mentioning any interpretation. This "shut up and calculate" approach has been the dominant approach in most university-level physics courses since the cold war, in which efficiently trained physicists were needed for the development of military technology; they had to be able to calculate, not to philosophise (Becker, 2018; Kaiser, 2007; Kaiser, 2011). This minimalist interpretation, which claims that the interpretational question is solved because the mathematical formalism of QP only says how an *ensemble* of quantum entities behaves, is unsatisfactory for many others (Bell, J. S., 1987; Beneduci & Schroeck, 2014; Cordero, 2003; DeWitt & Graham, 2015; Echenique-Robba, 2013; Filho, 2014; Freire, 2003; Garritz, 2013; Hermann, 1935; Howard, 2004; Karakostas & Hadzidaki, 2005; Ladj, 2017; Merali, 2015; Nikolić, 2008; Passon, 2004). Given the growing number of possible interpretations of QP, many physicists desire to understand more than the uninterpreted formulas of QP. They want to get closer to the underlying physical procedures that constitute our world. They aim for a sort of understanding beyond the prediction of experimental results (Spillner, 2010). Unlike the mathematical description, the interpretation of a theory cannot always be falsified experimentally. To justify their interpretational preference, physicists use other criteria such as simplicity, symmetries, unification, or their philosophical perspective on science. Which of these criteria is more substantial than another, is open to discussion and is often only a matter of taste. However, the dogmatic and low-inspirational period before the second quantum revolution showed that ignoring questions and discussions about a deeper understanding of QP can hinder or even prevent the development of new science (Becker, 2018; Kaiser, 2011).

Interpretations of QP in education

Paul Hewitt said, "Physics is easy to *teach* mathematically, but we make a mistake by assuming it is easy to *learn* mathematically" (Hewitt, 1983, p.305). This is definitely true for learning QP. The instrumental treatment of QP in the "shut up and calculate" approach is one reason why QP is experienced as incomprehensible and unsatisfactory by students (Johansson et al., 2018; Johnston et al., 1998). Not only is such an approach difficult for learners, but if interpretations are not mentioned, students are deprived of an honest representation of the current state of QP, potentially hindering further progress in understanding physics and the world around them (Becker, 2018; Hardy & Spekkens, 2010). Moreover, research shows that ignoring any interpretation while teaching QP enhances the chance that students make up their own — probably undesired — interpretation (Baily et al., 2010). Additionally, science education researchers state that discussing QP interpretations is stimulating and inspiring for students (Angell et al., 2004; Henriksen et al., 2014; Myhrehagen & Bungum, 2016; Pospiech, 2000). Finally, we will see in Chapter 3 that the existence of different interpretations in QP can serve as a context for NOS teaching because it is an excellent example of controversy in science in the making. Table 1-2 summarises three QP interpretations that might be interesting for secondary school physics classes and are used in my research (Becker, 2018; Garritz, 2013; Leisen, 2000). Below, I will shortly describe them in a way that could be used in secondary schools.

Table 1-2 Overview of the three QP interpretations used in this thesis (= Table S1 from Appendix B of Stadermann & Goedhart, 2020)

Name of the interpretation (proponents)	**Completeness of quantum theory and relation to reality**	**The role of measurement and relation to reality**
Copenhagen Interpretation (Bohr, Heisenberg, Dirac)	The state of a system is entirely described by the mathematical QP formalism, which is only an instrument to calculate possible outcomes of an experiment. It does not describe any directly measurable physical quantity.	As long as we do not make any measurement, a quantum particle exists in a superposition of all possible outcomes. By measuring, we determine (create) a specific outcome. Before measuring, it does not make sense to talk about the position of a particle; it does not have one.
Pilot wave interpretation (de Broglie, Bohm, Bell)	Quantum theory is not complete. To describe the state of a quantum entity completely, we need extra variables and equations. If we knew these additional variables, we could calculate the exact outcome of each experiment.	A quantum particle always has a well-defined (but unknown) position. Its motion is guided by a pilot wave which can be described by the mathematical formalism of QP. Measurement is just a way to make the existing position visible.
Many worlds interpretation (Everett, DeWitt)	Quantum theory is complete and describes the state of a quantum entity in many parallel universes (many worlds) simultaneously, of which we only see one. These multiple universes exist whenever the theory allows more than one possible state of a system.	In this interpretation, reality continuously extends into many parallel universes. A quantum particle always has a defined position, which can be different in each universe. However, we can see only one branch of reality; thus, the concrete outcome of a position measurement cannot be considered as real as it is just a delusion in the limited mind of an observer.

Copenhagen Interpretation

The Copenhagen interpretation, otherwise known as the orthodox or standard interpretation, is the most commonly used interpretation in university-level QP courses, and students might get the impression that this is the only correct interpretation. The name “Copenhagen interpretation” was coined by Werner Heisenberg around 1927 when he presented this interpretation as the one used by the “Copenhagen School” of physicists, led by Niels Bohr. Strictly speaking, the Copenhagen interpretation has never been defined, and even Bohr and

Heisenberg had disagreements about it (Beller, 1996; Howard, 2004; Maudlin, 2019). According to the commonly used form of the Copenhagen interpretation, which is very similar to the "shut up and calculate" approach (Mermin, 2004), the probability characteristic of quantum-theoretical predictions is not an expression of the imperfection of the theory but the principally non-deterministic character of QP processes. In this interpretation, physical systems (e.g. electrons in an atom) generally do not have definite properties such as position or momentum. They can exist in a superposition of all possible states.

A central feature of the Copenhagen interpretation is the complementarity principle, which states that quantum objects present themselves differently, depending on the experimental context. Consequently, incompatible observables exist, such as the momentum and the position of an electron, which cannot be measured simultaneously. The wave function fully describes a single quantum entity (not only an ensemble) but does not have any physical meaning (Faye, 2019). Its modulus squared represents the probability or probability density to find the system in one specific state. A measurement affects the system so that the Schrödinger equation does not describe the system anymore. This is also called the "collapse of the wave function". Philosophically, this is an exciting interpretation because we are used to objects that have probabilities at any moment. Furthermore, it is demanding to imagine objects that exist in a superposition and only get their properties in a measurement. Einstein did not accept this non-deterministic interpretation. He thought that quantum theory was not complete and that the outcome of a measurement is not only the result of probability. If we could find the hidden variables, he argued, we would be able to predict the result of any measurement. The famous paradox of Schrödinger's cat is a thought experiment that shows the weird consequences when the Copenhagen interpretation is applied to macroscopic objects.

In the last few decades, several researchers have suggested that the reasons for physicists' preference for the Copenhagen interpretation since the 1930s were due to several factors of the NOS-cluster "Human Elements of Science" (see *Figure 1-7*):

- The Copenhagen School, especially the personality of Niels Bohr, was very dominant. Scientists with deviating ideas were discredited or ignored, which often ended their careers as scientists (Becker, 2018; Faye, 2019; Svozil, 2018);
- Grete Hermann's refutation of John von Neumann's "No-Hidden-Variables-Proof" (Hermann, 1935) went unnoticed by the physics community. Therefore, everybody thought there could not be any hidden variables in QP. Similar to Bohr, von Neumann was an authority in physics and Mathematics. Hermann was a female mathematician and philosopher, an outsider of physics who never sought confrontation (Herzenberg, 2008; Seevinck, 2016);
- After World War II, the focus of university physics in the US shifted to calculating and engineering to train many physicists for possible future military projects. Philosophical questions were deliberately ignored during the cold war period (Kaiser, 2007).

The NOS elements “Subjectivity and Bias” and “Society and Culture” (see *Figure 1-7*) are visible in these historical examples.

Pilot Wave interpretation

This interpretation, also called Bohmian mechanics or the de Broglie-Bohm theory, was developed by Louis de Broglie in 1927 and rediscovered by David Bohm (1952). It is the simplest example of what is often called a hidden variables interpretation of quantum mechanics. In this interpretation, particles are still classical particles that are driven by a wave. This wave evolves, as in the Copenhagen interpretation, according to Schrödinger's equation. Additionally, there is a guiding equation for every object, which expresses its velocity and position and determines its trajectories instantaneously across the universe. Although explicitly non-local, it is a deterministic and realistic theory based on hidden variables (Holland, 1995).

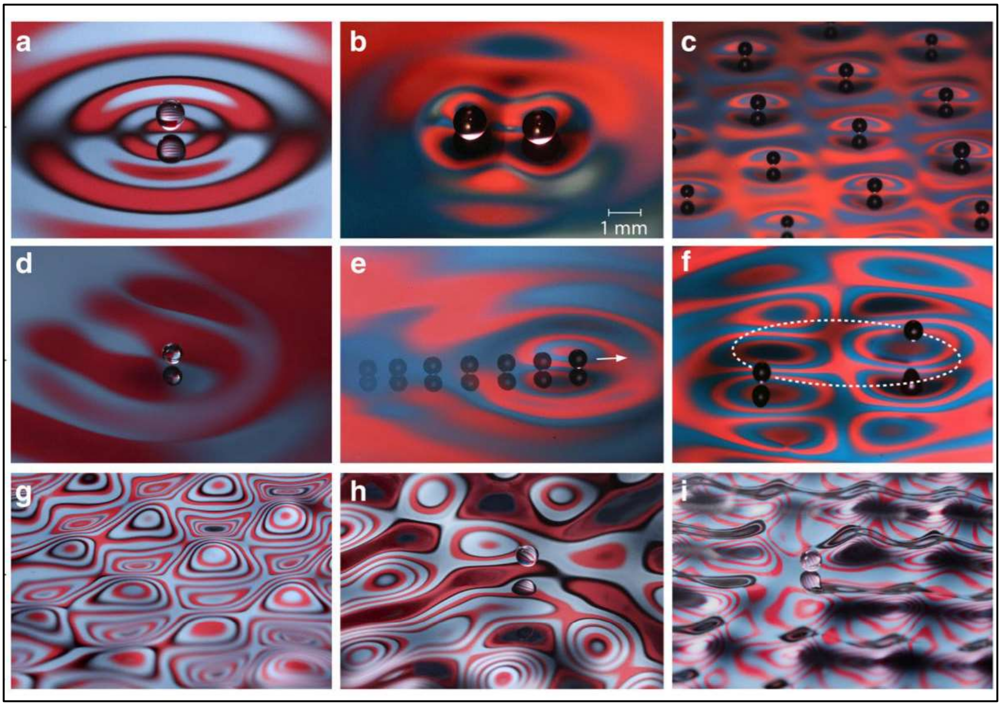

Figure 1-5 Some visualisations of millimetre-sized droplets bouncing off the surface of a vibrating liquid bath as a hydrodynamic quantum analogue. Adapted from (Harris et al., 2017)

This interpretation is much more imaginable for most people. For example, in the double-slit experiment, both the trajectory of the particle and the location where it arrives on the photographic plate are completely determined by the initial position and wave function of the particle. The pilot wave passes through both slits and interferes, but the particle only passes through one well-defined slit (Dürr et al., 2013). This interpretation is fascinating because research has shown that with Bohmian mechanics, the average trajectories of single photons in an experiment can be predicted (Mahler et al., 2016). When Bohm published his interpretation in a scientific article (1952), he was treated with hostility. Robert Oppenheimer is reported to have said: “if we cannot disprove Bohm, then we must agree to ignore him” (Oppenheimer, 1962, as cited in Peat, 1997, p.133). How the scientific community in the 1950s treated David Bohm is undoubtedly another illustration of the fact that science is less objective, neutral and independent than many people believe (Bell, J. S., 1987; Carroll, 2019).

For the educational context, it is particularly interesting to note that droplets on vibrating oil surfaces exhibit behaviour similar to that of quantum particles on a pilot wave (Harris & Bush, 2014; Harris et al., 2017; Muller, D. A. 2020). Beautiful pictures (see *Figure 1-5*) and videos of these experiments are easy to find on the Internet and could be used in class as an analogy to Bohmian mechanics.

Many-worlds interpretation

Although the many-worlds interpretation is popular in science fiction, it is a scientifically sound interpretation of QP. The physicist Hugh Everett formulated this interpretation of quantum mechanics in 1957. It states that all possible pasts and futures are real, and each represents an actual world or a universe (Everett, 1957). The hypothesis involves an infinite number of universes; everything that could have happened in the past indeed happened in the past of some other universes, and every possible outcome is realised in some universes (Aguirre & Tegmark, 2011; Vaidman, 1998). The many-worlds interpretation does not contain a collapse of the wave function, and the Schrödinger's cat paradox (Schrödinger, 1935) does not exist since any possible outcome of any event in its own “past” or “world” actually exists. The cat, therefore, is both alive and dead, even before the box is opened. Because the alive and the dead cats are in different branches of the universe, which do not interact with each other, we can only see one outcome of the experiment. However, another “we” in another branch of the universe can see another outcome.

1.4 Nature of Science in science education

In their report on science education in Europe, Osborne and Dillon wrote in 2008:

> The standard school science education has consistently failed to develop anything other than a naïve understanding of the nature of science, commonly called ‘how science works’. Today, many of the political and moral dilemmas confronting society are posed by the advance of science and technology and require a solution which, whilst rooted in science and technology, involve a combination of the assessment of risk and uncertainty, a consideration of the economic benefits and values, and some understanding of both the strengths and limits of science. (Osborne & Dillon, 2008, p. 8)

Probably now, after the COVID-19 outbreak became a pandemic in 2020, more people realise how real and vital this issue is for each of us. We all live in a world where getting information is easy, yet making critical decisions becomes more and more complicated because it is difficult to judge how to use which information. As described in the above quote, proper treatments of socioscientific issues require a complex combination of ethical, economic, political and scientific perspectives. In democratic societies, this process should involve open communication and public debates. However, potentially unreliable scientific information and abuse and misunderstanding of science in social media complicate the decision-making (McFarlane, 2013; Schreiner et al., 2005; Yacoubian, 2018). Therefore, science education should take responsibility for the scientific perspective by ensuring that all students leave school with a realistic view of what science entails and how scientific processes work. Accordingly, modern educational standards underscore that students should not only learn content knowledge and practical skills in their science lessons but also develop a contemporary constructivist understanding of science, which is often called learning about the nature of science or NOS (Hodson, 2014; Jenkins, 2013; McComas, William F. & Olson, 1998). In the US, for example, the term NOS is prominently presented as a primary goal in science education. For more than 150 content items in the K-12 (kindergarten to 12th-grade upper secondary school) curriculum, the standards contain a statement about the connection between an item and the NOS (National Research Council, 2013).

Although developing informed NOS views is regarded as a vital task of science education, there is no clear definition of what the term exactly means; perhaps that is why there is no Dutch equivalent (see 1.4.1). One of the reasons for the missing definition is the fact that many disciplines contribute to the understanding of NOS, as illustrated in *Figure 1-6*. Consequently, the term NOS is used in various ways by philosophers, sociologists, historicists, and science educators. Even in science education research, different scholars use different interpretations of NOS or express the importance of specific NOS aspects in education differently (Allchin, 2013; Dagher & Erduran, 2016; Lederman, N. G., 2007). Notably, the impactful studies of Norman G. Lederman (1952 - 2021) shaped the research on NOS in education for the last 30 years and made the concept of NOS familiar to many in science education, especially in the US (NARST. 2021).

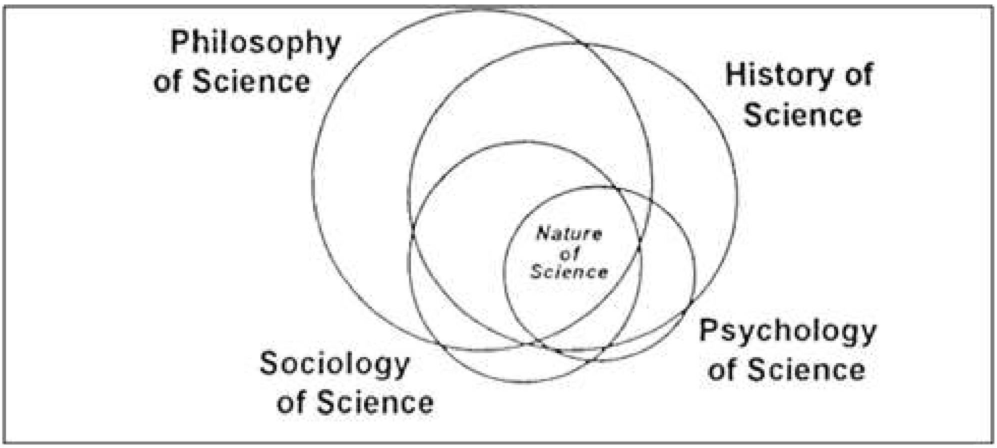

Figure 1-6 Illustration of the disciplines that contribute to the understanding of NOS from McComas, W. F., & Olson, J. K. (1998). The nature of science in international science education standards documents. *The nature of science in science education* (pp. 41-52).

In general, all science education researchers agree on the desirable goal of NOS teaching: to inform students about what science distinguishes from other ways of knowing and to refute myths about science. Unfortunately, even now, such myths are often conveyed through the way we teach science. Examples of these myths are: Scientific laws and ideas are absolute and unchangeable; A general and universal scientific method exists; Science and its methods provide absolute proof; Scientists are not creative; Science can answer all questions; Acceptance of new scientific knowledge is straightforward; Scientific models present reality (McComas, William F., 1998). Nevertheless, a clear demarcation or definition of what is meant by NOS does not exist in science education. In the past, discussions about the existence of a consensus view on NOS resulted in heated discussions between science education researchers (Hodson & Wong, 2014; Kampourakis, 2016; Lederman, N. G. et al., 2002; Matthews, 2012; Osborne et al., 2003).

The current understanding of what is generally considered essential for science teaching is shown in *Figure 1-7*. In this diagram, McComas (2020) summarises and structures different elements of NOS in three domains. He comments that "A complete view of NOS lies at the intersection of these three domains and is achieved when learners have a robust understanding of all nine elements" (McComas, W. F., 2020, p.40). Therefore, these elements should not be seen as a list of descriptions that have to be learned but as a guiding structure of themes that should be addressed regularly during science education, whenever there is a good case.

The NOS aspects in QP which are discussed in this thesis are mainly located in the domains "Science and its Limitations" and "Human elements of Science". Because these two domains are often neglected in traditional physics lessons, I expect teaching QP on secondary level could offer excellent chances to contribute to NOS learning.

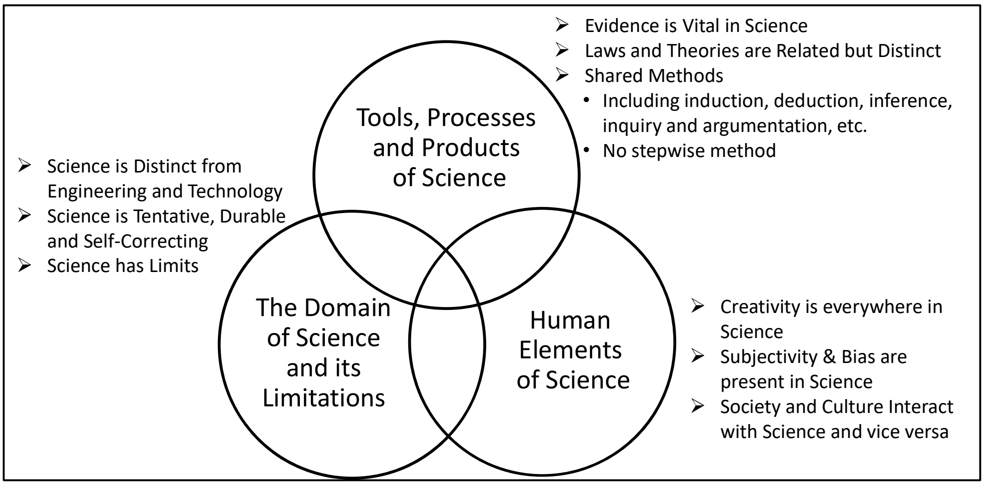

Figure 1-7 The major sub-elements or key NOS aspects often recommended for inclusion in science instruction, arranged in three related clusters according to McComas, W. F. (2020, pp. 36-65).

1.4.1 Nature of Science in the Dutch curriculum

In the Netherlands, the term used for what is called NOS is *aard van de natuurwetenschap (Dekkers & Kortland, 2017)*. But contrary to American science education, there is not such explicit attention to NOS in Dutch science curricula. Nevertheless, in the introductory texts and the objectives of, for example, the physics syllabus paragraph A9, we find specifications such as “The candidate […] can distinguish between scientific arguments, normative societal considerations and personal opinions.“[13] (College voor Toetsen en Examens, 2019, p. 14), which address aspects of NOS. However, such NOS aspects do not appear in the topics tested in the national final exam (College voor Toetsen en Examens, 2019, pp. 17-28). A recent analysis of science education standards documents found the same situation in all nine analysed countries; NOS ideas do not occur as expectations for student learning (Olson, 2018). Therefore, one could conclude that students are not expected to develop ideas about NOS.

1.4.2 Aspects of Nature of Science in conceptional quantum physics

As described in section 1.3, QP phenomena contradict our everyday experience and familiar principles of classical (Newtonian) physics, which is the major part of what students learned earlier in school physics. Therefore, students’ views of the natural world (their worldview) and their view on physics are challenged when they are introduced to QP. While this confusing situation makes learning QP difficult, it is also an excellent opportunity to reflect on the nature of physics. Moreover, research has shown that novice learners have undesired views on NOS aspects in QP and often spontaneously have NOS-related questions (Baily & Finkelstein, 2010a; Falk, 2007; Müller & Wiesner, 2002a), which seems to make discussing certain NOS aspects in QP lessons natural and even necessary.

Table 1-3 (Stadermann & Goedhart, 2020 p.1000) provides an overview of NOS views on five aspects that are relevant for learning conceptual QP. Below, I highlight three aspects of this overview and their connection to learning conceptual QP: models, tentativeness, and controversies. A detailed account of the various NOS aspects and their role in each part of this research follows in Chapters 2 to 5.

The role of scientific models

Students often mistakenly think that scientific models represent reality as much as possible (McComas, William F., 1998). Imagining an electron as a tiny negatively charged ball works well for most parts of school physics. Indeed, using this mechanical model is very productive for students because it helps them answer many exercises and exam questions. It should come as no surprise that students think that electrons *are* tiny negatively charged balls if we do not make them explicitly aware of the role, possibilities and limits of models. However, when they first encounter QP phenomena (for example, electron interference in the double-slit experiment), we expect them to handle different models for electrons flexibly. The

[13] Original text in Dutch: De kandidaat kan: […] onderscheid maken tussen wetenschappelijke argumenten, normatieve maatschappelijke overwegingen en persoonlijke opvattingen.

conceptual mathless way of presenting QP in secondary schools uses many visualisations in different situations when they understand the role and limitations of scientific models.

The tentativeness of scientific knowledge

Although Newtonian mechanics has brought us much insight into the mechanisms of the physical world, a new theory was needed to describe and predict QP phenomena. Even now, there are still many unanswered questions, such as, for example, the question of QP interpretations. If students believe that scientific knowledge is unchangeable (because scientific methods yield absolute proof), QP will confuse them. Therefore, introducing QP at secondary schools is an excellent opportunity to reflect on the fact that scientific knowledge is, in principle, always open to development, warranted change and improvement.

Table 1-3 Connection between aspects of Nature of Science and Quantum Physics (Stadermann & Goedhart, 2020)

NOS aspect	Example of an undesired view	Example of the 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 useful and mostly 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.

Controversies in science

Physics textbooks often present historical developments as if the scientific community immediately accepts new scientific knowledge (Niaz & Rodríguez, 2002). If students believe that good science is indeed directly welcomed by all scientists, the role of debates in science is problematic for them. They could argue that any new knowledge under debate is probably wrong or non-scientific at all. From such an inadequate NOS viewpoint, it would also be impossible for different scientists to interpret the same data differently. Consequently, a scientific controversy that is publicly debated could be misinterpreted as an ordinary disagreement with no basis in facts. The few controversies that might be addressed in traditional physics lessons have been resolved long ago. Therefore, students do not experience them as genuine controversies. For example, when discussing the Copernican Revolution, students have difficulty placing themselves in a neutral position. They have grown up with the heliocentric theory and consider it the obvious truth; the idea that the sun could orbit the earth seems ridiculous to them. Controversies about different interpretations of QP, on the other hand, are still open. Addressing the existence of different interpretations could make students aware that controversies in science are an essential factor in the development of scientific knowledge.

1.5 Research goals and structure of this thesis

As described in 1.2, one of the reasons for this research was the introduction of QP in the Dutch upper secondary curriculum. This introduction came as a surprise to many teachers and was surrounded by discussions about the value and the feasibility of QP in the curriculum. Five years after the first final exam with QP questions, textbook authors and teachers have some experience with the subject, and it seems certain that QP will remain in the Dutch curriculum. Current discussions are predominantly about difficulties of developing assessments and specific content issues, such as whether the Pauli principle is more important for learners than Heisenberg's uncertainty principle. It would enhance the value of the curriculum innovation if there was a more general reflection on what has been achieved in the first few years and what the desired goals of QP teaching in Dutch upper secondary education should be in the future. This PhD project aims to contribute to this reflection by exploring whether a focus on NOS aspects in QP teaching would be of added value for all students, both for the future quantum experts and for those who do not need QP content knowledge for their future studies and careers.

In 1.3, I discussed what makes QP different from many other school science topics. This difference is partly due to NOS-related aspects, making QP conceptually difficult — even without mathematical formalism. On the other hand, this difference seems to make QP perfect for addressing NOS aspects (see 1.4.2). Thus, I hypothesise that NOS and conceptual QP are theoretically intertwined and could complement and reinforce each other in secondary school physics education. However, integrating NOS in QP teaching is not common in physics classrooms, and textbooks rarely support this approach (see 1.2.1).

This PhD research aims to explore different perspectives on addressing NOS aspects in teaching conceptual QP. In the first project, I tried to understand how QP is taught at secondary schools in other countries and what goals might be visible in the curricula. Then, I explored students' views on NOS in QP. Along the way, I developed instructional materials that address known learning difficulties, support activating teaching methods, and explicitly address NOS aspects of QP. To complete this research, I investigated whether and how teachers in Dutch exam classes use the materials and, in particular, how and why — if at all — they address NOS aspects in their QP lessons. In the following section, I will shortly explain the considerations that led to the specific research goals in the different phases of this research.

1.5.1 International curriculum perspectives

Because the Netherlands is just a "beginner" in teaching QP at secondary school level, it is wise to learn from other countries with more experience. I was especially interested in potentially fruitful approaches to teaching NOS aspects of QP. To analyse the current state of QP in secondary physics education in different countries, an extensive comparison and analysis of QP and NOS in 15, mainly European countries was conducted (Chapter 2). The goals of this study were:

(a) to give a structured overview of QP topics in upper secondary school curricula of different countries;
(b) to identify similarities and differences between the content of QP in these curricula and to give an account of the possible rationale for the common and the specific components;
(c) to investigate how QP is placed in the perspective of learning about NOS in different educational systems.

1.5.2 The students' perspective

It was essential to return to the learner's perspective to investigate the practical possibilities to connect QP learning with NOS aspects. The question in this next phase of the research was if informed NOS views and QP comprehension reinforce each other. If that is the case, students with a well-developed understanding of NOS should also score higher in a QP concept test. Without any particular teaching intervention, it seems reasonable that students have various NOS views and undoubtedly different levels of conceptual understanding of QP. To investigate possible connections between conceptual understanding of QP and NOS views, a second study was conducted (Chapter 3) with the following goals:

(a) to test secondary school students' understanding of QP concepts after regular QP lessons;
(b) to investigate what NOS views students express when asked to explain their ideas about contexts they know from QP lessons;
(c) to find connections between students' conceptual understanding of QP and their NOS views.

1.5.3 Teaching resources

I have developed innovative teaching materials to bring the theoretically fruitful connection between QP concepts and NOS aspects into classrooms (Chapter 4). The main goal for these materials was to support teachers in natural teaching environments in teaching QP with explicit attention to NOS aspects. This teaching material draws on various studies on students' learning difficulties and the corresponding efficient teaching strategies for QP and NOS. In addition, through my own years of teaching experience, I know that each teaching situation sets different requirements for the teacher and the teaching material. Furthermore, lesson observations and extensive discussions with colleagues have made me realise that teaching materials are only helpful if teachers can link them to their own way of teaching, their teaching goals, and the classroom environment. Therefore, the teaching materials have a buffet style, enabling teachers to adapt the material to their own preferences and the needs of the students during a lesson.

1.5.4 Teachers perspectives

To explore the actual use of buffet-style teaching materials in authentic classrooms, a qualitative study was conducted. Ten teachers used the materials as an optional supplement or alternative to their usual teaching material (Chapter 5). This study aimed to

(a) explore which NOS aspects – if any – the teachers addressed in their QP lessons and what teaching activities they chose for this;
(b) relate teachers' goals in QP lessons to these addressed NOS aspects.

1.5.5 Structure of this thesis

The structure of research is often complex and difficult to summarise in a text. Because a picture offers more degrees of freedom, I prefer a graphical representation of the interrelationships of the different studies in my research, see *Figure 0-0*, page VII of this thesis . In this way, for example, the relationship between QP and NOS aspects in education is visible as the central theme of this thesis. The image also shows how the first five chapters of this thesis relate to each other and to the central theme.

Finally, in chapter 6, I discuss the insights I have gained through the separate sub-studies concerning the overarching aim of this PhD research and the contributions to educational research. I also reflect on the research method and my role as a researcher. Additionally, Chapter 6 discusses the possibilities for and practical challenges of including NOS aspects in learning and teaching OP in secondary schools. In conclusion, I offer recommendations for teacher trainers, researchers, textbook authors and curriculum developers, and I give methodological and content-related suggestions for further research.

Chapter 2:

International Curriculum Perspectives

Analysis of secondary school quantum physics curricula of 15 countries

Different perspectives on a challenging topic

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Abstract

Secondary school level quantum physics (QP) courses have recently been implemented in the national curricula of many countries. QP gives opportunities to acquaint students with more recent physics and its applications and to discuss aspects of the Nature of Science (NOS). Research has shown that QP is a challenging area for students. Because the inclusion of QP in national curricula is rather new in most countries, it is interesting to compare QP curricula from these countries to make the choices by curriculum designers visible. In this study, we provide a detailed overview of QP courses from fifteen countries. We collected and analysed official curriculum documents to identify key items present in most curricula. Our inventory identifies a shared current Core Curriculum of QP, which contains the following seven main categories: discrete atomic energy levels, interactions between light and matter, wave-particle duality, de Broglie wavelength, technical applications, Heisenberg's uncertainty principle, and the probabilistic nature of QP. We also found differences in the focus of the listed topics of certain countries, which indicate different views on teaching QP and might inspire curriculum designers struggling with QP. For instance, challenging items like QP interpretations or epistemological aspects of QP are taught only in a few countries. Although research suggests that epistemological aspects help students to comprehend novel QP concepts, many countries do not explicitly include these in the curriculum. We provide reasons and suggestions for this.

2.1 Introduction

QP is not all about calculating, and there are diverse reasons why it deserves a place in secondary school curricula. First of all, QP is crucial for our current scientific worldview; students should get the chance to learn this in high school and not be limited to 19th-century physics (Kaur, Blair, Moschilla, Stannard et al., 2017; Krijtenburg-Lewerissa et al., 2017; Pospiech, 2009). Furthermore, QP brought us devices like lasers, solar cells, and microchips that are indispensable for modern life, and there is an increasing number of research fields where QP offers new possibilities (e.g., DNA decoding with tunnelling, quantum computers or cryptography). School physics that aims to trigger students' interests with real-life contexts and future-oriented research may better replace some outdated topics in favour of quantum technology. And finally, popular science topics like quantum teleportation, parallel worlds or quantum computers appeal to the imagination. Similar to Einstein's theory of relativity, QP fascinates scientists as well as students (Angell et al., 2004; Bungum et al., 2015; Hadzigeorgiou & Stivaktakis, 2008; Johansson, 2018), and educators should not miss the chance to give physics a more attractive image.

The weird and fascinating, almost mythical, image makes QP appealing, though challenging to teach. In contrast to most classical physics topics, we cannot find a consistent visualisation for quantum phenomena. QP offers students new views on physical reality, which conflict with earlier learned classical concepts such as the nature of particles, locality, and determinism. Scientists still discuss how – and if at all – QP should be interpreted. In the opinion of some physicists, the interpretation controversy is needless (Fuchs & Peres, 2000) or even a scandal (van Kampen, 2008). Additionally, instructors have different opinions on discussing philosophical aspects with students. For example, Alonso (2002) stated: "My motto is: Learn first what quantum mechanics is good for, and afterwards analyse its epistemological implications." However, recent research shows that epistemological aspects can motivate and help students to understand QP conceptually (Hoehn & Finkelstein, 2018; Levrini & Fantini, 2013). Moreover, there are instructors who, indeed, use different interpretations of QP to teach students aspects of the Nature of Science (NOS) (Bungum et al., 2015; Klassen, 2011; Pospiech, 2003). In the views of these educators, the disagreement on interpretations is an excellent example of *science in action*: competing scientific theories can exist next to each other as long as there is no evidence favouring one theory over others (Garritz, 2013; Hogan, 2000; Latour, 1987; Sandoval, 2005). Thus, for secondary education, philosophical and historical aspects of QP are not only advocated to enhance students' conceptual understanding but also to serve the more general goal to develop their view on the NOS.

The reason for this research was the controversial introduction of QP in the Dutch national high school curriculum in 2014. Teachers and textbook authors had doubts if secondary school students would be capable of understanding QP concepts at the necessary level of abstraction. The general purpose of the introduction, the selection of content, and the nature of exam questions were subjects of discussion. In this situation, it is valuable to look at the practice of other countries. A similar occasion in 2005, when QP was introduced in Portuguese secondary school physics, led to a general analysis of official curricula of ten countries: Portugal, Spain, France, Italy, United Kingdom, Denmark, Sweden, Finland, Australia, and Canada (Lobato & Greca, 2005). It turned out that, at that time, only half of the analysed countries addressed pure QP themes like uncertainty or duality. The curriculum documents of the other countries only mentioned topics like the quantisation of energy levels in the context of atomic physics, which can also be explained with semi-classical models. Remarkably, this study did not include countries like Germany and Austria, which have a long history of teaching QP at the secondary level. In recent years the content of official secondary school physics curricula also changed in the countries mentioned in the Portuguese study. At present, most upper secondary physics curricula contain more aspects of QP. We are not aware of more recent and detailed overviews of QP on the secondary school level. Even one of the best known international studies on advanced science courses in upper secondary school Trends in International Mathematics and Science Study (TIMSS advanced) (Mullis et al., 2016) only gives a short overview of some aspects of QP in the curricula of nine countries. Therefore, the purpose of this study is three-fold:

(1) to give a structured overview of QP topics in upper secondary school curricula of different countries.

(2) to identify similarities and differences between the content of QP in these curricula and to give an account of the possible rationale of the common and the distinguishing components.

(3) to investigate how QP is placed in a perspective of learning about NOS in different educational systems.

2.2 Theoretical framework

Our research is about curriculum, quantum physics (QP) and the nature of science (NOS). In the following, we present some theoretical and pragmatic outlines and definitions for this article.

2.2.1 Curriculum documents

In this study, we collected and analysed curriculum documents from various countries. Although "curriculum" is a familiar term in educational literature, there is no consensual definition of this term. *Curriculum* has been defined in terms of learner experiences (Hass, 1987) or as a plan for teaching (Biggs & Tang, 2011). This latter might be a list of aims or objectives for learning or a more detailed description of all planned activities in classrooms, including teaching materials and assessment (Kelly, 1977; Wiles, 2008). Van den Akker (2010) differentiates five levels of curriculum: international/comparative (*supra level*), nation and state or system (*macro level*), school and institution (*meso level*), classroom (*micro level*), and individual and personal (*nano level*). This grouping is useful for our research; all examined documents stem from the macro level and have an official status, such as a national or federal curriculum which is legislated by the government or prescribed by a Department of Education and describes the intended learning outcomes on a specific level. In scientific literature about different curriculum perspectives, these documents are also categorised as the *written* or *formal* representation of the “Intended Curriculum” (Goodlad, 1979; Kelly, 1977; Van den Akker, 2003).

In this paper, we will further use the term *curriculum document*’ to refer to all official written sources we used for answering our research questions. If a document gives very detailed specifications, we might alternatively use the term *syllabus* or *exam syllabus*. We only use these specifying documents when they belong to the macro level so that they are binding legal guidelines for the textbook or exam developers and thus practically mandatory to be followed by educators.

Curriculum documents cannot be compared directly because these documents serve different purposes in disparate school systems. Especially in countries with compulsory final written examinations like the Netherlands, France, and several German federal states, the syllabi are very detailed. They precisely describe which skills and what content items are essential for the exam. In these countries, the curriculum documents serve as a practical source of information for students, teachers and textbook authors. In other countries, the national curriculum documents describe the learning outcomes in more general terms.

Indeed, there are more reasons for the diversity of the analysed curriculum documents: the traditions of a country, its general conception of education and the expectations of society affect the content and style of a formal curriculum. However, it is beyond the scope of this research to go into these complex backgrounds. A general classification of the function of a curriculum document can be made by the national examination practices. The kind of examination is usually defined in the curriculum documents and is a significant indication of the particular role and context of each document. We distinguish centrally set school-leaving exams and school-based exams. The former are standardised written final exams that are administered to large populations of students so that results can be compared across the country or state. School-based exams are written or oral final exams, locally developed at the school level or by individual teachers, giving them the opportunity to tune the exam with the curriculum document, but evidently, standardisation is difficult.

2.2.2 Quantum physics in secondary schools

Some time ago, physics undergraduates would not take a course called *quantum mechanics* until their third year at university. To understand the mathematical formalism of quantum mechanics, students first should have mastered partial differential equations, complex numbers, and linear operators in Hilbert spaces. This kind of sophisticated math is not taught in high school, and consequently, courses on the secondary school level cannot focus on a rigorous mathematical description of QP. Therefore, we prefer the more general term *quantum physics* (QP), emphasising that the focus is on the “big ideas” rather than the mathematical formalisms. The content of QP courses for secondary schools is comparable to introductory QP courses at college level for non-physics majors. These courses mostly cover some historical developments of quantum theory with key experiments and the following central themes:

photoelectric effect, wave and particle behaviour, de Broglie wavelength, double-slit interference, probability interpretation, uncertainty principle (Kragh, 1992; Wuttiprom et al., 2009). To meet our definition of QP in secondary schools, it is essential that the curriculum covers at least one of the following topics which are related to the fundamental principles: matter waves (e.g., interference of electrons or the De Broglie relation), wave-particle duality, the probabilistic nature of QP (i.e., QP can only give statistical predictions of measurement outcomes), Heisenberg's uncertainty principle or entanglement. A country is not included in our overview if the official curriculum document solely contains topics such as line spectra of gases, discrete energy levels in an atom or light-emitting diodes (LED). These topics are related to QP, but the first two can be explained with a semi-classical planetary (Bohr) model of the atom, and the LED appears in some syllabi only as an electronic component without any QP context.

2.2.3 Nature of Science

For more than a century, scientists and educational authorities have promoted the idea that teachers should not only present results of scientific research as *facts* but that students ought to learn how research is done and how scientific knowledge develops (Jenkins, 2013). Currently, this is referred to as teaching the Nature of Science (NOS), which is a term open to many interpretations. Even though the epistemological question as to what the nature of science precisely remains deeply philosophical, we want to use the term NOS in the current understanding in secondary education. It refers to what students should learn about the processes that are involved in scientific work and the methods scientists use. Knowledge about the NOS is seen as an indispensable part of students' scientific literacy within the development of their critical thinking (Holbrook & Rannikmae, 2007; Khishfe 2012). In the context of global challenges such as the impact of climate change and the need for sustainable energy use, knowledge about NOS becomes increasingly relevant for all citizens. Understanding how science works is a prerequisite for distinguishing between scientific and non-scientific claims. In the last decennium, NOS has, therefore, become an essential part of science curricula and policy documents in many countries (Yacoubian, 2018). What exactly teachers should teach and how it can be done successfully is the subject of discussion and research on its own (Allchin, 2013; Erduran & Dagher, 2014; Lederman, N. G., 2007; McComas, William F. et al., 1998).

Science education research indicates that several NOS aspects are particularly relevant for learning QP. Without an understanding of the function and limitations of models, students might stick to the classical idea that particles behave like downsized billiard balls (Johnston et al., 1998; Petri & Niedderer, 1998). QP concepts like superposition, interference and Heisenberg's uncertainty relation are not compatible with this model of a particle. A student who believes that science provides absolute truth – and this belief could be caused by previous physics lessons or textbooks (Abd-El-Khalick et al., 2017) – will have problems appreciating the different interpretations of QP. In practice, many students will get to know only one interpretation of QP, namely the instructor's favourite interpretation. Research in quantum physics teaching and learning shows that teachers' choice of an interpretation affects students' understanding of QP (Baily & Finkelstein, 2015) and that this choice should be explicitly explained to the students (Greca & Freire, 2014a).

Table 2-1 Aspects of Nature of Science and History of Science in Quantum Physics

NOS & history aspects		Example of relevance for QP
N1	Methodology (e.g., experiments and hypothesis)	The methodology used in classical physics (relation between experiment and theory) apply as well in QP. Additionally, thought experiments were an essential means to discuss fundamental concepts in the development of QP and eventually led to various quantum entanglement experiments.
N2	The role of scientific models	For some situations, it is appropriate to use the model of a wave for quantum objects; in other situations, the model of classical particles is more helpful. A model only serves to show some aspects of phenomena. (In QP lessons, students experience different models of light or matter.)
N3	Tentativeness of science	Even though physics can explain many phenomena, the history of physics, including QP, shows that science is tentative. To the long-held hypothesis that light is a wave, Einstein added the photon hypothesis of light as a possible explanation of the photoelectric effect. This was one of the many steps in a historical paradigm shift which eventually led to the development of QP. The current existence of different interpretations of QP shows that scientists question existing models and interpretations and that this is an ongoing process.
N4	Creativity in science	To invent famous thought experiments, scientists had to be creative and only by thinking out-of-the-box new quantum experiments can be developed. Many scientists want to find out if the wave function is more than just a conceptual tool. Therefore, they develop creative interpretations of QP.
N5	Controversies in science	The famous discussions between Bohr and Einstein were important for the development of QP. Currently, there is still discussion about different interpretations of QP. Only in an open atmosphere without dominating ideologies science can freely develop.
N6	History of science	More than in other parts of physics, the history of QP is regarded as relevant for education. Historical experiments illustrate why scientists had to change their mechanical worldview. (For students, this can give science a more human image, and it brings theory to life.)

To identify NOS aspects in curriculum documents, we use elements from two studies that focus on the practical use of NOS in education. The first one is McComas' and Olsen's (1998) analysis of science education standards documents, and the second one is a Delphi study that Osborne et al. (2003) performed with 23 international experts to find a consensus about which NOS ideas should be taught. To limit the scope of this research, we only focused on some NOS aspects from these studies that could be relevant in the context of teaching QP. We also searched for History of Science as a learning goal in the curriculum documents because many scholars advocate including the history of science in lessons to develop informed NOS views of students (Clough, 2017; Kim & Irving, 2010) and QP is often introduced via historical experiments. Table 2-1 shows how NOS aspects are essential for the development of concepts in QP.

2.3 Methodology

Our work consists of three main steps. First, we sought macro level secondary school curriculum documents that cover aspects of QP. Next, we scrutinised these curriculum documents with a focus on QP and NOS. To get an overview of how QP can be taught at the secondary level, we identified a list of QP items that are mentioned in different curricula. We also checked which of the aspects from Table 2-1 are described in the curriculum documents. Once we had an overview of which curriculum items are present in each document, we analysed the similarities and differences of the QP curriculum and NOS aspects.

2.3.1 Selection of curriculum documents

Although QP is taught in secondary schools in many countries, there is no straightforward way to find countries where QP is part of the mandatory curriculum. Furthermore, relevant curriculum documents are naturally written in the countries' languages and not always easily accessible. The most comprehensive international studies for secondary school education, PISA (*Programme for International Student Assessment*) and TIMSS, compare the educational achievement of students not older than fifteen years, and QP is usually not included in the science curriculum for this age group. Even "TIMSS advanced" about students in the final year of secondary school enrolled in special advanced mathematics and physics programs, covers only some aspects of QP. Moreover, the most recent report from 2015 only contains brief information about the intended physics curriculum of nine participating countries: France, Italy, Lebanon, Norway, Portugal, Russian Federation, Slovenia, Sweden, United States (Mullis et al., 2016).

In order to find official curriculum documents from countries where QP is taught, we identified physics education research literature by using the keywords "secondary school" and "quantum" or "high school" and "quantum" in databases (ERIC, Google Scholar, WorldCat) since 1996. Additional scanning of the reference lists of the articles found in this initial search and eliminating articles with no physics education context yielded a total of 76 documents dealing with QP in secondary education. The majority of these articles originated from European countries, in particular, Germany (28 articles), Italy (11 articles) and Norway (10 articles). The documents were about teaching and learning QP in advanced secondary physics courses, innovative QP teaching materials or teacher training programs. The QP content of the research articles concerned the following themes: (1) fundamental principles, which emphasise the difference between classical physics; (2) real or simulated experiments and phenomena to visualise concepts or to show real-world applications; (3) QP used in the context of atomic theory; (4) the wave function or other mathematical representations; and (5) philosophical aspects of QP. When the authors of an article mentioned the source of a written curriculum, we checked whether the documents were still up to date. In other cases, we contacted authors to get access to the most recent official curriculum documents. This search finally led to 37 current official curriculum documents originating from fifteen different countries plus the International Baccalaureate (IB) diploma program. Some countries have more than one official curriculum document (details are explained in Appendix 2-B). Although the IB cannot be linked to one country, we added the IB diploma program to our research because of its international and exemplary character (Zemplén, 2007).

Countries without accessible national curriculum documents for secondary schools or without QP, as we defined it above, are not included in our overview. Additionally, countries might not be listed because no published research in English emerged from our initial literature search. Accordingly, it is not our intention to give a complete overview of all countries around the world in which QP is taught in secondary schools. Instead, we want to analyse which content is typically used to introduce this challenging topic in different educational systems.

2.3.2 Identification and clustering of QP items

We scrutinised the curriculum documents and indicated text fragments related to QP, as defined above. To give a complete overview of what students are expected to know about QP in different countries, we derived a list of more than 30 QP items from the syllabuses. By clustering items that belong together into one synoptic term, we reduced a long list with details from all curricula to a manageable summary. For example, the term "matter wave quantitative" combines content items like "Wave character of electrons; the relationship between momentum and wavelength according to de Broglie; qualitative experiments with the electron diffraction tube, quantitative data analysis of double-slit or lattice experiments" (Bavaria, Germany) or "calculations with the de Broglie wavelength" (Netherlands). The guiding principle for developing the final list was that it should be as detailed as necessary and as short as possible. After a check of the list by three experts (a professor of theoretical physics and two physics education researchers), we arrived at a list of 17 QP topics that were mentioned in more than one curriculum document. We double-checked all documents, and in case of doubt, we asked a local expert to check the coding and our findings. We do not claim that these topics are fundamental or cannot be condensed more, but it gives a detailed and manageable overview of which aspects of QP are treated in secondary schools. Our final list of 17 QP curriculum topics is shown in Table 2-2. We ordered the QP items in a way that is convenient for our purpose: From "Blackbody radiation" (Q1) to "Wave-particle duality" (Q5), the list roughly follows the chronological historical development of QP, which is also a standard order in many curricula. From Q6 onwards, the position of a topic represents its frequency, across all documents, from the most to the least often mentioned ones.

To structure the list of curriculum items (Table 2-2), we adopted the literature themes we found during the selection of curriculum documents. Subsequently, we asked two faculty members that are involved in introductory QP lectures and two physics education researchers to assign the 17 curriculum topics according to the five content themes. Admitting that some curriculum items fit in more than one theme, we could agree on the following grouping:

Table 2-2 List of items for the comparison and analysis of different curriculum documents

Code	Description
Q1	Black body radiation;
Q2	Bohr atomic model (i.e., electrons on certain allowed orbits), also if it is only used for hydrogen;
Q3	Discrete energy levels in atoms (not orbits) and absorption line spectra of gases as a result of it ;
Q4	Interaction between light and matter (e.g., photoelectric effect or the Compton Effect);
Q5	Wave-particle duality, an example of Bohr’s complementarity principle (often introduced with the double-slit experiment or with a Mach-Zehnder interferometer);
Q6	Matter waves, quantitative (calculations with de Broglie wavelength of particles) the de Broglie wavelength might be used to determine if a situation should be regarded as a quantum system;
Q7	Technical applications (e.g., scanning electron microscope SEM, semiconductors, LED, laser);
Q8	Uncertainty (Heisenberg's principle);
Q9	Probabilistic nature of QP (statistical predictions are possible for the results of measurements);
Q10	Philosophical or epistemological consequences explicitly mentioned as a learning outcome (e.g., discussion of interpretations, thought experiments, Schrödinger’s cat);
Q11	One dimensional model (or particle in a box, potential well) mostly introduced with diagrams of the wave function to illustrate quantised energy levels of a system;
Q12	Tunnelling (the context might be alpha decay, explicitly presented as a result of tunnelling);
Q13	Atomic orbital model (also: electron cloud, 3-dimensional potential well, different quantum numbers);
Q14	Pauli Exclusion Principle (used as the motivation of the shell model of the atom and as an explanation of the periodic table);
Q15	Entanglement (also called non-locality, often with an explanation of the EPR-experiment);
Q16	Schrödinger equation (only one-dimensional time-independent);
Q17	Calculation of detection probability, Born rule (probability = square of the magnitude of the wave function or square of phasor length in the sum over path approach).

Fundamental QP principles

Q5 Wave-particle duality/complementarity;
Q8 Heisenberg's uncertainty principle;
Q9 Probabilistic / statistical predictions;
Q14 Pauli Exclusion Principle;
Q15 Entanglement.

The curriculum topics listed above represent fundamental concepts that show the disparity between classical physics and QP. For secondary school students, it is not possible to derive these Fundamental Principles from familiar characteristics of visible objects or any earlier learned school physics.

Phenomena and applications

Q1 Blackbody radiation;
Q3 Discrete energy levels (line spectra);
Q4 Interaction between light and matter;
Q6 Matter waves, quantitative;
Q7 Technical applications;
Q12 tunnelling (e.g., alpha decay).

The items in the previous category are helpful to show students that QP is not only a theoretical construct but that it can explain phenomena and that there are useful applications of the theory. Many of these technical applications are essential for the life of secondary school students.

Atomic theory

Q2 Bohr atomic model;
Q3 Discrete energy levels (line spectra);
Q11 One dimensional model / potential well;
Q13 Atomic orbital model;
Q14 Pauli Exclusion Principle.

In some countries, these topics are part of the chemistry curriculum rather than the physics curriculum of upper secondary school (see Appendix 2-B).

Wave function or other mathematical representations

Q11 One dimensional model / potential well;
Q12 Tunnelling;
Q16 Schrödinger equation;
Q17 Detection probability as the square of the magnitude of the wave function or square of the phasor length in the sum over path approach.

These items represent the mathematical side of QP. Unlike the "fundamental principles", all items in this category involve calculations or at least graphical solutions of, e.g., the Schrödinger equation. All these topics can also be found in traditional university QP textbooks, although the mathematical complexity at university level is undoubtedly higher than in secondary education.

Philosophical aspects of QP

Q5 Wave-particle duality/complementarity;

Q10 Philosophical or epistemological consequences explicitly mentioned as a learning outcome (e.g., discussion of interpretations, thought experiments, Schrödinger's cat);

Q15 Entanglement.

Arguably, teaching all aspects of the category "Fundamental Principles" of QP can or even should involve philosophical considerations. From a practical point of view, experts agree that the iconic experimental results of the double-slit experiment (Q5) and the EPR-experiment (Q15) are very suitable to stimulate philosophical discourse in classrooms (Crease, 2002; Feynman et al., 1965; Harrison, D., 1979; Pospiech, 1999; Pospiech, 2003). Moreover, with teaching about one of these two topics, teachers inevitably have to address ontological and epistemological questions. Research showed that even if the instructor does not talk about any philosophical consequences, students develop their own interpretations of the experimental results (Baily et al., 2010). In contrast to the previous theme, these epistemological items are often neglected in calculus-based QP university courses(Baily et al., 2010; W. K. Adams et al., 2006). For school physics, researchers argued that these philosophical aspects are especially valuable. For example, Myhrehagen and Bungum point out that it can help students to develop a qualitative understanding of QP if they compare their own interpretations with those of famous physicists (Myhrehagen & Bungum, 2016). Moreover, Pospiech argues that modern topics like teleportation and entanglement are fascinating topics for students because they need to modify their understanding of reality (Pospiech, 2000). Including the philosophical side of QP in education implies many aspects of NOS as described in the theoretical framework of this article.

2.3.3 Method of QP curriculum items analysis

To identify similarities and differences between the content of QP in secondary school physics in different countries (our second research goal), we analysed the results in two steps: First, we derived the international current Core Curriculum for QP. Subsequently, we analysed all curriculum items to explore possible thematic foci.

Determining the Core Curriculum

We identified the most prevailing curriculum items from our overview of 15 countries. To find these favoured curriculum items, we compared the frequencies of the items across the collected documents. To avoid an overrepresentation of countries with more than one curriculum document in our survey, we counted the countries – not the number of documents – in which each content item occurs. The set of items that are most common in teaching QP on the secondary level can be called the current Core Curriculum for QP.

Thematic analysis of curriculum focus

To determine the central themes of QP in secondary education, we compared the items of the current Core Curriculum with the five themes (1) Fundamental QP principles, (2) Phenomena and applications, (3) Atomic theory, (4) Wave function or other mathematical representations and (5) Philosophical aspects of QP. We further analysed the curriculum documents of educational systems, which introduce students to more aspects of QP than only the Core Curriculum. We sought to find the focus of these curricula by exploring if the extra content items concentrated around a specific theme.

NOS in physics curriculum documents

The goal of this part of the research is twofold. First, we investigate if the NOS aspects that we assume are essential for developing QP concepts are in principle addressed in the curriculum documents. And secondly, we explore if and how QP and NOS are linked in curriculum documents.

We first scrutinised each of the 23 entire curriculum documents for upper secondary school physics to identify passages that address one of the earlier identified NOS aspects: Methodology (e.g. working with hypothesis and experiments) (N1), The role of scientific models (N2), Tentativeness of science (N3), Creativity in science (N4), Controversies in science (N5), and History of Science (N6). For each curriculum document, we registered which of the NOS-item was visible in the text.

As summarised in Table 2-1, there are evident relations between QP and multiple aspects of NOS. After the identification of general NOS statements in the curriculum documents, we analysed if NOS aspects are addressed in the context of QP; We searched for descriptions of learning outcomes that combine NOS with QP. In this part of our study, we do not aim to make any quantitative statements but to find examples of documents in which certain QP content items are explicitly linked with NOS in different curriculum documents.

2.4 Results

2.4.1 Curriculum documents

Our search for curriculum documents containing references to the teaching of QP in secondary school gave a variety of macro-level sources differing in form and level of detail. Some are written as coherent reflective texts; other documents consist mainly of itemised tables. These documents are published under different names (after translation): national curriculum, national learning plan, learning standards, content standards, syllabus, examination program, or exam specifications. In some countries, several equivalent syllabi exist in parallel. To give an uncluttered international overview of the various curriculum contents, we selected only a few sample documents from these countries. In the country-specific information in Appendix 2-A and Appendix 2-B, we elucidated these selections. For the analysis in our research, we finally used 23 different curriculum documents originating from 15 different countries: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany (documents of 7 states), Italy, Netherlands, Norway, Portugal, Spain, Sweden, and the United Kingdom (2 documents). In most of these countries, QP items are taught in an elective physics course in the final high school years, typically for students aged 17 to 19. Only in the curriculum document of the German federal state of Bavaria, we found QP items, like wave-particle duality, in the general physics course for all 15- to 16-year-old students. In some countries, teachers have the option to choose between several advanced physics options (e.g., relativity or astronomy or quantum physics).

2.4.2 QP curriculum items

Although most analysed physics curricula are divided into thematic sections, QP is not a separate section in every country. Often QP items are combined with items from nuclear physics or relativity in a section called "Modern Physics" or alike. In some countries, the QP items are spread over different sections such as "atomic models", "radiation", or "revolutionary ideas". The curriculum content is often presented in a table-like structure, sometimes with extra information about contexts, explanations, lesson time, competence aims with the expected depth of knowledge, formulas or example questions. What kind of extra information is given in the document partly depends on the role the curriculum is expected to fulfil, as mentioned above. In countries with oral exams, teacher-set exams or QP as an optional subject (e.g. Belgium or Austria), the curricula are more general and mention various optional items, whereas countries with QP in an externally set high stake standardised school-leaving exam (e.g., the UK, the Netherlands, and most German states) give more detailed specifications.

To illustrate the various styles of curriculum documents, we show some – if necessary, translated – sections regarding the items Q5 and Q6 in Table 2-3: We gave the item code Q5 ("wave-particle duality") to all statements concerning the central idea that in QP light and particles cannot be described as in classical physics. Several curriculum documents mention key experiments like the Double-Slit experiment or the Mach-Zehnder interferometer, in which this quantum property can be explained conceptually. Other documents do not mention such details but cover the same concept in general terms. Item code Q5 thus stands for a qualitative understanding; calculations and formulas are not necessary. Item Q6 ("Matter waves, quantitative") concerns the mathematical use of the same aspect, mainly for calculations with the de Broglie wavelength.

Our examples in Table 2-3 demonstrate that the styles of official curriculum documents are noticeably different, which is related to the divergent functions these documents fulfil in the educational systems. Educators and textbook developers in all countries use these official texts, but the rigour of definitions in the curriculum documents differ from country to country. The quotes in Table 2-3 show that Finnish and Austrian curriculum documents use open terms to describe the required course content. This unspecific description gives teachers vast possibilities to interpret the curriculum document and define learning outcomes themselves. On the contrary, the intended student competencies are described in great detail in the curriculum document like that of the German federal state of Baden Württemberg. Although teachers have the freedom to design their own lessons, such a syllabus will ensure that the physics lessons will cover all listed competencies to prepare students for their high stakes exams.

Table 2-3 Example Q5 and Q6 in different curriculum documents

Country (chapter in the curriculum)	Citation of a part of the curriculum document: In italics are the statements regarding Q5 and Q6	Item code
Finland (speciali-sation course F8: 'Matter and Radiation')	The particle nature of radiation and the wave nature of particles;	Q5
Austria (Compe-tence module 'quantum phys-ics')	Special characteristics of the quantum world, the double-slit experiment, Heisenberg's uncertainty principle, statistical interpretation. Insight into theory development and the world view of modern physics.	Q5
Norway (Physics 2: Modern phy-sics)	The studies aim to enable pupils to give an account of Einstein's explana-tion of the photoelectric effect and give a qualitative account of how re-sults from experiments with the photoelectric effect, Compton scattering and the wave nature of particles represents a break with classical physics.	Q5
Canada, Ontario (Revolutions in Modern Physics: Quantum Me-chanics and Special Relativity)	Light can show particle-like and wave-like behaviour, and particles can show wavelike behaviour. By the end of this course, students will describe the experimental evidence that supports a wave model of matter (e.g., electron diffraction).	Q5
England, Wales and Northern Ireland (AQA A-level specifica-tions, The discovery of photo electricity)	de Broglie's hypothesis: $p = \frac{h}{\lambda}$; $\lambda = \frac{h}{\sqrt{2meV}}$; Low-energy electron diffraction experiments; qualitative explanation of the effect of a change of electron speed on the diffraction pattern. Electron microscopes: Estimate of anode voltage needed to produce wavelengths of the order of the size of the atom.	Q6 Q6 Q5 Q6
Germany, Baden Württemberg (Two-hour course with emphasis on quantum physics)	The students recognise that any classical model fails to describe the behaviour of quantum objects entirely and consistently. In particular, they recognise that quantum physical experiences and experiments call into question familiar concepts and question concepts like determinism, cau-sality or trajectory. They describe the behaviour of quantum objects using probability statements. The students can: Describe similarities and differences in the behaviour of classical waves, classical particles and quantum objects at the double-slit experiment. Explain that for quantum objects, probability statements replace the determinism of classical physics. Describe interference experiments with single quantum objects using probability statements, and explain the outcome of the experiments. Describe that quantum objects always have wave and particle properties, but that these properties cannot be observed independently of each other. Students use quantum interference properties and which-way information for individual quantum objects (for example, double-slit experiment or Mach-Zehnder interferometer) (…) Explain how quantum objects can be described by their energy and their momentum, $E_{quant} = h \cdot f$, $p = \frac{h}{\lambda}$, de Broglie wavelength of matter waves	Q5 Q5 Q5 Q5 Q6

Table 2-4 Overview of some NOS aspects and QP topics covered in upper secondary school curriculum documents

		UK (England)	UK (Scotland)	Netherlands	Intern. Baccalaureate	Denmark	Norway		Finland		Germany (Baden-Württemberg)		Germany (Lower Saxony)		Germany (NRW)		Germany (Hesse)		Germany (Saxony)		Germany (Bavaria)	France	Italy (Liceo Scientif.)	Portugal	Sweden		Germany (Rhineland Palatine)		Belgium (Flemish community)		Austria	Spain	Australia (National)	Canada (Ontario)
	Implementation year of curriculum/syllabus	2016	2015	2016	2016	2008	2006		2016		2016		2017		2014		2016		2012		2011	2012	2010	2003	2011		1998		2015		2014	2015	2016	2009
	Name or abbreviation of the physics course	A	HA	na	HL	stx A	1	2	1	7	2	4	G	E	G	L	G	L	G	L	Ph	Fi	Fi	Fi	2	3	G	L	F	K	Ph	F2	4U	4U
Exam	Written leaving exam, centrally set	●	●	●	●	●		●	●	●		●	●	●	●	●	●	●	●	●	●	●	●*	●	●									
	Written leaving exam, locally set																						●*	●	●	●	●	●	●	●	●			
	Oral examination possible					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●			
Quantum Physics	Q1 Black body radiation	■	■	■	■		■			■													■	■	■							■	■	
	Q2 Bohr atomic model		■	■	■		■			■						■	■	■	■	■			■		■		□	□		□	□	■	■	
	Q3 Discrete energy levels (line spectra)	■	■	■	■	■	■			■			■	■		■	■	■	■	■	■	■	■	■	■		■	■		□	■	■	■	■
	Q4 Interactions between light and matter	■	■	■	■			■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	■		■	■		□	□	■	■	■
	Q5 Wave-particle duality / complementarity	■	■	■	■	■		■		■	■	■	■	■	■	■	■	■	■	■	▲	■	■	■	■		■	■		□	■	■	■	■
	Q6 Matter waves, quantitative (de Broglie)	■	■	■	■						■	■	■	■	■	■	■	■	■	■	▲	■	■	■	■		■	■		□	■	■	■	■
	Q7 Technical applications (SEM, LED, laser)	■		■	■	□		■					■	■				■	■		■	■		■		■		□		□	□	■	■	■
	Q8 Heisenberg's uncertainty principle		■	■	■			■				■	■	■		■	□	■	■	■	■		■			■	□	■		□	■	■		
	Q9 Probabilistic /statistical predictions		■	■	■						■	■	■	■	■	■	■	■		■	▲	■	■				■	■		□	■	■		
	Q10 Philos. consequences / interpretations							■						■		■	□	■		■			■				□	□		□	□			
	Q11 One dimensional model / potential well			■									■	■		■		■		■	■					■		□						
	Q12 Tunnelling		■	■	■													□			■					■		□						
	Q13 Atomic orbital model													■			□			■	■							□						
	Q14 Exclusion principle / periodic table																	■			■					■		■						
	Q15 Entanglement							■						■						■														
	Q16 Schrödinger equation																	□			■					■								
	Q17 Calculations of detection probability													■		■		■																
Nature of Science	N1 Working with a hypothesis	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		○	○	○		○	○	○	○
	N2 The role of scientific models	○		○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		○	○	○		○	○	○	
	N3 Tentativeness	○	○		○	○		○	○		○	○	○	○	○	○	○	○	○	○	○		○	○	○		○	○			○	○	○	○
	N4 Controversies in science	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○		○		○	○	○		○	○	○	○
	N5 Creativity in science				○	○	○	○	○				○	○			○	○	○	○	○						○	○			○		○	○
	N6 History of science	○	○		○	○		○	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○			○	○	○		○		○	○

Legend: Exam: ● common exam for this course; ●* possible exam form, rarely applied (see country-specific information in Appendix 2-B)
QP items: ▲ in compulsory physics course grade 10, age 15-16; ■ in advanced physic course grade 11 - 13; age 17-19; □ optional for teachers in an advanced physic course
NOS items: ○ mentioned in the curriculum of this physics course

Despite the differences in styles, it is our goal to give a clear overview of curriculum items. Therefore, we grouped countries with similar examination systems next to each other in Table 2-4 because a similar way of examination makes the curriculum documents more comparable, as explained in the introduction of this article. The symbols we used in Table 2-4 are explained in the legend, but for clarity about the use of *compulsory* or *optional*, some extra information: A filled square (■) indicates a compulsory item of an upper secondary school physics course (students age 17-19). In most cases, this is an elective course. If the curriculum document explicitly mentions an item as optional *for the teacher* (e.g., some curricula allow teachers to choose between different advanced physics topics), we use an open square (□).

2.4.3 Results of the curriculum items analysis

As indicated in the Methods section, we conducted two types of analysis: a compilation of most frequently included curriculum items and an analysis of differences between curriculum documents. After collecting the data in Table 2-4, we found it problematic to include "black body radiation" (Q1) and the "Bohr model of the atom" (Q2) in our study. Historically both items were steps in the development of QP, but they are not necessary to understand or support any other QP concept. Furthermore, in some countries, blackbody radiation is mentioned in the context of astrophysics, not QP. Moreover, the Bohr model of an atom belongs to chemistry in several countries. In some educational systems, physics and chemistry are taught as a combined subject, and Bohr's atomic model is solely used to explain atomic spectra and chemical bonding without relation to QP. Consequently, the presence of Q1 and Q2 in the list is ambiguous. For completeness, we included these items in the frequency table, but we decided to not include them in our further analysis.

Current Core Quantum Curriculum

In Table 2-5, we show the frequency of different items across countries and across all documents in this study. As explained in the Method, our units of analysis are countries for this part of the research. "Discrete energy levels" (Q3), "Interaction between light and matter" (Q4), "Wave-particle duality" (Q5), "Matter waves, quantitative" (Q6) and "Technical applications" (Q7) are undoubtedly the most commonly occurring QP items. At least 12 of the 15 different countries and the IB program (see Table 2-4) mention these learning outcomes. The next two items, "Heisenberg's uncertainty principle" (Q8) and the "Probabilistic nature of QP" (Q9), are included in at least 8 of the 15 national curriculum documents. Although the probabilistic nature of QP is not explicitly mentioned in all curriculum documents, this concept is probably included in textbooks and lessons in most countries. It is inevitable to address the statistical character of predictions for a correct description of the double-slit experiment with single quantum objects.

Table 2-5 Frequency of QP curriculum items for different countries and all scrutinised documents. In brackets are the items that are not clearly QP and too ambiguous for further analysis

Content item mentioned in the curriculum document		Countries /15	Documents / 23
Q1	(Black body radiation)	(9)	(11)
Q2	(Bohr atomic model)	(13)	(15)
Q3	Discrete energy levels (line spectra)	15	22
Q4	Interactions between light and matter	13	21
Q5	Wave-particle duality / complementarity	15	23
Q6	Matter waves, quantitative (de Broglie)	12	20
Q7	Technical applications	13	18
Q8	Heisenberg's uncertainty principle	9	16
Q9	Probabilistic /statistical predictions	8	15
Q10	Philosophical consequences / interpretations	5	9
Q11	One dimensional model / potential well	3	8
Q12	Tunnelling	4	7
Q13	Atomic orbital model	1	5
Q14	Exclusion principle / periodic table	2	4
Q15	Entanglement	2	3
Q16	Schrödinger equation	2	3
Q17	Calculations of detection probability	1	3

The items that are mentioned in the majority of the countries (Q3 to Q9) define the international current QP Core Curriculum on the secondary level. The QP curriculum content of the following countries is a subset of this Core Curriculum: Australia, Canada (province Ontario), Denmark, England, Finland, France, Germany (state Baden Württemberg), Portugal, and Spain. The name Core Curriculum is even more appropriate, if we consider educational systems with two different advanced physics courses – either consecutive courses or alternative courses: Table 2-4 shows that nearly all basic courses solely mention content items confined to the Core Curriculum.

The curriculum items Q10 to Q17 only occur in a few documents. The topics are diverse and can be seen as extensions of the Core Curriculum (*Figure 2-1*). Items that exist in the curriculum documents of at least three countries are: “Philosophical consequences” (Q10), the “One-dimensional model or potential well” (Q11) and “Tunnelling” (Q12). These items are not necessarily related to each other and occur independently in some curriculum documents.

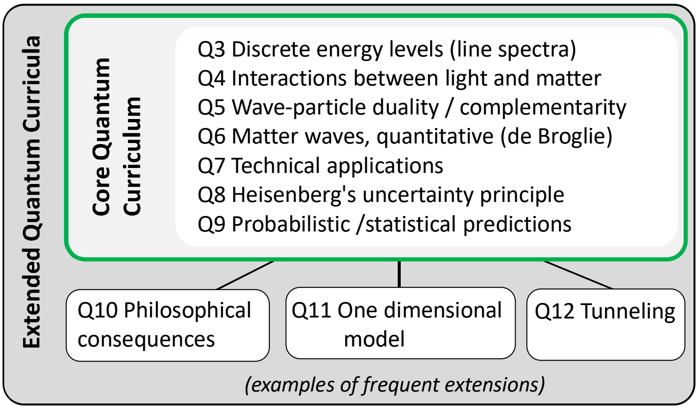

Figure 2-1 International Core Curriculum and extensions

Thematic foci of curricula

We found that the content focus of the secondary school QP curricula lies primarily in the "Fundamental principles" and the "Phenomena and applications". All of the seven content items from the Core Curriculum belong to these two categories. Consequently, high school students from most countries will mainly get to know fundamental principles, phenomena and applications of QP in an advanced physics course. It is interesting to note that the three items from the Bavarian general physics course for 15- to 16-year-old students all belong to the category "Fundamental principles"; Phenomena and applications are not explicitly mentioned.

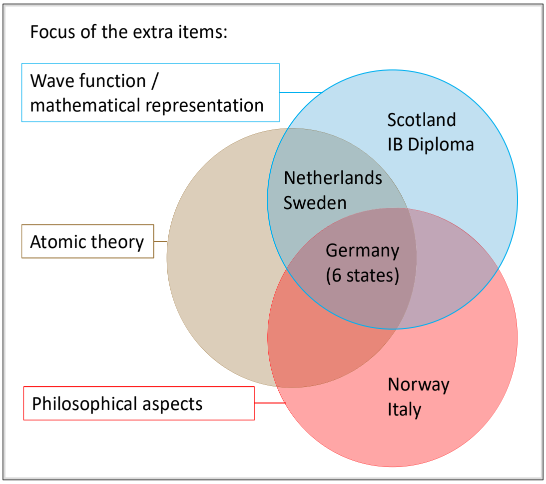

Figure 2-2 Different national curriculum documents grouped according to the thematic focus of extensional QP items

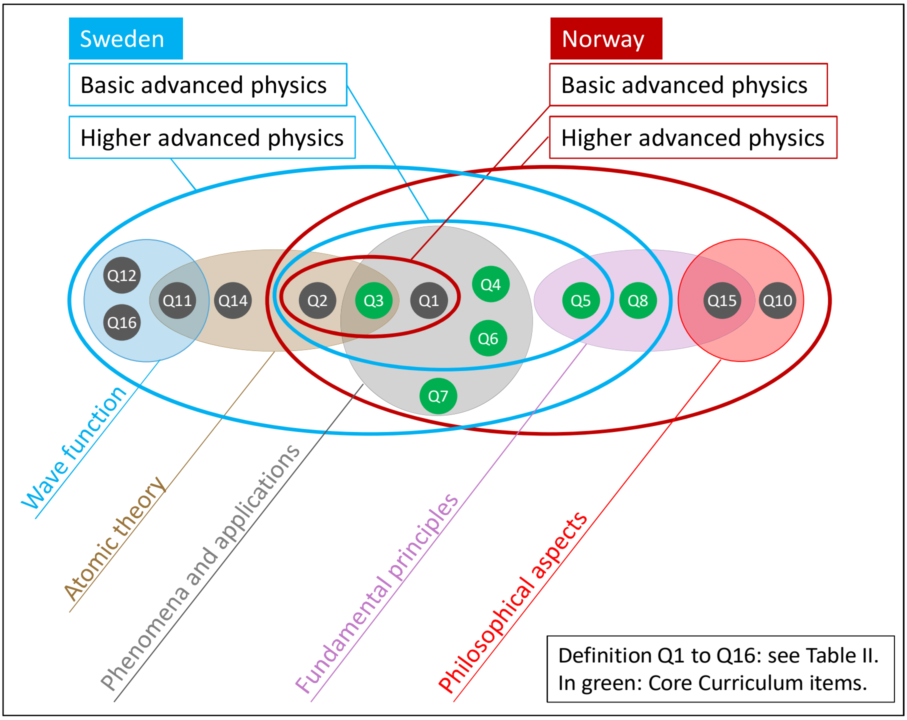

Figure 2-3 Thematic foci of two Scandinavian curriculum documents: The Swedish curriculum is strong in mathematical descriptions and atomic theory whereas the Norwegian focus lies on philosophical aspects

The extra content from advanced physics courses stems from the other three categories. *Figure 2-2* shows how the extra items of different curriculum documents can be categorised: The IB diploma program and the Scottish advanced higher physics course focus on the wave function and other mathematical representations; The Nether-lands and Sweden have additional items from the atomic theory in their extra content; Most German states have extra items from all three categories. In contrast, the extra items of Norway and Italy focus solely on philosophical aspects. Also, the Belgian and the Austrian curriculum documents contain philosophical consequences, but in both countries, they are only mentioned as an optional suggestion. There was no QP curriculum document that mentioned atomic theory without any item from the category "wave function or other mathematical representation".

We take the two Scandinavian countries Sweden and Norway, to illustrate how the core curriculum of the two countries is similar, but the extensions have a very different focus. Both countries have two successive advanced physics courses; for clarity, we call them *basic advanced* and *higher advanced* for both countries. *Figure 2-3* shows the themes of these courses according to our thematic content analysis

2.4.4 NOS in curriculum documents

NOS in every curriculum document

In the majority of the curriculum documents, the NOS aspects are formulated as desiderata and not as a list of mandatory test items or detailed descriptions like the QP topics. Examples of these generic formulations from Denmark and Italy can be found in Appendix 2-C. In some countries, though, NOS aspects are explicitly formulated as learning outcomes. For example, in most German curriculum documents, all content items are linked to specific investigation skills or competencies that the students should master at a particular stage of their school career. These competencies also contain analytical, epistemological, argumentation and judgment aspects that are related to NOS and scientific literacy. Also in the curricula of Australia and Ontario (Canada), NOS aspects play an important role. Achievement levels of the intended learning outcomes for several NOS aspects are accurately described in the investigated documents from these countries (see examples of Australia in Appendix 2-C).

Remarkably, in the physics guide of the IB Diploma Programme, six pages are devoted to a discussion of NOS and scientific literacy. In the syllabus, each content topic is linked to NOS by an "Essential idea". The connection between content topics and NOS is clearly explained, and for each topic, NOS aspects are also integrated into the internal assessments of the IB program but not in the written external exams.

While the way in which NOS is presented in curriculum documents is very diverse, all countries mention most or even all aspects from the six categories we identified as relevant for QP (see Table 2-1 and Table 2-4). "Methodology (e.g., working with hypothesis and experiments)" (N1) is explicitly mentioned in all curriculum documents. "The role of scientific models" (N2), "Tentativeness" (N3), "Controversies in science" (N4) and "History of science"

(N6) can be found in at least 20 of the 23 curriculum documents (or at least in 12 of the 15 countries). Only the NOS aspect "Creativity in science" (N5) is not very common. We found it in 12 of the 23 curriculum documents and only in six of the 15 different countries.

Scarce explicit QP –NOS connections

Only a few curriculum documents make the connections between QP items and specific NOS aspects explicit in their learning outcomes. Generally, these are the elaborate documents with well-defined multi-dimensional achievement levels. In the examined documents, we basically found three variants of coupling between QP items and NOS aspects: (1) Explicit connection of content-related specifications of defined competencies. (2) Integration of NOS in the structure of the curriculum document, and (3) Single NOS aspects mentioned as an integrated part of a content item. In the following, we will show examples for each of these explicit connections.

(1) Intended achievement levels from the curriculum document of North Rhine-Westphalia, Germany:

"The students

- show examples of the limits […] of wave and particle models for light and electrons (B4, K4),
- describe and discuss the controversy surrounding the Copenhagen interpretation and the wave-particle dualism (B4, K4)." (p.31)

In this document, the abbreviations B4 and K4 refer to earlier defined evaluation and communication skills that are related to the NOS aspects N2 (The role of scientific models) and N4 (Controversies in science) from this research.

(2) As mentioned above, in the IB physics guide, NOS is central. Each paragraph of the curriculum document starts with the NOS aspect that is visible in the content of this paragraph. For the paragraph *The interaction of matter with radiation* this is:

> Nature of science;
> Observations: Much of the work towards a quantum theory of atoms was guided by the need to explain the observed patterns in atomic spectra. The first quantum model of matter is the Bohr model for hydrogen;
> Paradigm shift: The acceptance of the wave-particle duality paradox for light and particles required scientists in many fields to view research from new perspectives." (p.90).

In our categorisation of NOS items, these statements belong to N1 (Methodology (e.g., working with hypothesis and experiments)) and N6 (History of science).

(3) The paradigm shift - as an aspect of the history of science - is in several curriculum documents the only explicit connection between NOS and the QP content. For example, the Scottish document says: "Quantum theory can be introduced by consideration of experi-

mental observations that could not be explained by classical physics, together with the various efforts made to resolve these dilemmas." (p.23). In the Norwegian curriculum, it is formulated like this: "The aims of the studies are to enable pupils to […] give an account […] of how the wave nature of particles represents a break with classical physics." (p.6)

In summary, we can say that explicit connections between QP content items and NOS are only given for certain NOS aspects in some countries. The most extensive connections between NOS and QP can be found in documents that do not treat NOS in a separate chapter but structurally integrate cognitive skills and epistemological aspects in the physics curriculum.

2.5 Discussion

2.5.1 Core Curriculum and NOS

In this article, we gave a structured overview of QP topics in upper secondary school curricula of 15 different countries. Identifying the seven most prevalent QP content items in these countries led to our definition of a current QP Core Curriculum (see *Figure 2-1*). What does this Core Curriculum tell us about QP in secondary schools?

First, from the fact that we were able to find QP topics in 15 countries, we conclude that it is not only accepted to teach aspects of QP on the upper secondary level in some experimental setup but that it has now become the standard educational practice in many countries. In most investigated countries, QP is part of an elective advanced physics course for 17 to 19-year-old students typically taken by 5% to 20% of the overall student population (Mullis et al., 2016). In pre-university schools of Germany or the Netherlands, 40% to 50% of the upper secondary students take advanced physics in their final exams (Heise et al., 2014; Vermeulen & de Boer, 2017). Notably, we found one curriculum document in which some central aspects of QP are even taught to a broader and younger group of students. In the German state of Bavaria, wave-particle duality and the probabilistic nature of QP is in the compulsory science curriculum for all 14 to 16-year-old pre-university students (in 2017, 31% of the cohort (Bayerisches Landesamt für Statistik, 2018)). While it is not common and might seem ambitious that students learn some central ideas of modern physics at middle school age, there are some indications that this is possible. For instance, a comparable teaching project with 14 to 16-year-old students in Australia shows that core concepts of "Einsteinian Physics" are intelligible for students of this age group and that the program significantly increased girls' interest in physics (Kaur et al., 2020; Kaur et al., 2018). Secondly, in contrast to the difficulty to define a core content of introductory quantum mechanics courses on the undergraduate level (McKagan et al., 2010), our research shows that on the secondary school level, there is a high correspondence of core QP content items in different countries. Certainly, it is important to bear in mind that for secondary education, the intended learning outcomes of each authority is more than a list of content items. Most curriculum documents contain overarching goals and describe the desired development of students' understandings, competencies, and skills like the level of problem-solving abilities. These pedagogically elaborated goals are not the subject of this study. However, by perusing the items of the current Core Curriculum, we got an impression of what topics are regarded as achievable basic of QP for upper secondary schools in many countries. We will discuss the content items of the international current Core Curriculum in detail.

(Quasi-)history

Remarkably, the two most common items, “Discrete energy levels (line spectra)” (Q3) and “Interaction between light and matter, for example, the photoelectric effect” (Q4), do not necessarily require QP. For example, spectral lines can be – and frequently are – explained with a planetary Bohr model of the atom (Fischler & Lichtfeldt, 1992). Likewise, several authors point out that the presentation of the photoelectric effect in many textbooks is oversimplified and might not enhance students’ understanding of QP (Jones, D. G. C., 1991; Niaz et al., 2010; Passon et al., 2019; Strnad, 1986; Whitaker, 1979). However, the popularity of these items supports the findings of Kragh, who already in 1992 found that “Virtually all textbooks introduce the quantum postulate - that is, the necessity of conceiving physical processes as discontinuous at the atomic or subatomic level - by referring to a number of experimental facts which were discovered in the early part of the twentieth century and which seem inexplicable without the hypothesis of quantisation.” (Kragh, 1992) (p. 351). He found that most textbooks oversimplify the actual course of history by presenting the photoelectric effect as an unsolved problem that was brilliantly explained by Einstein and consequently led to the introduction and acceptance of the new quantum theory. Science education researchers identified this praxis as a quasi-historical approach in which historical experiments and discoveries are presented as if the chronological order of evidence of failures of classical physics made the development of a new theory necessary (Kragh, 1992; Whitaker, 1979). Historically, the development of ideas in science is much more complicated. In particular, the early years of QP were characterised by controversies, presuppositions, contradictions, and inconsistencies (Klassen, 2011). Leaving away all these struggles seems to be a justified simplification in textbooks, but on the other hand, it is a deprivation of giving students more insight into NOS (Garritz, 2013; Niaz et al., 2010).

A reasonable explanation for the popularity of line spectra and the photoelectric effect is that both phenomena can be demonstrated in relatively simple experiments within the means available in most high schools. Especially for a theoretical topic like QP, experiments are regarded as important for students’ understanding (Prutchi & Prutchi, 2012). Moreover, for example, interactive computer simulations in which students can manipulate the setup of the photoelectric effect can be useful to stimulate inquiry-based learning (McKagan et al., 2009; Prutchi & Prutchi, 2012). Nevertheless, curriculum developers should be aware of the disadvantages of a quasi-historical introduction to QP. They might consider a genuinely historical approach that offers many chances for NOS teaching or a different introduction of QP, for example, via two-level systems (see below).

Tradition and uncertain interpretation

The items "Wave-particle duality, also called complementarity" (Q5), "Matter waves, quantitative (calculations with De Broglie wavelength)" (Q6), "Heisenberg's uncertainty principle" (Q8), and "Probabilistic /statistical predictions" (Q9) are all indispensable in the academic tradition of QP teaching (Feynman et al., 1965) and they also emerged in the list of key topics in a recent Delphi study amongst Dutch academic experts about teaching QP in secondary education (Krijtenburg-Lewerissa et al., 2019). On the one hand, the reason for this seems obvious: Stating that light and particles have both particle and wave nature is evidently different from classical physics and a fundamental key concept in QP. Moreover, emphasising the differences between a classical worldview and a QP view is advocated to be crucial in developing students' understanding of quantum concepts (Gil & Solbes, 1993; Müller & Wiesner, 2002a; Pospiech, 2000). On the other hand, it is remarkable that wave-particle duality also can be found in syllabi of countries with high stake exams that do not mention any philosophical aspects. One may wonder what kind of examination problems can be developed on wave-particle duality because answers depend on the interpretations of QP and consensus on a "correct interpretation" (Beneduci & Schroeck, 2014; Cheong & Song, 2014). McKagan et al. (McKagan et al., 2010) have pointed at the problem of developing good concept test questions on duality because of different QP interpretations. Although wave-particle duality can be found in virtually every QP curriculum, and it is seen as a central concept in teaching QP (Greca & Freire, 2014a; Krijtenburg-Lewerissa et al., 2019; Marshman & Singh, 2017; McKagan et al., 2010; Müller & Wiesner, 2002a; Pospiech, 2000), students and teachers might not be aware of different possible interpretations. Most curriculum documents do not give detailed information on how wave-particle duality should be understood. We often found formulations such as "By the end of this unit, students (…) evaluate the experimental evidence that supports (…) wave-particle duality" (Australia, p. 42) or "The candidate can (…) apply the wave-particle duality for explaining interference phenomena in electromagnetic radiation and in matter particles" (Netherlands, p.26), which are open to various QP interpretations but do not address the existence of any interpretations at all.

Teachers, textbook authors or test developers who work on the basis of these curriculum documents have to decide if they avoid interpretations of QP, if they use a specific interpretation, or if they want to address several interpretations. Research in American university courses shows that if instructors do not mention any interpretation of the wave-particle duality, that students are more likely to use realist interpretations which is commonly not the desired understanding of QP (Baily et al., 2010). However, leaving the choice for a specific interpretation to the educators is also problematic because different interpretations of wave-particle duality require different analogies, different educational strategies like simulation, and different test questions (Greca & Freire, 2014a). For the development of unambiguous test marking schemes, it seems a prerequisite to state which interpretation of QP has to be taught. Therefore, more clarity for the use of QP interpretations in most curriculum documents would be desirable.

That it is actually possible to offer more support in how to address wave-particle duality is shown by the French, some German, and the Norwegian documents. The French national curriculum document mentions one specific interpretation, namely that the photon is neither a wave nor a particle. In additional curriculum texts and some French textbooks, such quantum objects are called *quantons* to underline the novelty of QP (Bunge, 1967). However, in 2015 Lautesse et al. found that most French secondary school physics textbooks still use classical terminology like wave and particle to describe light or electrons, which contradicts the intended clarity of the official curriculum document (Lautesse et al., 2015).

Some other curriculum documents explicitly address the interpretations of QP. For example, the German document of North Rhine-Westphalia (NRW) says, "The students describe and discuss the controversy surrounding the Copenhagen interpretation and the wave-particle dualism." (p.31) and "The students explain that the wave-particle dualism is abolished by the probability interpretation" (p.45). The Norwegian curriculum document emphasises the qualitative description of quantum phenomena and requires students to be able to discuss philosophical and epistemological aspects of NOS (Henriksen et al., 2018). For educational research, it would be interesting to examine how teaching different interpretations affects students' understanding of QP and NOS.

Technical applications

A unique item of the current QP Core Curriculum is "Technical applications (e.g., scanning electron microscope SEM, Light-emitting diode LED, semiconductors, and laser)"(Q7). This curriculum item reflects the effort to show students real-world applications of physics theory, which is often advocated as making physics lessons more attractive to students (Alonso, 2002; Jones, A. & Kirk, 1990). Without the evidence of real quantum technology, students might regard QP as some weird theoretical – philosophical or mathematical – construct. Frequently working with different examples also enables students to transfer theoretical concepts to various new contexts (Fensham, 2009; Taconis et al., 2016; Whitelegg & Edwards, 2001). In contrast to the other Core Curriculum items, technical applications commonly do not belong to the academic tradition of introductory QP teaching (Johansson et al., 2018). Certainly, there are diverse university courses that cover applications of QP in various scientific fields, but for the early introduction of QP, this curriculum item is unique.

2.5.2 Thematic foci and NOS

In our analysis of the less common curriculum content outside of the Core Curriculum, we were able to identify three thematic foci: "Wave function or other mathematical representation", "Atomic theory", and "Philosophical aspects". Countries that introduce secondary students into more than the QP Core Curriculum expand the curriculum into one or a combination of these three themes (see *Figure 2-2*). In comparing the national curricula of Norway and Sweden, we showed how these two countries share similar content in their basic course but introduce students to very different aspects of QP in the higher advanced physics courses (see *Figure 2-3*). Why would a choice for a specific focus be made in a curriculum?

Each focus offers possibilities to present a different facet of the nature of physics, and *what* is taught might illustrate a specific understanding of *why* we teach physics. A focus on atomic QP connects the content of chemistry and physics. Including the wave function or other mathematical descriptions resembles the traditional introduction of QP at university level and could serve as an orientation on this, whereas a philosophical focus facilitates discussing the NOS (Henriksen et al., 2018). Different foci thus reflect what Osborn and Dillon (2008) call the dual mandate of science education: serving "the needs of future scientists and the need of the future non-scientists" (p.21). In their critical reflections on European science education, they state that traditionally "the content of the science curriculum has largely been framed by scientists who see school science as a preparation for entry into university rather than as an education for all" (Osborne & Dillon, 2008, p.21). Clearly, the mathematical representation of QP in curriculum documents (see the Swedish example in *Figure 2-3*) is a result of this traditional understanding of the purpose of science education. It also explains why experts from Dutch universities chose the mathematically demanding wave function as a relevant content item for secondary school physics in a recent Delphi study (Krijtenburg-Lewerissa et al., 2019). If, in contrast, an upper secondary QP course also aims to develop students' ideas *about* science, a philosophically-oriented curriculum focus offers more possibilities. The Norwegian example shows how students can get acquainted with NOS aspects like controversies about the interpretation of QP and actively participate in argumentations about philosophical aspects of QP (Bøe et al., 2016; Bungum et al., 2018; Henriksen et al., 2014). While such integration of NOS in school physics is favoured in contemporary science education literature, it seems difficult to assess it in standardised exams because there typically is no "right" or "wrong" answer. This is presumably why we found philosophical aspects of QP mainly in the curriculum documents of countries with oral exams or locally set final exams (see Table 2-4).

2.6 Conclusion, challenges and future possibilities

We can conclude that – in contrast to the research results from 2005 (Lobato & Greca, 2005) – QP is taught in upper secondary schools in many countries now, and there is a common Core Curriculum. However, in the light of physics education research, we see more possibilities to connect NOS teaching with QP, and the current Core Curriculum might not necessarily be the best way of introducing QP on a conceptual level. As mentioned earlier, our analysis of curriculum documents cannot always give an authentic image of what happens in classrooms. Textbooks and teachers make their own choices in the framework of the curriculum and exam requirements. It would be valuable to study textbooks and classroom practices in different countries in the future. At the moment, it seems that the most common approach is quasi-historical with elements from traditional university quantum mechanics courses. Certainly, it is unrealistic to expect surprising curriculum innovations in most countries because developing and changing national standards is generally a complex and slow process that often involves different stakeholders (Fullan, 1993). However, we discovered interesting details in the curriculum of some countries, which makes secondary QP more than a copy of the "what-we-have-always-done in higher education" without the mathematical depth. Some of these “unusual” items might be seeds that grow bigger and might appear in a larger number of national curriculum documents over time. Items we want to mention in this category are not only the philosophical consequences of QP but also quantum entanglement and its application. At the moment, the latter is only mentioned in the Norwegian and two German curriculum documents.

Quantum entanglement has far-reaching philosophical consequences which not only evoke NOS teaching but also have the potential to motivate students (Pospiech, 1999). Many authors argue that understanding QP concepts could become much easier for students if we would introduce the concepts with entanglement experiments of two-level systems (Dür, W. & Heusler, 2016; Dür, Wolfgang & Heusler, 2014; Grau, 2004; Kohnle et al., 2014; Michelini et al., 2000). This approach, which is also called the qubits approach, spin first approach or Dirac approach (Manogue et al., 2012; Michelini et al., 2000; Sadaghiani, 2016), emphasises the fundamental role of the superposition principle in QP. Several real or simulated experiments for students to work with the two-level approach have been developed (Kohnle et al., 2015; Lopez-Incera & Dür, 2019; Pereira et al., 2009). The proponents of this pedagogical approach expect that students grasp the key concepts and philosophical consequences of QP directly and much easier with two-level systems because they do not have to go through all the same problems as physicists in the first phase of the development of quantum theory. Further research has to be done to investigate the educational possibilities that could be pursued on a larger scale.

Chapter 3
Students' Views

Secondary School Students' Views of Nature of Science in Quantum Physics

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Abstract

Epistemological and philosophical issues have always been relevant for the foundations of physics but usually do not find their way into secondary physics classrooms. As an exception to this, the strangeness of quantum physics (QP) naturally evokes philosophical questions, and learners might have to change their ideas about the nature of science (NOS). In this exploratory mixed-method study, we examined possible connections between upper secondary school students' QP content knowledge and their ideas about relevant aspects of NOS in the context of QP. We administered a QP concept test to 240 Dutch secondary students (age 17-19) after they attended classes on QP without a focus on NOS. Next, we selected 24 students with a range of test scores for individual semi-structured interviews about their understanding of wave-particle duality and their views on five aspects of NOS. Contrary to NOS studies in other contexts, the interviews showed that all 24 students had well-informed NOS views in the context of QP. We contend that NOS in QP might be more easily accessible than in many other contexts. Our results suggest that QP can have an additional role in the physics curriculum by enhancing students' understanding of NOS.

3.1 Introduction

Modern upper secondary school physics curricula would be incomplete without some basic quantum physics (QP) concepts. QP has been one of the most important areas of physics since the beginning of the twentieth century when theoretical work by Bohr, Einstein, de Broglie, and many other famous scientists laid the foundation for the development of a new theory. Theoretical insights from QP have opened new possibilities and new ways of thinking not only in physics and chemistry but also in philosophy, biology, electrical engineering, medical diagnostics, and communication technology. Indeed, many electronic devices that students consider indispensable are based on quantum technology.

In upper secondary physics courses, concepts like the wave-particle duality and Heisenberg's uncertainty principle are taught qualitatively without complex mathematics (Stadermann et al., 2019). Such an introduction to QP is fascinating for students (Bungum et al., 2018), but also challenging to learn and to teach (Krijtenburg-Lewerissa et al., 2017): QP phenomena are not only different from what students experience in the visible world, but many QP principles might not fit with their ideas about physics. For example, when QP is introduced with the so-called standard (Copenhagen) interpretation, students have to abandon their diligently constructed deterministic and realistic worldview of Newtonian physics to predict and explain the outcome of QP experiments (Johnston et al., 1998; Ke et al., 2005). Learning QP concepts, therefore, causes a cognitive conflict, ideally resulting in changes in students' epistemological beliefs. To explore this relationship, we first compile some research results about students' conceptions of scientific models, the role of interpretations in QP, and nature of science (NOS) in secondary schools. Next, we will present our theoretical framework by connecting NOS aspects to learning QP.

3.1.1 The role of scientific models and interpretations in learning QP

Models in QP

Empirical studies have found that for learning QP, students must understand the reasons for the development of models and learn to handle different models in appropriate contexts (McKagan et al., 2008; Niaz & Rodríguez, 2002). After years of physics lessons in which electrons are modelled as negatively charged tiny billiard balls, students might think that they *are* tiny billiard balls. With that idea, a student can handle most parts of secondary school physics and chemistry. However, quantum entities do not have simple, consistent visualisable equivalents in classical physics. For example, in the iconic double-slit experiment, individual electrons are detected on a screen as single dots as if they were miniature billiard balls. Still, the exact place of detection is unpredictable. After repeating the same experiment with many individual electrons in the same setup, an interference pattern builds up. Within familiar school physics, an interference pattern is only plausible for students if electrons are waves. This "wave-particle duality" is confusing to students because they are not only missing a useful framework to build on (Taber, 2005), but QP also seems in contradiction with their idea of what physics is: predictable (deterministic) and universal (physical laws should explain phenomena on all scales) (Dutt, 2011; Tsaparlis & Papaphotis, 2009).

Similarly, several studies have shown that students do not easily adopt a new quantum model of the atom but rather stick to the earlier learned planetary model or Bohr model (Adbo & Taber, 2009; Griffiths & Preston, 1992; Petri & Niedderer, 1998). Even after QP lessons about atoms, many students still describe an electron as a classical particle (Mannila et al., 2002) and an atom as *being* the Bohr model (Müller & Wiesner, 2002a).

Interpretations of QP

While the impact of QP on modern technology and all natural sciences is immense, there is still no consensus on how to understand the foundations of QP (Bunge, 2003; Merali, 2015). In the early 20th century, physicists explored theoretical descriptions of subatomic processes. Coming from a classical, deterministic, and mainly positivist understanding of physics, they developed a new explanatory framework: the quantum theory. The mathematical formalism of the newly developed theory can describe and predict experimental results. What this formalism says about reality was and still remains the subject of controversies which have their origin in different philosophical perspectives (Hermann, 1935; Nikolić, 2008). In subsequent decades, several physicists developed diverse interpretations of QP like the Copenhagen interpretation (Bohr, 1935), the pilot wave interpretation (Bohm, 1952) or the many-worlds interpretations (Everett, 1957). These different interpretations are all consistent with the QP formalism but have, at the same time, peculiar philosophical consequences (Merali, 2015), which result in different understandings of the micro-world. For an introduction to different QP interpretations, see, for example, Laloë (2001); distinctive features of these three interpretations we used in this research are summarised in Table Appendix 3-B.

To explain QP concepts on a qualitative level, secondary school teachers necessarily use everyday language. Therefore, it is not surprising that textbook authors and educators—explicitly or unconsciously— use metaphors and visualisable analogies to describe quantum objects and their features (Brookes & Etkina, 2007). By doing so, authors and teachers use specific interpretations, although they seldom make explicit which one they use (Greca & Freire, 2014a). While there is no single accepted interpretation of QP, it is argued that it is unavoidable to address interpretations in teaching QP (Baily & Finkelstein, 2015; Müller & Wiesner, 2002b) and that the choice of interpretation should be made explicit (Greca & Freire, 2014a).

Teaching about different interpretations of QP requires discussing connections between physical theories and reality and inevitably leads to questions that do not have final answers. Addressing such epistemological and philosophical questions on the NOS is not common in traditional secondary school physics classrooms (Bøe et al., 2018) and might feel uncomfortable for physics teachers (Davies, 1997).

3.1.2 NOS in secondary school

In 1998 McComas identified 15 myths about science in educational sources. He found, for example, that textbooks communicate the view that science provides absolute truth, that scientific models represent reality and that scientists use strict procedures not allowing creativity (McComas, William F., 1998). While it is clear that these myths about science and scientists create an unrealistic and undesired view of NOS, it appears to be challenging to define the "desired" view of NOS (Allchin, 2013; Dagher & Erduran, 2016; Lederman, N. G., 2007). Independently of the detailed definition of the term, the general goal of teaching NOS in secondary education is to make students familiar with how and why the scientific enterprise works (Jenkins, 2013). For our research, we prefer not to meticulously define the desired NOS perspective because, for some epistemological aspects, this would imply a preference for one philosophical perspective on QP. In this approach, we follow physics educators who emphasise that it is essential for students' QP learning to develop their own epistemological perspective (Bungum et al., 2018; Hoehn et al., 2019). Therefore, we will focus on those NOS views which are relevant in the context of QP learning (see Table 3-1).

Many scholars advocate including history and philosophy of science in science teaching to help learners develop informed NOS views. Indeed, empirical studies have found that students' understanding of NOS improves if epistemological aspects are explicitly and reflectively addressed in historical narratives (Abd-El-Khalick & Lederman, 2000; Allchin et al., 2014; Arya & Maul, 2012; Höttecke et al., 2012; Irwin, 2000; Kim & Irving, 2010). However, explicit and reflective NOS teaching within a historical context is demanding for science teachers and rarely happens in regular lessons (Henke & Höttecke, 2015; Wang & Marsh, 2002).

3.1.3 The role of views of NOS in teaching and learning QP

Understanding QP on a qualitative level can be challenging in many ways, as illustrated above. Many physics education researchers compare the process of learning QP with the paradigm shift from classical physics to QP, described as conceptual change (Shiland, 1997; Tsaparlis & Papaphotis, 2009). In the case of QP, conceptual change not only affects students' understanding of concepts but also their ideas about the nature of physics. Researchers expect that students can more easily change their conceptions from classical to quantum physics if they understand science as a continuously evolving, creative human endeavour influenced by social circumstances and historical contexts (Barad, 1995; Dutt, 2011). Students who are not aware of such aspects of NOS would expect one "right" explanation for experimental results and, for example, one single correct model for elementary particles; incommensurable models and interpretations would only confuse them. However, students who understand science as a human endeavour could, for example, appreciate the development of different explanations for experimental results because it helps to develop their own understanding of difficult concepts.

In an international comparison of curricula, five NOS aspects were identified as particularly relevant for teaching and learning QP (Stadermann et al., 2019). Table 3-1 illustrates the connection between these NOS aspects and QP with some examples, and it summarises desired and undesired views of NOS for the understanding of QP.

Table 3-1 Connection between aspects of Nature of Science and Quantum Physics

NOS aspect	Example of an undesired view	Example of the desired view	Illustration or relevance for QP in secondary education
The role of scientific models	Scientific models represent reality as much as possible.	Scientific models and analogies serve to show some aspects of phenomena in a simplified way.	For some situations, it is appropriate to use the model of a wave for quantum particles; in other situations, the model of classical particles is more helpful.
Tentativeness of scientific knowledge	Science and its methods provide absolute proof. Scientific knowledge is unchangeable and certain.	Scientific knowledge is always open to development, change and improvement.	With Newtonian physics, it is not possible to understand quantum phenomena like the double-slit experiment. Scientists had to change their mechanical worldview to develop QP.
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 thinking out-of-the-box. To find out if the wave function of QP is more than just a conceptual tool, scientists develop creative (thought) experiments to test their interpretations.
Subjectivity in science	Science is objective. Therefore only one correct interpretation of phenomena is possible.	The same phenomenon can be interpreted differently.	The well-documented discussions between Einstein and Bohr show how different philosophical positions of two scientists result in contrasting interpretations.
Controversies in science	Evidence accumulated carefully will result in certain knowledge. Acceptance of new scientific knowledge is straightforward.	Discussions and disagreements about scientific ideas belong and are essential in scientific development.	An open atmosphere without strict ideologies made new developments in QP possible. Currently, there is still no consensus about the interpretations of QP.

Considering how NOS and QP are tightly intertwined, researchers assume a positive effect of the development of students' NOS views on their conceptual understanding of QP and vice versa (Bungum et al., 2018; Garritz, 2013; Greca & Freire, 2014a; Pospiech, 2003). Our research aim, therefore, is to investigate the connection between NOS views and QP learning for 12th-grade physics students. Our research questions are:

(1) What NOS views do secondary school students express in contexts they know from QP lessons?
(2) What, if any, is the connection between students' conceptual understanding of QP and their NOS views?

3.2 Method

3.2.1 Overall setup

To uncover possible connections between students' NOS views in QP and their QP content knowledge, we were particularly interested in the variations of NOS views between students with a good or poor conceptual understanding of QP concepts. Therefore, we designed a mixed-methods study in which we used a QP concept test to select low, medium and high achieving students and investigated their NOS views in semi-structured interviews. To get necessary context information about the QP lessons, especially if NOS-topics were addressed, we observed lessons and interviewed all teachers. *Figure 3-1* shows the overall design of our study.

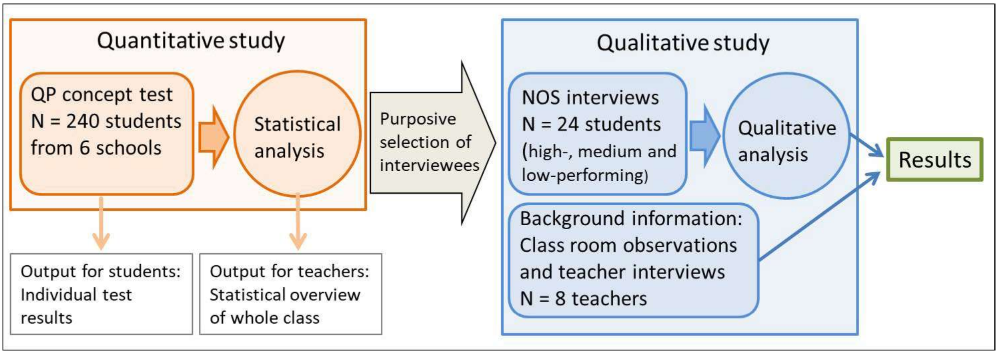

Figure 3-1 Schematic overview of research design

3.2.2 Design of the QP concept test

The primary purpose of the QP concept test is to select students in regular physics courses for the next stage of the research. In the Netherlands, QP is usually one of the last subjects to be taught before the national final exams. In that phase, teachers and students can be motivated to participate in research if it supports the exam preparations. Therefore the test covers the content of the Dutch QP curriculum. To avoid spending much lesson time on administering the test and enabling fast data processing and feedback, we designed an online multiple-choice test.

QP curriculum items in the Netherlands are similar to those in other countries (Stadermann et al., 2019). The concepts in our test are: light as wave (interference and diffraction), radiation and matter (energy absorption and emission in atoms), photoelectric effect, matter waves (de Broglie relationship, interference in the double-slit experiment), Heisenberg's uncertainty relation, the quantum model of atoms (particle in a box), and tunnelling.

Starting from existing validated QP concept tests, designed for different educational contexts (Ambrose, 1999; Baily, 2011; Falk, 2004; McKagan et al., 2010; Muller, D. A., 2008; Müller, 2003; Vokos et al., 2000; Wuttiprom et al., 2009), we selected 24 conceptual questions and added three items about interference and diffraction to cover all QP themes from the Dutch exam syllabus. After content validation by a panel of four experts, we piloted the questions in think-aloud interviews with four pre-university students. To make the test as compact and clear as possible, we deleted questions that probed the same concept and made some adjustments to the wording. This reduction resulted in a multidimensional 20 item digital multiple-choice concept test that students can answer on their own devices. We provide the (translated) test in Appendix 3-A.

3.2.3 Assessing students NOS views in the context of QP

To our knowledge, no test instruments that assess students' NOS views in the context of QP have been published. For diverse other contexts, three review articles on conceptions of NOS in science education present an overview of research instruments. Abd-El-Khalick (2014) reviewed 241 empirical research studies and describes how NOS assessments between 1954 to 2013 gradually evolved from forced-choice tests to more open-ended qualitative test instruments. He concluded that open-ended questionnaires and interviews are the most appropriate measures to portray students' NOS perceptions. Abd-El-Khalick, as well as two more recent reviews (Azevedo & Scarpa, 2017; Cofré et al., 2019), found variants of the Views of Nature of Science Questionnaire (VNOS) (Lederman, N. G. & O'Malley, 1990) the most widely used instruments. VNOS test instruments contain open-ended questions with slightly different examples, contexts and different levels of complexity depending on the age and background of the students. The authors emphasise that their test instrument should only be used in combination with post-test interviews of a representative subgroup of participants to clarify written answers (Lederman, N. G. et al., 2002).

Despite the widespread use of the VNOS and other NOS instruments, recent studies found it questionable if students or teachers have a universal, context-free NOS understanding (Khishfe, 2017; Leach, Millar, Ryder, & Séré, 2000). Therefore, our NOS test instrument is based on the rich research tradition of VNOS tests, but all questions are focused on the context of QP. This strict context definition enhances the comparability of students' answers and improves the validity of our analysis, but it limits data collection to students who are familiar with QP. A pretest would, therefore, be meaningless, and we consequently do not intend to report on any changes in students' NOS views.

To get an insight into students' understanding of the five selected NOS aspects (see Table 3-1) for central QP concepts like wave-particle duality, we carried out individual semi-structured interviews of our selected students. All selected students were cooperative to our request for an interview. We used a prestructured interview scheme with follow-up questions making it possible to reduce misinterpretations. In this, we follow other researchers who used interviews to achieve an authentic understanding of students' NOS views of specific topics (Dagher et al., 2004; Moss et al., 2001; Ryder et al., 1999; Tsai, 2002).

3.2.4 Context

Our target group consisted of Dutch upper secondary school physics students (grade 12: aged 17 to 19) from public pre-university schools. Eight teachers (five male, three female) with 2 to 20 years of teaching experience from six schools volunteered to test their 12th-grade physics students. Interviews with the eight teachers revealed that each of them spent 16 to 22 hours of lesson time on QP, depending on the textbook and the school's class schedule. Neither the national physics exam syllabus nor the used textbooks contain mandatory NOS aspects in the QP section. Classroom observations and teacher interviews confirmed that teaching focused on content transfer and solving textbook problems. Only one of the teachers explicitly addressed philosophical questions like interpretations of QP and Schrödinger's cat in her lessons.

Two hundred forty students (133 female, 104 male, three unknown) participated in the concept test. All students answered the online QP concept test in their regular classrooms during a physics lesson one to eight weeks after the QP lessons. The period between lessons and test did not have any significant influence on the test results. Spread over the different schools, we selected 24 students for individual interviews; six students with less than 6 points (the "low achieving" subset), five with more than 12 points ("high achievers") and thirteen of the "medium achieving" group with 6 to12 points. The students of one teacher (not the one who had introduced philosophical issues to the students) were not available for the interviews. We interviewed at least two students of each of the other seven teachers.

3.2.5 The NOS-QP test instrument

The interview scheme consists of three phases with distinct goals in which we adapted test questions from various sources about scientific models (phase 2a), interpretations of QP (phase 2b and c) and NOS views (phase 2a and 3). Table 3-2 gives an overview of the interview design; see Appendix 3-B for the full (translated) interview scheme.

After anonymising, four randomly selected verbatim transcribed interviews were individually coded by three independent researchers; the two authors of this paper and a university physics education lecturer. First, each researcher related interview passages to QP content, and the NOS aspects are summarised in Table 3-1. During this first round, all three researchers got the same findings regarding the first two interview phases for each student. Only the comparison of NOS codes (phase 3) revealed differences: while one researcher labelled each statement with only one NOS aspect, the others marked some expression as belonging to multiple aspects like subjectivity, creativity or controversies in science. After discussing these statements, we agreed on possible multiple codes. By doing so, we acknowledged that students' views on different NOS aspects are naturally related to each other.

In a second individual coding round, each researcher categorised the answers per NOS aspect as *informed views* (desired) and *uninformed views* (undesired). A comparison showed the same results of each researcher in all cases. We applied this two-step coding procedure again to another four randomly selected interviews which resulted in agreement between the three researchers. The residual 16 interviews were mainly analysed by the first author, who consulted the second author in case of doubt.

Table 3-2 Different phases of the interview

Phase	Goal	Related research	Example questions
1. Introduction	Demographics & Background information		Is QP an easy or difficult subject? Why? Have you heard of 'philosophy of science'?
2. Conceptual understanding	2.a) Determining students' conceptions of electrons and atoms.	(Abd-El-Khalick et al., 1998; Harrison, A. G. & Treagust, 1996; Petri & Niedderer, 1998)	What are the properties of an electron? Tell me as many as possible. How would scientists describe an atom? Could you draw it? Describe exactly what you are drawing.
	2.b) Testing students' knowledge of the double-slit experiment.	(Baily & Finkelstein, 2010b)	Can you describe the setup and the results of the double-slit experiment?
	2.c) Determining students' conception of wave-particle duality.	(Baily & Finkelstein, 2010b)	Watch the simulated double-slit experiment with electrons. Respond to each statement (*statements represent different interpretations of wave-particle duality*)
3. NOS views	Determining students' NOS views in the context of QP	VNOS-B & D (Abd-El-Khalick et al., 1998; Lederman, N. G. et al., 2002)	Respond to each statement (statements represent different NOS views) How is it possible that physicists have different ideas about what an electron is?

3.3 Results

3.3.1 QP concept test

The analysis of students' answers in the 20 item QP concept test showed a left-skewed distribution with a mean score of 7.7 (standard deviation = 3.1), indicating that it was a difficult test (see *Figure 3-2*).

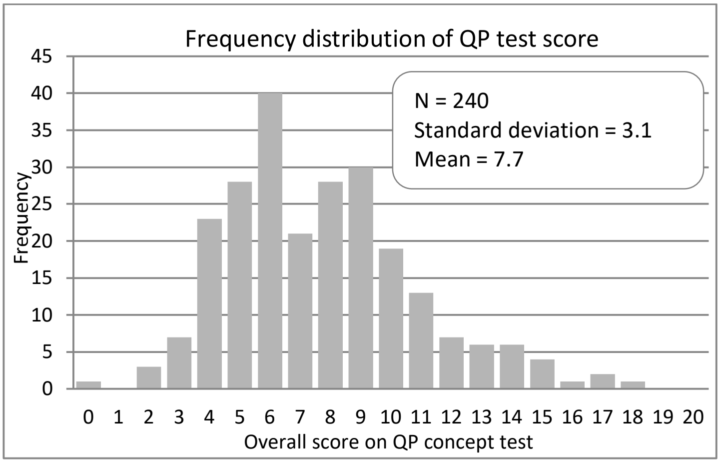

Figure 3-2 Frequency distribution of QP concept test results

A comprehensive analysis of the QP concept test is not the scope of this study, but we want to share some interesting results. The best-scoring questions were about the relation between de Broglie wavelength and energy state (Q15, see Appendix 3-A; 72% correct), the double-slit experiment with single electrons (Q11; 67% correct) and Heisenberg's uncertainty relation for everyday objects (Q14; 63% correct). The three least-scoring questions were on energy absorption in an atom (Q4; 9% correct), tunnelling (Q20; 19% correct), and the photoelectric effect (Q12; 21% correct).

3.3.2 Results of the NOS-QP interviews

In the following, we summarise the results of the three phases (see Table 3-2) of the individual student interviews.

Phase 1: Attitude and prior knowledge

As we do not use the introductory phase of the interview to answer our research questions, we only give a summary and some examples of answers that gave rise to possible educational implications in the discussion section of this article. An overview of students' responses and demographics are given in the table in Appendix 3-C.

Six of the 24 interviewed students reported knowing about the philosophy of science, either from a philosophy course (N=4), from a general science course (N=1) or because of personal interest (N=1). We found no relationship between the students' prior knowledge of the philosophy of science and their achievement level on the QP concept test (see Appendix 3-C). We discovered notable differences between students' reasons why they liked or disliked the subject: only one student thought that QP was just a regular item like every other item in school physics, others thought it was more interesting because QP is more mysterious than usual school physics and because there are still open questions, yet others did not like QP because of its "haziness" compared to standard school physics. In their explanations, several students mentioned that QP was very different from other school physics, which makes it at the same time difficult but more fascinating.

For students of different achievement levels in the QP concept test, the classroom discussions made QP more attractive than other parts of school physics:

> I like QP, mainly because there is more than one interpretation. That is why I find it more interesting because it is not yet clear what it really is. On other things in physics, it is agreed on, and it is easier to learn, but here it is nice that you can figure out yourself what you think. (Student 12)

> I think it is very important to know that there are still many things in this world that are unclear. That is also useful to know. This is more interesting than everything that is so well known, as if there is nothing more to discover. (Student 5)

Phase 2a: Conceptions of electrons and atoms
When asked for properties of an electron, all interviewees described a bound electron in an atom as a small, negatively charged (elementary) particle, orbiting the nucleus consistent with the planetary or Bohr model. After the interviewer prompted them to tell more about electrons and their properties, only five of the 24 students added other descriptions, such as wave properties (N=4), electric current in metals (N=2), and beta radiation (N=1).

Phase 2b: Knowledge of the double-slit experiment
We asked the question, "Can you describe the setup and the results of the double-slit experiment?" before students saw a simulation of the experiment. Nevertheless, 20 of the 24 interviewed students started by explaining the experiment with electrons. Only four students (medium achievers) started their explanation with light. Asked if the described example is the only possible double-slit experiment, all students knew that the double-slit experiment could be done with light and with electrons. In their explanation of what would happen if electrons were sent one by one through the double-slit, 23 out of 24 students knew that the same interference pattern builds up over time. Only one student (a low achiever) was wrong; he thought that electrons would be detected in two regions behind the slits.

Phase 2c: Conceptions of wave-particle duality in the double-slit experiment
In this phase of the interview, students were asked to respond to given quotes from three fictitious students representing different interpretations of QP (see Appendix 3-B). We heard many vague or inconsistent statements in which students tried to make sense of what they

saw in the simulation of the double-slit experiment. All students were struggling with expressing their view, as illustrated by the following quote:

> I just don't know very well if it is really the case that the electron is spread out over space, I think it's more of a chance. But I am not sure what to imagine. So it goes through both slits and it interferes with itself ... that is necessary, … that is also the reason for the interference pattern. (Student 10)

Only two of the interviewed students (one medium, one high achieving) thought that QP is only a tool to calculate experimental results and that further interpretation is not necessary (similar to the Copenhagen interpretation, see Table 3-4, Appendix 3-B). All others, independently of their achievement level in the concept test, had no explicit preference for one interpretation. In their answers, they combined more realistic (statistical) statements and representations of electrons as matter-waves.

Table 3-3 Overview of students NOS views (N=24)

NOS aspect	Uninformed view	Informed view	Remark
The role of scientific models	0	24	Various functions of models were mentioned, all suitable.
Tentativeness of scientific knowledge	0	24	All students understood science as a process that continues to develop.
Creativity in science	1	23	For one student, creativity was compatible with QP but not with physics in general.
Subjectivity in science	0	24	No student had an uninformed view about subjectivity in QP as a scientific discipline.
Controversies in science	0	24	As in the previous item, students distinguished between QP and school physics.

Phase 3: Students' NOS views in the context of QP

The results of this phase of the interview (summarised in Table 3-3) are specified for each of the five NOS aspects. The student numbers in the citations correspond to those in Appendix 3-C.

The role of scientific models

All (24/24) students knew that there are different atomic models, and they understood the basic role of a model.

> Atoms are too small to see. The only thing you can do is to make a model. And then you try …can I make predictions with this model? And does it confirm everything we observe? (Student 1)

> Humans are very curious, and of course, we want to know everything. I think a model is needed to be able to explain certain physical phenomena, or chemical or biological. (Student 13)

Most (22/24) students mentioned that better research methods and growing knowledge lead to more detailed models and that this process will go on. One student stated that this process would stop eventually:

> But at some point, you also have to say that this is correct enough […] At that point, we come to a model [….] that you can almost say: this is what it looks like, but we will never know exactly. (Student 15)

Another student thought that it might be impossible to find a complete model:

> We only have three dimensions, and an electron could quite well be something completely different …, which we simply cannot understand. Then, a model cannot be completely complete. (Student 24)

Tentativeness of scientific knowledge

None of the interviewed students questioned the continuous development of science. They all knew that scientific knowledge in QP now is different from what it was in the past and that it will change in the future. Students saw this tentativeness of science as fundamental and as a result of human curiosity:

> Because you can always repeat the why question. If you know one answer, you can ask again. For example: why does the object fall? Then you have the answer: because gravity works. But then you can ask again: why does gravity work? And even if you can explain that, you can ask again: why? I think you can never get to the bottom of the why. (Student 1)

Students understood that tentativeness – due to new interpretations or improving methods – is a characteristic of science, as can be seen in the following example.

> Of course, you can investigate what has already been discovered, but [in science] you must be able to think differently than the people before you who have already done experiments. Because only then you might be able to find something else, which leads to new results or new investigations. (Student11)

Creativity in science

For this question, students were asked to comment on three given statements about interpretations in QP. The most popular one (23/24) was the statement that scientists need creativity to develop new interpretations. One student articulated the noteworthy opinion that creativity belongs to QP but that QP could not be regarded as physics because of the philosophical character of QP interpretations.

> I think quantum physics is not really part of physics. […] I think that it is just an entire subject of its own….Because this is so philosophical, I think. Most physics is not really

> philosophical. I think that's the difference. […] If everything is clear and does not need to be discussed, then it is not philosophical. And that is certainly the case with the rest of physics. (Student 6)

Although the interview question was situated within the context of QP, 15 students spontaneously connected creativity more generally with science:

> I think that as a researcher, scientist or physicist, you need a lot of creativity ... You have to think out of the box because you want to investigate something unknown. (Student 11)

> To find an explanation [as a scientist], you need a lot of creativity, a lot of experiments, and diverse ways of thinking. (Student 12)

Subjectivity in science

The interview question aimed at students' ideas about subjectivity in science addressed the existence of different QP interpretations. We asked students how it is possible that different interpretations exist and if it would be better to have only one interpretation. Most students (23/24) thought that physicists developed different interpretations of QP because of their diverse personal backgrounds.

> Maybe [scientists develop different interpretations] because of what they are, their profession, what they are most involved in. They developed certain ideas in their studies or so. What you think is based on that. You think: Oh, with what I learned, I could explain that. So with that in mind, you look at quantum physics. Through your environment, your upbringing, you develop your ideas. (Student 16)

Five students described a difference between physics as an academic discipline and the physics they learn at school. Two low achieving students saw a diversity of interpretations as part of professional scientists' research but as undesired for learning.

> I don't think they should choose an interpretation, but I do want them to show us only two or three. […] Yes, for real scientists, it is different. They have to do research… but not so many different possibilities for students. (Student 4)

> I think at school you should only learn one interpretation. But as soon as you have more understanding of the subject you can learn more about other interpretations. But as long as you don't understand the basics, I think it will only get confusing. (Student 7)

Controversies in science

All students understood, in the context of QP interpretations, that controversies belong to science.

> In principle, it is useful if there is a consensus. But maybe it's just not yet the time for it. If there is not enough evidence to accept one interpretation generally over the others. In that regard, it is important that there is a discussion; that you can choose one side and try to prove it. But you must be open to other interpretations if it turns out that yours is wrong. (Student 20)

Several students (7/24) spontaneously articulated that controversies are normally not part of the physics curriculum and that this makes QP special.

> This topic [QP] is not yet done to death. I think there is still a lot of research. If there is no fixed interpretation, which everyone agrees on; so there is no right interpretation either. From what I know, we see this only in QP. You don't learn in other physics topics that there could be other theories for gravity or even three different ones. (Student 4)

3.4 Conclusion and Discussion

In this study, we explored secondary students' views of NOS in the context of QP and their achievement level on a QP concept test. We then sought a possible connection between both. The students were tested after their regular school physics lessons about QP. We did not ask the teachers to pay attention to NOS, and most of them (seven out of eight) indeed did not mention NOS, as interviews and classroom observations showed.

Concerning the first research question, we found that all interviewed students exhibited desired views for the probed QP-related NOS aspects. The second research question, regarding a possible relation between students' NOS view and their ability to master QP concepts, accordingly has an unexpected answer. Because students of all QP achievement levels were able to express a variety of informed NOS views in the context of QP, it is not possible to relate performance levels in a QP concept test to specific views of NOS.

Additional to the answers to the research questions, students' interview answers gave us some insights into existing opinions about school physics and the possible role of QP in developing students' NOS views. In the following, we will discuss the results in detail.

3.4.1 Students' conceptions in QP

The first research step was to identify students with different performance levels in QP for the interviews. The overall low score on the QP concept test showed that our pre-university students have difficulties understanding QP. This is hardly surprising, as even university physics students find it difficult to answer similar questions on basic concepts of QP (Johnston et al., 1998; Vokos et al., 2000; Wuttiprom et al., 2009).

The next step was to interview selected students to determine their conceptions of electrons, atoms, and wave-particle duality (interview phase 2 in Table 3-2). The interview revealed that most students gave ambiguous descriptions of electrons as a classical particle or as a wave. This result accords with a large number of findings in research on introductory QP education (Adbo & Taber, 2009; Baily & Finkelstein, 2010b; Harrison, A. G. & Treagust, 1996; Hoehn et al., 2019; Mannila et al., 2002; Petri & Niedderer, 1998). In an atom, electrons are mainly described as classical particles but to explain the outcome of the double-slit experiment, all interviewees also used wave properties. We agree with Hoehn and her colleagues (2019), who argue that the tentative and messy reasoning about the wave-particle duality— mixing of and switching between different interpretations —is not a problem but an essential and productive step of students' sense-making in QP. In their study, the authors analysed students' explanations of the double-slit experiment with the conceptual blending framework. The researchers explicitly mentioned that students' phrasings when grappling with quantum ideas are very similar to the discourse of professional physicists. We return to this topic later when we analyse the role of NOS in QP from a student perspective.

All results from this part of the research confirm that our students are comparable to those in many other studies about learning introductory QP.

3.4.2 NOS views in QP

Contrary to our expectations, nearly all students were able to articulate informed views on all five selected NOS aspects, although the lessons they followed did not explicitly address NOS aspects. This finding differs from those from earlier studies into the NOS views of students, which found that students generally have uninformed NOS views and contextualised NOS teaching requires explicit and reflective teaching strategies (Abd-El-Khalick & Lederman, 2000; Clough, 2017; Khishfe, R. & Abd-El-Khalick, 2002; Lederman, N. G., 2007).

Although surprising, our results are robust. The labour-intensive way of data collection through individual interviews gives rich information on students' NOS views. Additionally, we were able to interview a large variety of individuals with different achievement levels and from different teachers and schools.

To explain our unexpected finding, one could argue that, by contextualising our NOS questions in QP, we unavoidably created an explicit and reflective learning situation for the students. While this reasoning might partly be valid, it is still remarkable that students, who were not explicitly exposed to NOS aspects during physics lessons and had never heard of the philosophy of science, all spontaneously exhibited informed NOS views—even those students who struggled with answering QP concept questions.

It seems that in the context of QP, uninformed views on the selected NOS aspects are so untenable for students that they are naturally led to more informed views.

So, is QP so different from other physics topics? In our opinion, there is one outstanding advantage of QP above historical narratives in other research (Abd-El-Khalick & Lederman, 2000; Höttecke et al., 2012; Irwin, 2000): just like professional physicists, secondary students experience the need to make sense of the results of the double-slit experiment. This becomes evident in their elusive way of answering interview questions. Students can understand that the discussion around the "right" interpretation of QP is still not resolved. In that sense, QP is *science-in-the-making* where fundamental aspects are still controversial (Latour, 1987) in contrast to *ready-made science* as traditionally taught in school physics.

For other implicit NOS teaching approaches which cover episodes from the history of science, learners have to put themselves mentally in a historical context. Researchers found that this necessary change of perspective is difficult for learners (Abd-El-Khalick & Lederman, 2000). The authors found that many students perceived alternative historical controversies to be non-scientific by modern standards. To make scientific controversies more accessible for students, contemporary socioscientific issues (SSI) are another potentially fruitful context for NOS teaching (Holbrook & Rannikmae, 2007; Khishfe 2014). However, students' emotional involvement makes it difficult for them to see these controversies as fundamentally scientific (Allchin et al., 2014; Mesci & Schwartz, 2017). Moreover, teachers commonly avoid SSI in physics lessons (Dunlop & Veneu, 2019).

The findings of this study suggest that QP provides excellent opportunities to teach NOS aspects because (1) it is a contemporary science topic that fascinates students, (2) it includes scientific controversies, (3) it is included in the regular advanced physics curriculum of many countries, and (4) students develop informed NOS views in the context of QP even without extra lesson time.

3.4.3 Views on school physics and QP

Although we did not ask for it, we found that some students expressed differences between school science and professional science. This is in accordance with findings from the literature and constitutes a possible additional explanation of the surprising outcome of our NOS test. Hogan (2000) distinguishes between two different understandings of science, *proximal knowledge,* which is related to students' epistemologies and beliefs about the nature of learning science ("What the teacher is telling us are trustworthy facts") and *distal knowledge* as views of science of professional scientists, their ways of doing research and social processes to develop scientific knowledge (Hogan, 2000). Similarly, Sandoval (2005) discovered a difference between students' practical epistemologies (students' views on their own laboratory experience) and formal epistemologies (views of what science in general is). This difference is precisely what one low-achieving student expressed when he gave his opinion on various interpretations of QP: "Yes, for real scientists it is different; they have to do research… but not so many different possibilities for students." (Student 4). We conclude that he and several other students had an informed view on physics as a professional science but a rather narrow view of physics as a school subject. Unfortunately, this is not at all a naïve or uninformed view; it is just the result of previous physics lessons in which questions only have right or wrong answers (Bøe et al., 2018; Elby & Hammer, 2001). As a consequence, students see a difference between professional science and school science (Hodson & Wong, 2014; Sandoval, 2005). Since many NOS test instruments use non-contextualised questions and do not differentiate between school science and real science, we question their validity.

3.4.4 Implications for education

Our findings suggest that NOS teaching could benefit from the ease with which students develop insights into NOS in the context of QP. Although we do not expect that students will transfer their informed NOS view in QP to other contexts, QP seems to be a good starting point to talk about the processes and properties of the scientific enterprise in general. Some students already spontaneously mentioned the possibility of different interpretations for other physics concepts such as gravity.

Our research could also encourage teachers to address different QP interpretations in their lessons because many interviewees mentioned that the idea of the “unsolved problem of QP” makes the subject more attractive than the “facts” physicists agreed on long ago. By including philosophical aspects in QP lessons, teachers could not only broaden students’ views on the subject but also involve and attract a larger variety of students (Johansson et al., 2018).

3.4.5 Implications for further research

Our study raises some opportunities for future research. We noticed, for example, that most teachers in our research did not explicitly address NOS aspects, although NOS is clearly connected to the learning of QP. This evokes the question of whether integrating explicit and reflective NOS teaching in QP lessons could help students to master this conceptually difficult subject.

To investigate if students experiences with QP leads to a change in NOS views in future learning. It would be interesting to investigate the NOS understanding of younger pupils who learn some QP concepts, for example, in the *Einstein-First* project (Kaur et al., 2018). Could controversies in QP also be addressed in middle school physics lessons? And what effect would this have on students’ development of NOS views?

Easy-to-implement, adaptable instructional materials that link quantum physics to aspects of Nature of Science

Chapter 4:
Teaching Resources

“Why don’t you just tell us what light really is?”

Easy-to-implement, adaptable instructional materials that link quantum physics to aspects of Nature of Science

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Abstract

High school students' difficulties with quantum physics (QP) are partly due to their limited understanding of the Nature of Science (NOS). The essence of QP can only be understood with informed views about NOS aspects, such as the role of models and the relevance of controversies between physicists. Inversely, QP is an ideal topic for teaching aspects of NOS. However, secondary school textbooks seldom support teachers to explicitly address NOS in QP. Drawing on a five-year research program, including observations of students and teachers, we present teaching resources that link NOS aspects with QP. Our materials support active and reflective learning activities while being adaptable to teachers' individual needs and affordances. We hope to inspire teachers to address NOS in their QP lessons.

4.1 Teaching quantum physics at secondary school level

This project started with a question from a girl in class when I (the first author) was teaching about the photoelectric effect in a secondary school. "First, you told us that light travels in a straight line, then it was a wave, and now, light comes in portions as if there were particles of light! Why don't you just tell us what light really is?". This made me think about what makes quantum physics (QP) different from other content of the physics curriculum and why QP is difficult for students. As with others (e.g. Johansson, 2018), my own learning experience with QP (or quantum mechanics) at university was ambivalent. I was looking forward to finally being initiated into the order of those who live with dead-and-alive cats. However, all I really got were recipes for solving the Schrödinger equation in various complex situations: mathematics seemed to make QP difficult. Now, as a secondary school physics teacher, I realise that QP is challenging even without partial differential equations and *n*-dimensional Hilbert spaces.

My students found it difficult to abandon previously-learned models of light and matter. This is understandable as they have learned classical models for many years. Certainly, I am guilty, too, of neglecting to explain that our descriptions of light are helpful models, but not *what it really is*. After teaching my students for four years, I felt compelled for the first time to explain that science never claims to tell the truth, that physicists use different models in different situations, and that they often — certainly in QP — disagree on what can be said about reality. Such aspects of the very Nature of Science (NOS) seemed new for many students.

Triggered by students' difficulties in learning QP and understanding associated aspects of NOS (see explanation below), we began a research project five years ago to investigate the use of NOS in teaching and learning QP. In the course of the project, we became aware that the learning objectives of QP and NOS are so closely intertwined that it might be helpful to teach them simultaneously. The two learning objectives seem to reinforce each other and could offer mutually enriching instructional possibilities. We met teachers who also saw the added value of integrating aspects of NOS into the teaching of QP. To support teachers in various teaching situations, we developed QP teaching materials as an adaptable resource. The materials contain an editable presentation with (concept) questions to spark critical thinking about NOS, as well as discussion prompts, essay questions, links to explanatory videos, and free interactive QP simulations.

4.2 Theoretical background

4.2.1 NOS in science education

NOS in science education is an umbrella term for topics which are important for understanding science but do not represent content knowledge, such as physics phenomena, laws and formulas. NOS addresses epistemological aspects of how scientific knowledge is created, how it differs from other sources of knowledge and the limits of science. It also deals with sociological aspects, such as recognising that scientists are affected by historical circumstances and personal beliefs (Dagher & Erduran, 2016; McComas, W. F., 2020). Common uninformed NOS ideas among students (and teachers) are expressed in statements such as “Scientific knowledge is true and therefore”, “Scientific research is uncreative procedural work”, “Only brilliant individuals (probably white men) can do science”, and “Good scientists always agree about the true interpretation of data; if they do not agree, we cannot trust them”. Well-developed NOS views are a critical component of scientific literacy, which is regarded as essential for all students, not only for personal decisions but also for participation in science-related public debates (Yacoubian, 2018). Therefore, many national science curriculum documents mention NOS in their general intentions. However, explicit, measurable NOS learning outcomes are rarely expressed in these documents (Olson, 2018), and students’ NOS views are not tested in most exams.

Research on teaching and learning NOS at different levels of education has a long tradition. Although no “best way” of teaching NOS has emerged, there are indications for effective instruction: NOS needs explicit attention in science learning because informed views do not develop as a by-product of content learning or inquiry-oriented activities (Khishfe & Abd-El-Khalick, 2002; Lederman, N. G., & Lederman, J. S., 2004). NOS teaching should include reflective elements and ideally be provided in both highly contextualised and decontextualised activities (Clough, 2006; Khishfe 2015; McComas, William F. et al., 2020). Typical examples for decontextualised NOS instruction are black (or even pink) box activities (Miller, 2014; Pols, 2021; RSC. 2009), which are engaging, entertaining and low-cost. These are especially suitable to model specific aspects of scientific research, such as the difference between observation and inference. Contextualised NOS activities can occur in many physics lessons if the teacher is alert to suitable occasions and knows how to use them effectively (Hansson & Leden, 2016).

Developing informed views on NOS can be considered to be one of the most important goals of physics education as it contributes to scientific literacy. Most of our students will not need physics content knowledge in their future studies or careers. However, all of them are exposed to discussions about scientific data in the media. Not knowing how to judge science-related information can be harmful for citizens and society. The COVID-19 pandemic has shown that misjudgements can lead to a distrust of virologists and a misunderstanding of the effects of vaccinations (Fleming, 2020).

Unfortunately, there are many reasons why NOS receives little attention in physics lessons: teachers lack the necessary teaching strategies (Backhus & Thompson, 2006; Leden et al., 2015), physics textbooks generally pay little attention to NOS (Abd-El-Khalick et al., 2017; Zhuang et al., 2021), and teachers do not see it as their task to teach NOS because it is not tested in summative exams (Bartholomew et al., 2004; Kahana & Tal, 2014).

4.2.2 Teaching and learning QP in secondary schools

Conceptual (or qualitative) QP — without mathematical formalism — is currently taught in secondary schools in many countries (Stadermann et al., 2019). Representatives from universities and industry argue that QP should be in the school curriculum to create a future “quantum workforce” as QP is the basis for various modern technologies (Venegas-Gomez, 2020). However, topics in the physics curriculum should also serve those students who will not study sciences beyond school (Osborne & Dillon, 2008; Reiss, 2007). Reflecting on NOS in the context of QP would be an excellent way to make QP learning fruitful for all students. Research shows that students develop informed views on NOS aspects such as the tentativeness of scientific knowledge, the role of scientific models and controversies in science when discussed in the context of QP (Stadermann & Goedhart, 2020).

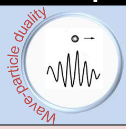
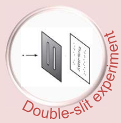
NOS aspect	Example of the NOS aspect in Quantum Physics
The role of scientific **Models**	 Depending on the situation, either the wave model or the particle model is useful to describe electrons or light.
Tentativeness of scientific knowledge	Although Newton's laws of motion have formed the undisputed basis of classical physics for hundreds of years, it is not possible to understand quantum phenomena with Newtonian physics. 
Creativity in science	 The development of Quantum Physics (QP) was only possible through applying new mathematics to unsolved problems, out-of-the-box thinking, and creative (thought) experiments.
Subjectivity in science	Depending on personal preferences, some physicists are content with QP purely as a tool to describe and predict phenomena, whereas others are searching for a underlying meaning of the QP formalism for reality. (⇒ Interpretations of QP) 
Controversies in science	 Discussions between physicists 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.

Figure 4-1 Connection between NOS aspects and QP (classroom poster)

Many of the problems students have with conceptual QP are related to NOS aspects. For example, if students stick to their previously learned ideas (models) of particles, they may not be aware that different aspects of phenomena require different models. The belief that QP is incomprehensible might have its origin in the prevalent Copenhagen interpretation of QP. In this "orthodox" interpretation, particles generally *do not have* the property of position or velocity. This is very difficult to accept, especially if students (and teachers) think they must swallow the Copenhagen interpretation as a "fact". It can be a relief for students to see that there are different interpretations of QP. The existence of alternative interpretations of scientific phenomena and controversies between scientists exemplifies a feature of NOS. To make connections between QP and aspects of NOS explicit, we designed the classroom poster in *Figure 4-1* (see Appendix 4-A). This poster gives an overview of NOS aspects relevant to teaching conceptual QP. It is practical support for teachers because textbooks commonly do not emphasise these NOS aspects (Mohan, 2020); they merely present some QP phenomena, visualise the wave function or give "recipes" to calculate the outcome of experiments. Discussion about how to imagine quantum entities before and during a measurement is usually avoided. However, that is what students want to know. By explicitly addressing NOS aspects such as the role of models and controversies in science, teachers can respond to students' questions. Therefore, teaching conceptional QP could benefit from the inclusion of NOS aspects in QP classes and the use of NOS as a common thread to connect several QP concepts.

4.3 Purpose and design of adaptive QP-NOS teaching resources

Although addressing NOS aspects is helpful for teaching QP, many physics teachers lack NOS teaching strategies and are not familiar with interpretations of QP. Therefore, we developed innovative resources for a variety of teaching/learning activities directly useful in teachers' practice. According to Doyle and Ponder (Doyle & Ponder, 1977), teachers perceive innovations as useful and practical if they fit into their specific teaching environment (a complex interplay of school conditions, teaching goals, students' and teachers' characteristics), provide concrete classroom activities, and require little effort and time for implementation. Therefore, we chose to present our buffet-style material in the form of a PowerPoint presentation with several directly usable teaching/learning activities for different classrooms and teaching preferences. In our study, teachers typically used elements of the resources in combination with their usual — mostly textbook-based — teaching activities.

The editable format of our materials enables teachers to customise the presentation for their particular class situation. Some parts of the materials are intended to provide teachers with content about unfamiliar topics (for example, different interpretations of QP); other parts are intended to stimulate higher-order learning activities.

Based on research on teaching QP and NOS, the adaptable teaching resources cover the content of secondary school QP curricula. They aim to:

- Connect to students' prior knowledge;
- Address well-known conceptual problems in learning QP;
- Stimulate active reflections on NOS aspects in QP.

The resources provide a range of ready-to-use materials for meaningful learning, such as:

- Explanatory videos for topics that might be unfamiliar for teachers;
- Examples of applications to show the relevance of QP;
- Simulation applets to make abstract concepts more tangible;
- Prompts for whole-class discussions or written reflection tasks;
- Concept questions to initiate peer instruction or whole-class discussions.

4.4 Semi-finished materials

In the first two years of the project, we have had intensive contact with teachers who used the PowerPoint slides. Their suggestions and questions have been incorporated into the material so that the original version has grown to more than 100 optional slides. These facilitate a variety of teaching activities for all topics in the curriculum and contain additional information about different QP interpretations and applications of QP; most slides lend themselves to addressing NOS-related questions. Each slide contains teaching activities that can be used as building blocks for lessons. The material is offered as a semi-finished product, requiring an active role for the teacher depending on their preferences and intentions, such as discussions (individual or small groups), peer instruction, or written reflection tasks. Teachers can customise the material before or during lessons. Links on the slides enable teachers to "jump" to other parts of the resources. A representative set of the resources has been translated into English and can be found in Appendix 4-B (H. K. E. Stadermann. 2021). The full, original Dutch version is available on request from the first author. Below are some examples to illustrate the underlying ideas and to show how we applied and combined elements from physics education research and online resources.

4.5 Examples

The introductory slide (*Figure 4-2*) gives teachers a sense of the type of material in the presentation. Teachers will probably not use this first slide in class.

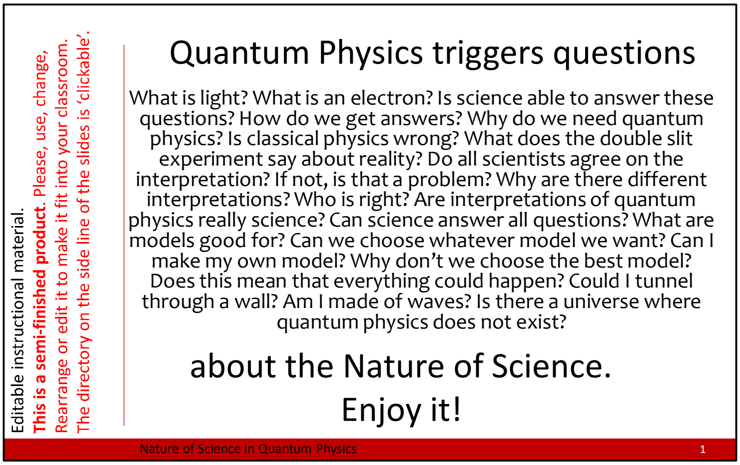


Figure 4-2 First slide of the Teaching material

In the development of the resources, we used input from relevant educational research. For example, research on students' understanding of electrons inspired the question shown in *Figure 4-3* (Baily & Finkelstein, 2015). This slide is typically used after the introduction of the double-slit experiment, which shows that electrons have wave properties. The question "What is an electron?" does not have a straightforward, correct answer and provokes many new questions, which is an ideal way to address NOS aspects (Clough, 2020). Similar to the designers of the Norwegian ReleQuant (Bungum et al., 2018; Myhrehagen & Bungum, 2016), we think it is valuable to discuss such questions in the classroom. We chose the format of a concept question because it is easy to implement in the classroom and engages students in thinking and reasoning. One way to introduce this question and spark a discussion is a free online response system for smartphones, which teachers can use for clicker questions. Eric

Mazur (1997b) introduced the use of clicker questions at university level to reveal misunderstandings and actively engage students in lecture courses. Students respond individually and subsequently discuss their answers in small groups (peer instruction); often, they find the correct solution during discussions (Smith et al., 2009). We use this format to allow students to discuss NOS-related questions for which there is often more than one answer possible. The multiple answers in *Figure 4-3* are also suitable to begin a class discussion on NOS aspects such as “the role of scientific models” and “the tentativeness of science knowledge”.

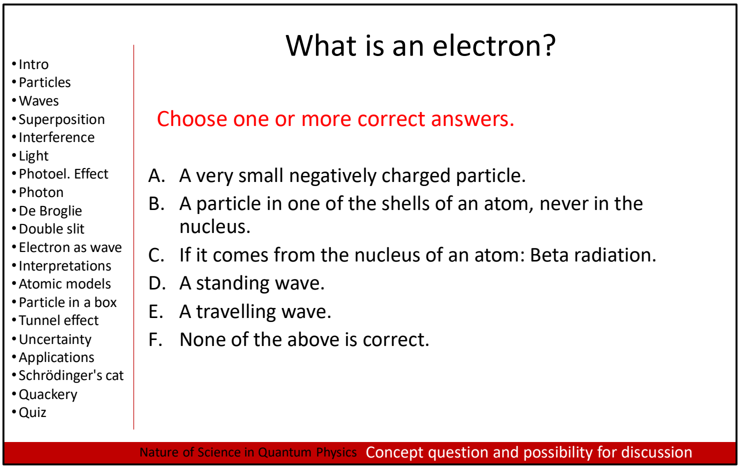


Figure 4-3 Example slide with a concept question without a clear answer

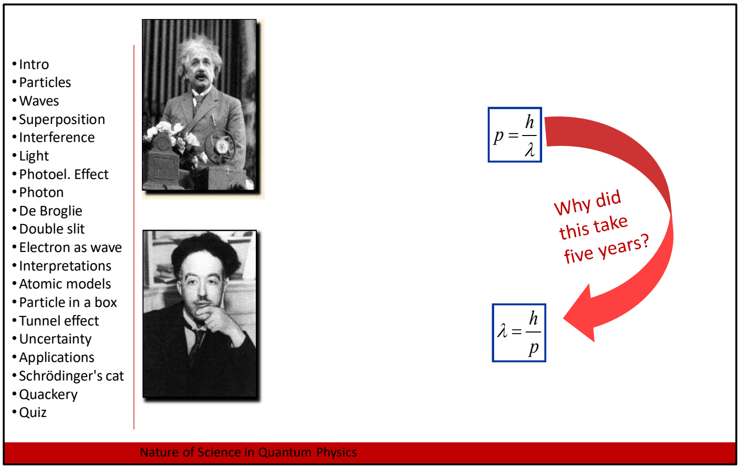


Figure 4-4 Example of a discussion prompt

Another way to start a discussion is by introducing the history of QP. Education researchers point out that students who encounter QP for the first time experience similar problems to those experienced by scientists at the beginning of the 20th century (Kalkanis et al., 2003; Levrini & Fantini, 2013). *Figure 4-4* shows a slide that offers a prompt for an open discussion about the historical developments of QP. Depending on teachers' preferences and intentions, the slide can also be used for individual written reflections.

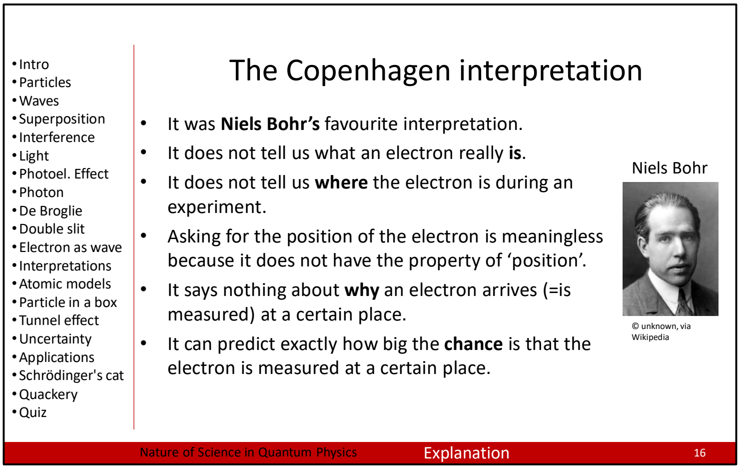


Figure 4-5 Example of an explanatory slide

The material explicitly addresses some conceptual problems which are often neglected in QP teaching (Müller & Wiesner, 2002b). For example, the slide in *Figure 4-5* states the epistemological issues of the Copenhagen Interpretation. By actively reflecting on interpretations, students can develop a deeper understanding of the unique characteristics of QP. Additionally, they see that different perspectives of scientists are necessary for scientific development (Stadermann & Goedhart, 2020). The resources include links to short explanatory videos, enabling teachers to address topics in which they lack expertise. The video on the pilot wave interpretation (*Figure 4-6*) triggers discussions on NOS-related questions such as: "What is a scientific theory?" and "How sure can we know if an explanation is correct?"

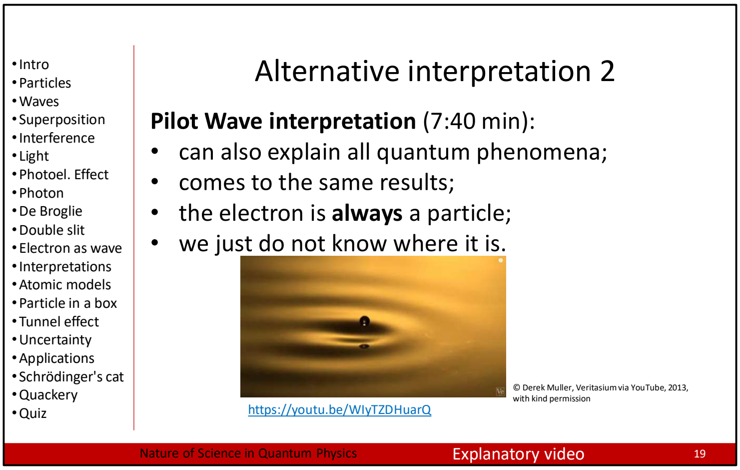


Figure 4-6 Example slide with an explanatory video

4.6 Some experiences and perspectives

As previously mentioned, research on the use of NOS in other curriculum topics has shown that NOS content is seldom explicitly addressed in physics classes, and it is seen by teachers as an extra burden. However, when we provided teachers with resources to use in their regular pre-exam physics classes, nine out of ten addressed NOS aspects in their QP lessons (Stadermann & Goedhart, 2021). These teachers felt that addressing at least some NOS aspects was necessary to give students a framework for the paradoxical quantum phenomena. Among these teachers, classroom discussions were the most popular teaching strategy to prompt students to reflect on their ideas about NOS.

We have observed engaged discussions about the concept question “What is an electron?” (*Figure 4-3*) in different classrooms. In one class, a student stated that the answer “All of the above answers are right.” is missing. Another said that the whole question is wrong because you could only ask, “How can we represent an electron?”. During the discussion, profoundly philosophical or epistemological conversations arose that gave students insights about NOS. In another class, students stated that all models are wrong because no single model correctly describes all features of an electron. Again, students arrived at a point where they reflected on the function and limits of scientific models. The teacher said afterwards that through this discussion, he became more careful in choosing his words when introducing electrons or atomic models in lower grades.

A thorough analysis of the use of the resources in the classrooms of ten teachers from different schools is provided elsewhere (Stadermann & Goedhart, 2021). The purpose of this study was not to investigate the learning effects on students, but it would be very worthwhile to do so in the future. The resources proved to be helpful for Dutch teachers and could be used in other countries too. Ready-to-use discussion prompts, and concept questions were especially welcomed because they facilitated the opening of discussions. Since all supplementary materials are freely available, they will hopefully inspire more teachers to enrich their QP teaching with NOS.

Chapter 5:
Teachers' Views

Why and How Teachers use Nature of Science in Teaching Quantum Physics

Research on the use of an ecological teaching intervention in upper secondary schools

Previously published as

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Abstract

Students at upper secondary and college level in many countries are introduced to quantum physics (QP) in a mostly math-less course. Research shows that addressing epistemological and philosophical aspects would be beneficial for novice students' conceptual understanding. However, physics teachers seldom address these Nature of Science (NOS) aspects in their lessons. We take the view that teachers only implement these aspects if this serves their goals. This study explores whether experienced Dutch high school teachers, who are not trained for NOS teaching, address NOS in their QP lessons when provided with NOS-infused teaching resources. We based our framework on literature about pedagogic content knowledge and on the principles of the practicality of educational innovations. Teacher interviews (N=10) supported by classroom observations provided insights into how and why teachers use specific elements from the resources. Our research reveals teachers' perspectives on teaching QP in secondary schools and why they think NOS aspects can be helpful to reach their teaching goals. Our findings support the view that conceptual QP is valuable for all students because an informed NOS view is vital for everybody in today's society. Additionally, we expect that an ecological intervention that supports teachers and at the same time recognises their professionality and environment has potential implications for other fields of science education and could have a significant positive impact in classrooms.

5.1 Introduction

Quantum physics (QP) has been introduced as a compulsory topic in the physics curriculum at pre-university level in many countries (Stadermann et al., 2019) because of its scientific and societal importance. The unparalleled explanatory and predictive capacity of quantum theory has made it the basis of all contemporary models for the constituents of matter. Furthermore, the rapid development of information technology in the last decades has only been possible because of progress in QP. If secondary school physics only dealt with 19^{th}-century physics, students would receive an outdated worldview and would be unaware of what to expect in higher education physics (Kalkanis et al., 2003; Müller & Wiesner, 2002a). Additionally, science education researchers have labelled QP as one of the biggest cultural achievements of science (Olsen, 2002; Pospiech, 2003), with a status similar to the Copernican and Darwinian revolutions. Therefore, learning about QP is regarded as being valuable not only for future scientists but for all students as part of liberal education, even if they lack the mathematical background to comprehend the formalism of quantum theory (Kalkanis et al., 2003; Muller, R. A., 2010; Müller & Wiesner, 2002a).

Indeed, we have seen an increasing number of studies on innovative ways to teach QP in secondary schools in the last few years (Bitzenbauer & Meyn, 2020; Foti et al., 2021; Hughes et al., 2020; Malgieri & Onorato, 2021; Michelini & Stefanel, 2021; Müller & Mishina, 2021; Satanassi et al., 2021; Woitzik, 2020). Most of these innovations are concerned with new technical or cognitive approaches to teaching QP concepts; students' epistemological problems rooted in their ideas about the nature of physics are rarely explicitly addressed. Additionally, it is seldom mentioned what valuable learning goal QP offers for all those students who do not plan a career in quantum technology. Research suggests that discussing distinctive aspects of Nature of Science (NOS) in QP could be such a learning goal (Garritz, 2013; Kalkanis et al., 2003). Explicit attention to NOS would additionally provide possibilities to address students' epistemological questions (Greca & Freire, 2014a; Henriksen et al., 2018). As teachers are instrumental in enabling students to benefit from NOS-informed QP approaches, we want to explore practising teachers' views on teaching QP with explicit attention to NOS aspects.

At university level, the approach to QP is mainly mathematical; any philosophical interpretations of the formalism have commonly been neglected in teaching since the 1950s (Johansson et al., 2018; Kaiser, 2007). QP interpretations form the link between quantum formalism and the reality of experimental results. In contrast to the undisputed mathematical description of QP, its interpretations are responsible for the most famous and long-standing controversy in physics (Freire, 2003; Garritz, 2013; van Kampen, 2008). Fundamental ideas of different interpretations have even found their way into popular science media. For example, the so-called Copenhagen interpretation, attributed to Bohr and Heisenberg, postulates that particles such as electrons do not have a specific place but exist in a superposition of all possible measurement outcomes; only by making a position measurement, we create a specific outcome. However, in the pilot wave interpretation, advocated by famous physicists such as de Broglie, Bohm, and Bell, a quantum particle always has a well-defined position, although we miss information to predict the outcome of position measurements. The ongoing controversy between proponents of different interpretations may seem purely philosophical, but it is also relevant for physics education because the way students imagine an electron largely depends on how QP is interpreted in their lessons (Baily & Finkelstein, 2010a).

The complex calculations used in university courses are beyond the math skills of secondary school students, and even simplified versions of quantum formalism do not usually belong to the school curriculum in most countries (Stadermann et al., 2019). Therefore, secondary school teachers use a conceptual approach to QP. Here we use *conceptual QP* in the same sense as *conceptual physics* is commonly used in physics education to describe qualitative teaching of the central concepts of physics. Instead of focusing on mathematical expressions, the conceptual approach aims to engage students in model-based reasoning to construct and consolidate new concepts (Hewitt, 1983; Sands, 2014). To acquaint students with some QP ideas, secondary education physics courses spotlight key concepts such as wave-particle duality, Heisenberg's uncertainty relationship and quantum physical atomic models. Although the presumed most significant obstacle – complex mathematics – is eliminated from this conceptual approach, learners still struggle with quantum concepts, mainly because QP phenomena contradict not only their common-sense notions but also the classical Newtonian physics they previously learned. It therefore seems necessary to guide students towards a new understanding of the physical world, recognising the essential role of interpretations and models in QP.

5.1.1 Why NOS aspects should be included in QP teaching

The development of new models and interpretations is inherent to science-in-the-making and part of the Nature of Science (NOS). NOS is a prominent and widely discussed term in science education. It refers to a spectrum of ideas that describe the development and status of scientific knowledge; it characterises science as a human endeavour and includes epistemological, philosophical and societal aspects (Allchin, 2013; Lederman, N. G., 2007). While science education researchers do not always agree on how – if at all – NOS should be defined (Romero-Maltrana & Duarte, 2020), it is beyond question that students should learn how scientific knowledge is constructed and how science is practised. Some aspects of NOS, such as the importance of empirical evidence or the use of observations and inference, are commonly addressed in physics lessons because they relate to students' activities in practical inquiries (Bell, R. L., 2009). However, aspects such as the role of scientific models, the tentativeness of scientific knowledge or the existence of controversies in science are rarely discussed in school physics (Gogolin & Krüger, 2018; Henriksen et al., 2018; Mesci & Schwartz, 2017). This omission is problematic because what is clearly visible in the development of the foundations of QP is quite unique for school physics: existing theories and models were not rejected but framed in their validity, and with the help of classical analogies and familiar words (electron, atom), completely new concepts were developed. Therefore, these NOS aspects play an essential role in learning QP.

Table 5-1 Examples of connections between NOS and QP content for teaching

NOS aspect	Example of intended NOS views	Related QP items	Examples of how the NOS aspect can be explicitly addressed in QP teaching
The role of scientific models	Scientific models are not a complete repre-sentation of reality, but they serve to explain or predict certain aspects of real phenomena.	• Wave-particle duality* • Photoelectric effect* • Atomic models* • Particle in a box*	Depending on the situation, either the wave model or the parti¬cle model is useful to describe electrons or light. Some properties of atoms can be illustrated with the Bohr model, but to explain the existence of atomic energy levels, we use the *particle in a box* model.
The tentativeness of scientific knowledge	Scientific knowledge is, in principle, always open to development, warranted change and improvement.	• Quantum tunnelling* • Double slit experi-ment with single particles* • Atomic energy levels*	It is not possible to explain these quantum phenomena with Newtonian physics.
The role of controversies in science	Discussions and dis-agreements about scientific ideas are essential in scientific development. Different interpre-tations may exist.	Different interpre-tations of QP (what quantum theory means for reality)	There is no consensus about the (need for) interpretations of quantum theory. Different scientists adhere, for example, to the Copenhagen (or agnostic), the pilot wave, or the many-worlds interpretation.

(* = item listed in Dutch exam syllabus)

Learners' difficulties with conceptual QP are often rooted in the tenacity of classical concep-tions and rigid epistemologies (Krijtenburg-Lewerissa et al., 2017). To overcome these problems, many researchers advocate enriching conceptual QP lessons with NOS themes related to philosophy and epistemology (Garritz, 2013; Greca & Freire, 2014a; Kalkanis et al., 2003; Levrini & Fantini, 2013; Weissman et al., 2021). Philosophical and epistemological is-sues have always been associated with the development of QP concepts. Famous examples are Schrödinger's Cat and the Bohr–Einstein debates about the meaning of the mathematical formalism for reality (Merali, 2015). Table 5-1 shows more examples of how NOS aspects are linked to the content of the QP curriculum.

In physics education literature, we find two main reasons why NOS can help students learn conceptual QP. First, if historical and controversial philosophical elements are addressed adequately, physics is more appealing to students, as they experience it as a living, human endeavour instead of a rigid collection of abstract facts (Abd-El-Khalick, 2005; Gil & Solbes, 1993). Second, discussing NOS aspects such as scientific controversies and the historical development of quantum theory can be helpful to overcome conceptual problems (Bungum et al., 2018; Dunlop & Veneu, 2019; Galili, Igal & Hazan, 2001; Garritz, 2013; Niaz & Rodríguez, 2002). For example, authors argue that the conceptual difficulties students commonly experience are very similar to those of pioneering physicists during the development of quantum theory. Therefore, NOS helps students to construct knowledge by addressing the historical development of physics concepts (Clough, 2017; Galili, Igal & Hazan, 2001; Leone, 2014). Additionally, some researchers state that discussing philosophical questions is important for students who are encountering QP for the first time (Baily et al., 2010; Mohan, 2020) because, even if not intended, NOS issues are always part of conceptual QP teaching. Whenever invisible quantum entities, such as electrons, are visualised in textbooks, computer simulations or animations, the developers make implicit interpretational choices, which might lead to misconceptions. Additionally, teachers unavoidably interpret mathematical formalism and influence the development of students' ideas about QP concepts by using models, metaphors, or analogies (Etkina et al., 2006; Ireson, 2000; Ubben & Heusler, 2019; Wiener, 2020).

The aforementioned arguments from physics education literature explain how NOS is helpful for learning QP. From the viewpoint of NOS learning, a relevant science context is crucial (Irwin, 2000; Khishfe 2014; Nouri & McComas, 2019), and it is argued that QP could provide such a context. In conceptual QP, for example, students can realise that a model or analogy cannot explain all the properties of an electron and that controversy between scientists is an essential element in the development of scientific knowledge (Stadermann & Goedhart, 2020). Additionally, if students themselves discuss the use of scientific models or rival interpretations, they experience an essential scientific practice: debating various viewpoints to obtain a better conceptual understanding (Niaz & Rodríguez, 2002).

5.1.2 Why NOS aspects are not included in QP teaching

Exam syllabus and textbooks

There are no mandatory NOS aspects in the QP section of the national final exam syllabus for physics in the Netherlands and most other countries which assess this topic at secondary school level (Stadermann et al., 2019). As long as NOS is not one of the explicitly stated learning objectives in the curriculum, teachers do not see it as their task to teach it (Bartholomew et al., 2004; Kahana & Tal, 2014). Additionally, textbooks, the most commonly-used teaching resource in physics classrooms, rarely support teachers in their integration of NOS aspects. Generally, most physics textbooks stress science as a body of knowledge with little attention to NOS (Abd-El-Khalick et al., 2017).

Traditional physics lesson; teachers' and students' expectations

Teachers who do not see the utility value of informed views of certain NOS aspects are unlikely to include these NOS aspects in their physics lessons. A recent study on the use of controversies in science lessons revealed that all participating teachers indicated that controversy is essential to science, but they preferred to discuss it with students outside of class. In the opinion of the participants, teaching "the facts" is most important. They assumed that discussing scientific controversies might confuse students rather than help them in the national exams (Dunlop & Veneu, 2019).

The Norwegian ReleQuant project in upper secondary classrooms is the only reported broadly implemented teaching approach with a focus on qualitative understanding, NOS, history, and philosophy of QP (Henriksen et al., 2014). The web-based instructional materials in this project include several activating pedagogies stimulating students' philosophical and epistemological reflections. In an evaluation of the project, in addition to positive results, the researchers found that students were frustrated by tasks such as discussing their interpretational views on QP because they lacked the possibility to check whether their answer was correct or not; students also did not recognise NOS aspects as learning goals in their own right (Bøe et al., 2018). The authors explain students' resistance to elements of the new approach as being a result of their expectations and socialisation in traditional physics classrooms.

Pedagogic content knowledge

Although most Dutch physics teachers hold a master's degree in physics and have attended QP courses at university, these courses concentrate on mathematical formalism rather than interpretational and conceptual aspects. Additionally, QP was introduced into the upper secondary curriculum in the Netherlands four years ago, and the majority of teachers were not prepared to teach conceptual QP and lacked a broad repertoire of QP pedagogical content knowledge (PCK) (Shulman, 1986; Shulman, 1987). To describe the dynamic construct of PCK, we adopt the five PCK subcategories of Magnusson et al. (1999), which are teachers' personal knowledge and beliefs about (1) goals and purpose of subject teaching; (2) curriculum content; (3) students' situation-specific learning difficulties; (4) assessment of subject matter; and (5) topic-specific instructional strategies. Teachers' lack of PCK subcategories 2 to 5 is a natural start-up problem for new curriculum content. How their teaching of QP will develop depends largely on teachers' knowledge and beliefs about purposes and goals for teaching QP in secondary school (PCK subcategory 1). Therefore, part of our research concentrates on revealing teachers' ideas about the purposes of teaching QP. Unlike others, who describe a separate "NOS PCK" developed in NOS courses (Faikhamta, 2013), we adopt Van Dijk's (2014) notion of PCK, which contains knowledge of topic-specific NOS aspects, that "*emerge* from the content that is being taught and should not be treated as general features that can be *placed* into a particular context when teaching science." (van Dijk, 2014, p. 408).

Even without participating in a NOS course, teachers might feel that NOS aspects such as historical, philosophical, and epistemological themes are directly related to learning conceptual QP. Therefore, in this study, we consider NOS as a possible educational goal and part of teachers' PCK.

Before formulating the resulting research questions in section 5.1.4, we briefly introduce a key instrument for this study; the instructional materials for teaching QP with explicit attention to NOS, and describe how these materials are used in interventions.

5.1.3 Teaching material

Practicality

While the entanglement of QP and NOS is apparent, even a perfect theoretically and pedagogically developed innovative teaching module is useless if teachers do not use it. In everyday classrooms, teaching comprises much more than finding the best cognitive route for students to reach the learning goal; in a fast-paced, information-rich environment, teachers are expected to implement lesson plans, prepare for exams, enforce school rules and at the same time build interpersonal relationships with students to help, inspire, correct, comfort, challenge or support them, not only in their subject learning but also in their emotional and general cognitive development. Therefore, implementing any "research-based" teaching strategy – with new subject content and pedagogies – is not straightforward for teachers. Teaching strategies which are not perceived as useful are unlikely to make their way into classrooms.

To achieve a successful implementation of teaching innovations, Doyle and Ponder (1977) distinguish three preconditions or practicality dimensions: (1) Instrumentality: Rather than imposing abstract principles (e.g., NOS tenets) on teachers, innovative teaching practices should be translated into concrete classroom procedures; (2) Congruence: Practices should fit the way teachers perform classroom activities, their self-perception, and the classroom setting in which they work; and (3) Low cost: Practices should not demand a significant amount of time and effort. In a follow-up study, Westbroek, Janssen, and Doyle (2017) found that it is essential to connect teachers' professional core goals with the proposed innovation. These goals reflect teachers' fundamental beliefs about good teaching. Therefore, useful teaching resources support teachers' individual teaching goals, add value to their expertise and ideally work with little extra investment of time and effort.

Ecological Intervention

Because QP is a new curriculum domain and thus not burdened with ingrained, difficult to change teaching practices, it is particularly suitable to develop new PCK, which includes relevant NOS elements. This QP PCK can be supported by teaching/learning material that meets the above-specified criteria of Doyle and Ponder (1977). Janssen et al. (2014) showed how building blocks, or lesson segments, can be used to customise available teaching resources. Adapting, recombining, or rearranging the order of lesson segments can lead to different teaching-learning processes suitable for specific demands of classroom ecologies (Janssen et al., 2013). Elaborating on this idea, we developed buffet-style teaching resources to support teachers' QP PCK. The design of the resources was guided by Doyle and Ponder's prerequisites for successful innovation and findings from research on students' learning difficulties in QP, and topic-specific teaching strategies were applied in the teaching material. The development and further details on the content of these learning resources will be presented in a separate publication, which is in preparation.

Table 5-2 Structure, content, and supported activities of the instructional material

Section of the slide presentation	Covered content items	Mandatory in the Dutch exam syllabus	Addressed NOS aspect			Material to support instructional activities										
			Models	Controversies	Tentativeness	Narrative / Concept Explanation	Explanatory Video	Examples of Applications	Animated Graphics	Overviews, Definitions	Demonstration of Phenomena	Simulation Applet	Problem Solving (Calculating)	Reflection /Discussion Prompt	Concept Question	Short written task
Introduction	Electrons as particles (repetition)	yes	×					○					○		⊗	
	Atomic models (repetition)	yes	×		×	○				○				⊗		
	Waves (repetition)	yes				○		○	○	○	○	○			○	
	Wave interference	yes				○		○	○	○	○	○	○		○	
	Superposition	yes				○			○						○	
Light	Light as wave	yes				○		○		○			○			
	Double slit experiment with light	yes	×	×	×	⊗					○	⊗			○	
	Photoelectric effect	yes	×			○		○		○		○		○	⊗	
	Quantisation of light	yes	×	×		⊗				⊗					○	
Matter	Wave-particle duality	yes	×	×	×	⊗				⊗		○		○	⊗	
	Double slit exp. with particles	yes	×	×	×	⊗	⊗					○		⊗	○	⊗
	Probability distribution	yes				○						○				
	De Broglie wavelength	yes	×			○		○		○			○	⊗	⊗	
	Electron microscope	yes				○		○					○			
QP interpretations	Copenhagen interpretation	no		×		○	⊗							⊗		
	Many worlds interpretation	no		×			⊗									
	Pilot wave interpretation	no		×			⊗									
Atomic models	Discreet energy levels	yes	×			⊗		○	○	○		○	○	⊗	○	⊗
	Particle in a one-dimensional box	yes	×			⊗		○		○		○	○	⊗	○	⊗
	Hydrogen atom quantum model	yes	×		×	○		○					○	⊗		⊗
Phenomena & principles	Heisenberg's uncertainty principle	yes				○		○	○	○					○	
	Quantum tunnelling	yes	×			○		○	○		○	○		○	⊗	
	Alpha decay	yes	×			⊗		○								
Applications & technology	Scanning Tunnelling Microscope	yes				○	○	○								
	Quantum dots	no				○		○								

[a]Legend:
× = suggested NOS aspect in the material
○ = supported teaching activity (no explicit NOS)
⊗ = intended NOS aspects in instructional activity

The educational material was made available to teachers in the form of a presentation containing 142 editable presentation slides, covering all the learning objectives from the Dutch QP curriculum. Additionally, we intertwined NOS-related elements into building blocks to facilitate (or tempt) teachers to address NOS aspects in QP teaching. To make the resources *instrumental*, we prepared elements teachers could use directly in the classroom, such as concept questions for online voting (see *Figure 5-1*), discussion prompts (see *Figure 5-2*), and a selection of publicly available explanatory videos. The buffet-style format made the resources *congruent* because, by selecting specific parts of the slide presentation, teachers tailor the material to their specific situation and their preferred teaching activities. The ready-made slide presentations with pre-arranged online concept questions and short videos make the material easy to use in classrooms, and therefore *low cost*.

In contrast to a conventional instructional intervention, where teachers have to follow steps precisely, we call our approach an ecological intervention. Following Janssen et al. (2013), we adopt Doyle's (1977b) ecological perspective on the classroom as a social-ecological environment. From this perspective, it is possible to describe how teachers' decisions influence and depend on a complex interaction between personal characteristics and environmental factors such as student population, technical possibilities, time constraints, and behavioural patterns. An ecological teaching intervention provides teachers with a flexible toolbox with various possibilities for situation-dependent actions.

In our context, a teacher could, for example, skip or delete slides with discussion prompts if there is not enough time for discussions or decide to discuss the videos about different interpretations of QP if they consider this as meaningful. They could also change the order of the slides to make them compatible with the textbook they use. Table 5-2 provides an overview of the content items that relate to NOS aspects (scientific models, tentativeness, and controversies in science). Table 5-2 also shows the various activity formats supported by the instructional material.

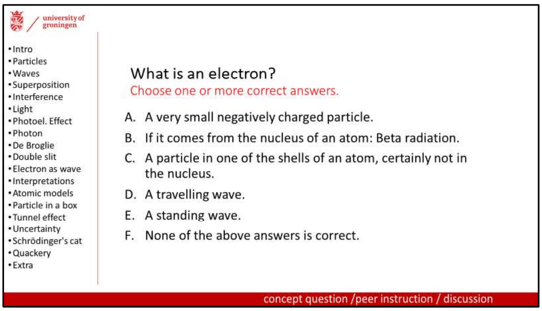

Figure 5-1 Example of a concept question

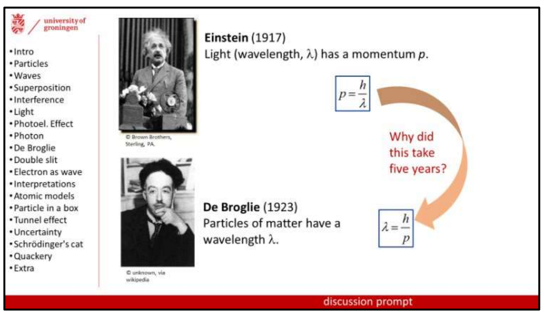

Figure 5-2 Example slide with a concept question

To illustrate the slide presentation, we show two (translated) slides in *Figure 5-1* and *Figure 5-2*. In contrast to common concept questions, the question "What is an electron?" does not have a straightforward, correct answer and provokes many new questions. It could even be discussed if the question itself is valid. Discussions can be facilitated by first collecting individual answers using a web-based student response system with smartphones, followed by peer discussion (Mazur, 1997a). Teachers could alternatively choose to use the multiple answers to begin a class-wide discussion on NOS aspects such as "the role of scientific models", "the tentativeness of science knowledge", or general epistemological and philosophical questions about our possibilities to understand reality. Teachers could, on the other hand, skip the whole question and only use the slides which contain explanations or teach from the textbook instead of the provided slide presentation. *Figure 5-2* shows a slide that offers a prompt for an open discussion. Again, teachers could remove the question "Why did this take five years?" and just present it as the transformation of a formula.

5.1.4 Research Questions

This study's context is defined by a recent curriculum change, which highlighted in-service physics teachers' lack of experience in teaching QP and the fact that NOS is not part of mandatory teaching requirements. To support teachers' PCK for qualitative QP, they were offered easy-to-enact and easy-to-adapt (buffet-style) teaching/learning material with several possibilities to explicitly address and integrate NOS aspects in QP lessons. When teachers choose to use NOS teaching opportunities in the instructional material, we wish to explore their motives. In Shulman's PCK framework (1986; 1987), addressing NOS aspects in the lesson supports their beliefs about the purpose of QP teaching or, viewed from the practicality perspective of Doyle and Ponder (1977; Janssen et al., 2013), NOS fits in teachers' goals of QP teaching. Through teacher interviews, lesson observations, and learning activity responses from students, we attempt to answer the following questions:

RQ1: Which NOS aspects – if any – do the teachers address in their QP lessons, and what teaching activities do they choose for this?

RQ2: How do teachers' goals in QP lessons relate to these NOS aspects?

The order of the research questions reflects our evidence-based research design. As explained in the following section, we ask questions to elicit teachers' intended goals based on their actual classroom activities. We choose not to ask about teachers' goals first. In this way, we avoid that teachers might state desirable goals that are not realised in real lessons. This enhances the validity of our results.

5.2 Research design and methods

In this study, we aim to collect evidence of teachers' use of NOS aspects in teaching QP and to obtain insights into why and how they address NOS in their physics classrooms. To understand our methodological choices and to emphasise the specific nature of this study, we first distinguish it from other types of research with thematic and methodological overlap. In contrast to many other science education studies, our aim is not to investigate the effectiveness of NOS teaching material for students; instead, we focus on teachers' practices and goals. We also do not probe the characteristics of educators who use NOS in their classrooms or the problems they experience. Our research is performed in natural, authentic school conditions and deals with upper secondary QP courses, in which teachers have the freedom to decide how to reach their teaching goals. With an ecological intervention, we acknowledge teachers' professionality and their expertise to choose teaching strategies useful for their specific situation. An in-depth analysis of interviews gave us insights into why and how different teachers in a similar situation use NOS in their lessons. *Figure 5-3* gives an overview of our research design.

5.2.1 Context and Participants

Since 2016, QP has been a mandatory part of the national written physics exam in the Netherlands and is usually taught in pre-exam classes (grade 12, students aged 17-18). NOS is not explicitly included in the QP learning objectives. The official national curriculum does not prescribe any instructional framework or pedagogy for teaching.

Table 5-3 Teacher Characteristics and Data Availability

Name	Gen-der	Age Group	Years Teaching Grade 12	Educational Back-ground[a]	Taught Groups	Available lesson data: Observed Class Periods	Video Class Periods	Student res-ponses[b]	Teacher Re-ports	Interview Length (min)
Nina	f	30-39	5 -10	A	2	4	-	CQ, PI	4	36
Emma	f	40-49	5 -10	A	1	1	-	CQ, WT, PI	2	35
Daan	m	40-49	5 -10	B	1	2	-	-	1	58
Oliver	m	40-49	> 10	A	1	1	-	CQ	1	35
Karim	m	> 50	> 10	A	1	2	-	PI	1	52
Liam	m	> 50	> 10	A	2	2	-	CQ, PI	0	38
Ben	m	> 50	> 10	A	2	4	-	CQ, PI	6	60
Hanna	f	> 50	> 10	A	1	3	3	CQ, WT, PI	2	40
Tim	m	> 50	> 10	A	1	3	3	PI	0	40
Milan	m	> 50	> 10	C	1	3	3	-	0	45

[a]Educational background: A = MSc(physics) + postgrad. teacher training; B = M. Ed (physics); C = PhD(physics) + postgrad. teacher training
[b]Student responses CQ = online results of concept questions, WT = students' written tasks, PI = written results of peer instruction

Ten physics teachers from six different Dutch public secondary schools volunteered to participate in the study; three of them taught parallel classes. Table 5-3 gives an overview of teachers' characteristics (names are changed). Because we wanted to investigate the participating teachers' authentic needs, practices, and lesson goals, they were not pressured to use the material in a specific way. Four to six weeks before teaching QP, the teachers received the full teaching material and written instruction about how students could use the online voting system on their smartphones for concept questions. Additionally, teachers received a short individual oral introduction to the material to explain how the slide presentation could be adapted and how peer instruction could be effectively used. NOS aspects were not discussed during this instruction. Before and during the teaching period, the first author was available for individual questions via email.

5.2.2 Data Sources and Data collection

The primary data source for this study is teacher interviews; we collected additional data (left side in *Figure 5-3*) with the aim to triangulate the interview results. For this, we observed at least one lesson of each class, and we recorded lessons from three schools to see how teachers implemented the material. Additionally, we collected student responses to online concept questions and written tasks and emails from teachers reporting on the progress of the lessons or asking questions about the provided material. The data collection during lessons reflects the possibilities and problems of data taking in everyday school life. Therefore, we do not see the diversity in our data set as a shortcoming but rather as a characteristic of an ecological intervention study.

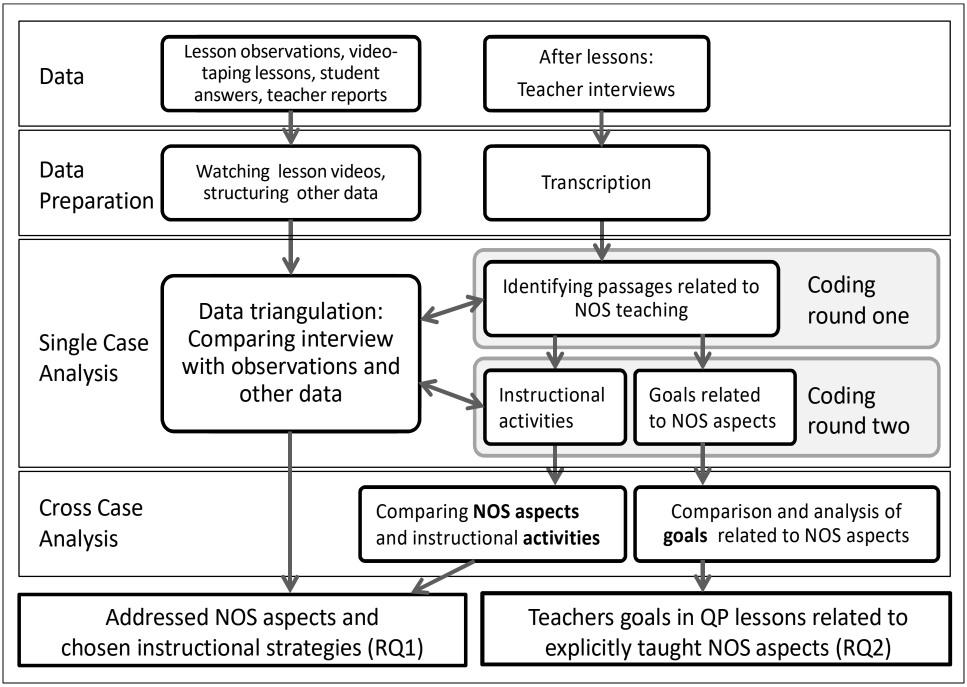

Figure 5-3 Research design overview

To understand teachers' goals related to integrating NOS into their QP lessons (RQ 2), the first author conducted individual semi-structured interviews (35 to 60 minutes) with each teacher (see Appendix 5-A for the interview guide). These were audiotaped and transcribed verbatim for further analysis. For the interviews, we adapted the technique of practical reasoning from Janssen et al. (Janssen et al., 2013) to find the goals that underlie teachers' decisions regarding the parts of the instructional materials they used. The interviews followed the thematic structure of the instructional materials (Table 5-2), and teachers were asked to explain whether and how they used each part of the slide presentation. If teachers mentioned that they addressed NOS aspects, the interviewer asked follow-up questions to understand why they decided to teach QP in this way. Through this interview strategy, we got detailed insights into teachers' intentions, goals, and students' responses to each element of their lessons. In this study, we focus only on the goals teachers mentioned when addressing themes related to NOS.

5.2.3 Data Analysis

In the first round, three anonymised interviews, selected on diversity, were individually analysed by three researchers, the two authors, and a university physics education lecturer. First, each researcher filtered out all fragments that were related to NOS teaching and deductively coded for the three NOS aspects on which this research focuses: role of models, tentativeness, and controversies (see Tables 5-1 and 5-2). Additionally, we coded interview passages about NOS aspects that did not completely fit into one of the three targeted NOS aspects. A comparison revealed that all researchers selected the same interview passages and decided that henceforth only the first author would select the relevant passages. To cover the NOS statements that did not fit in the three targeted aspects (see Table 5-2), we agreed on adding two new codes: "Limitations of science" for interview passages in which teachers discussed unanswered questions in QP, and "Science as Human Endeavour" in which teachers highlighted the importance of scientists in historical contexts. This first round of coding hence provided us with interview excerpts on five NOS aspects (see Table 5-4) which we analysed further.

In the second round, all three researchers independently coded the selected interview passage from the first three interviews for (a) specific instructional strategies and (b) reasons and goals teachers mentioned for using – or not using – NOS-related teaching activities. The codes for teaching activities were based on the NOS supporting instructional material: "Narrative/Explanation" (for mainly informative teacher monologues, supported by the instructional material), "Explanatory video", "Concept question" and "Short written task" stem directly from the NOS-supporting instructional material (see Table 5-2), and "Peer instruction" and "Dialogic discourse" specify how the discussion prompts or concept questions were used in the classroom. This part of the coding was deductive and straightforward without any discrepancy between the three researchers. It was therefore decided that the first author coded the remaining interviews. To improve validity and reliability, the first author triangulated the findings with other available data (lesson observations, teacher reports, and digital and written student responses).

Table 5-4 Overview of NOS aspects used instructional activities and related goals in QP lessons

Teacher	Used instructional activity						Mentioned NOS aspect					Related goals in QP lessons				
	Narrative/ Explanation	Explanatory video	Concept question	Peer instruction	Dialogic discourse	Short written task	Role of models	Tentativeness	Controversies	Human Endeavor	Limits of Science	Enhance conceptual understanding	Stimulate thinking / argumentation	Evoke curiosity and interest	Connect to prior knowledge & contexts	Show how science works
Nina			x	x	x		●					x				x
					x			●					x			x
		x			x				●					x		
	x				x					●				x		x
	x				x						●		x			
Emma			x	x	x	x	●					x	x		x	
					x			●						x	x	
	x									●					x	x
Daan	x									●				x	x	
Oliver			x		x		●					x				
Karim	x		x		x		●					x	x			x
	(x)				x				(●)					x		
Liam			x	x	x		●					x			x	
					x			●						x		
Ben	x		x		x		●					x				
	x							●								x
	(x)								(●)					x		x
Hanna	x		x	x	x	x	●					x			x	x
					x			●					x		x	x
		x	x		x				●					x		x
Tim			x	x	x	x	●					x				
		x			x				●					x		x
					x						●			x		
Milan	No NOS addressed															

[a]Legend: (●), (x) = discussed after the lesson with a small group of students

For the coding of goals, we chose an inductive thematic analysis (Guest et al., 2012) to be open for all possible teaching goals which arose during the interviews. A comparison between the coding by the three researchers of the first three analysed interviews revealed differences in how fine-grained each researcher formulated the themes. After discussing all themes of the first three interviews, we agreed on combining some themes with similar meanings in our context; for example, the preliminary themes “make students think scientifically”, “stimulate critical thinking”, “stimulate reasoning”, and “scientific argumentation” were merged to “stimulate thinking and argumentation”. We also agreed that double coding would do justice to the teachers’ statements in some cases. After agreeing on five themes of goals (see Table 5-4), the two authors independently analysed three additional randomly selected interviews. The five goal codes proved to be broad and varied enough to categorise all emerging statements, and disagreements were discussed until consensus was reached. The first author then analysed the remaining four interview transcripts. She consulted the second author for some unclear cases.

5.3 Results

Table 5-4 provides an overview of the results of our interview analysis. Data triangulation shows that teachers’ interview statements about which NOS aspects they addressed and the use of specific teaching activities agree with what we observed in classrooms.

5.3.1 NOS aspects that were addressed in QP lessons

From Table 5-4, we see that nine of the ten teachers addressed one or more NOS aspects and that most teachers (8/10) discussed the role of scientific models in their QP lessons. The tentativeness of scientific knowledge was a topic in the lessons of five teachers.

Also, five teachers used different currently discussed QP interpretations to thematise controversies in science. Two of them only did it after the lesson with a small group of students because they did not want to “waste” time on a subject that is not in the exam syllabus and presumably would not interest many students. Additionally, three teachers stressed the development of QP as a human endeavour, and two teachers explicitly addressed the limits of science. One teacher (Milan), interestingly, the one who holds a PhD in quantum theory, clearly expressed that he did not see any usefulness for NOS in teaching QP.

One teacher (Milan), interestingly, the one who holds a PhD in quantum theory, clearly expressed that he did not see any usefulness for NOS in teaching QP.

> I hardly ever talk about models. […] I don’t think it’s that interesting. I’m pragmatic; quantum mechanics works perfectly, so it is easy to work with. When we interpret it, we lose it. […] Yes, it is a conscious choice not to discuss interpretations. I really don’t find the philosophical interpretation of quantum interesting. I think it is unfinished. (Milan)

5.3.2 Chosen instructional activities in which NOS aspects were addressed

A comparison of the applied instructional activities (Table 5-4) shows that teachers created very different lessons with the material provided, reflecting their personal preferences. For example, in the observed lessons, we could characterise Nina and Ben as talented storytellers; their students listened attentively and participated in the interactive elements of *narratives and explanations*. Although both teachers used monologues, they constantly connected with the students by appealing to their imagination, as illustrated in this passage from Nina’s lesson.

> …try to imagine how it was at that time. [pause] You wrote letters to your colleagues about your thoughts, your ideas. It was not immediately on the internet. [pause] There was no internet.

A different instructional strategy was visible in Hanna, Emma, and Tim's lessons: often walking through the classroom, they skilfully involved students in dialogues, questions, and discussions. Emma explained that this is her preferred way of teaching: "*I don't really like to lecture, so I try to arrange for them to talk to each other*."

Overall, episodes of *dialogic discourse* were the preferred classroom activity to address NOS aspects. We use the term *dialogic discourse* to refer to classroom situations in which teachers acted as facilitators of a whole-class dialogue in which students were encouraged to express their ideas and respond to others. For example, teachers asked students to give argued reasons for their answers to concept questions and ensured that different students were intellectually engaged in the exchange of ideas. As the dialogues evolved, teachers provided direction for digressive discussions and regularly summarised the results. Although in some lessons only a small number of students participated in the discussion, teachers saw benefits for those who only listened:

> I think a lot of students have never thought about it [reasons for different models of electrons], and some of them did not contribute much to the conversation either. But I had the feeling that no one thought it was nonsense to talk about it. Apparently, it's still interesting to listen to what others say. It is a way to construct your own understanding. That's what I like about such a conversation in a class. If you don't participate in the discussion because you're perhaps not that far yourself yet, you can still learn from others. (Hanna)

Concept questions were especially popular to address the role of models. For example, a question about the nature of electrons (see *Figure 5-1*) was used by eight teachers to address the purpose of particle models in different situations. They collected students' answers using the online voting system (six teachers) or by raising hands (two teachers). Five teachers used concept questions to initiate small-group *peer instruction*, as intended in the instructional material; the others directly initiated a whole-class discussion. Reasons given for not implementing peer instruction were limited lesson time and the possibility to guide students' discussions.

> I don't think that's a good idea [to have peer instruction]; a teacher is very much needed to remove misconceptions, to manage the discussions. […] Maybe it will work eventually, but it is not efficient. (Ben)

The three teachers who addressed controversies in science in class used *explanatory videos* to introduce this topic: they appreciated this compact and informative type of presentation.

> I actually knew very little about different interpretations. When I studied QP at university, we only did the math. So, the videos are great, and those filmmakers have more tools to visualise something than I have. (Hanna)

After the students had watched the short videos in class, the teachers engaged them in discussions about different interpretations, students' personal ideas, and the significance of controversies in science.

Liam and Ben, who taught parallel classes, experienced differences in the interest for certain topics between the two groups of students they taught and adapted their lessons accordingly. Ben described students' reactions on a short, animated video on quantum behaviour:

> The first group was very interested; they just thought: wow, something's happening here that I've never seen. They were motivated by the subject. But the other group thought: I don't understand what's happening. They weren't ready yet, I think, for the intellectual challenge.

We also observed teachers struggling to find the right way to teach NOS concepts. Karim, for example, was unhappy because his teaching goals did not seem to fit most of his students' expectations. He wanted to engage them in scientific conversations about QP interpretations, but he did not know how to achieve this goal:

> I think for some students, it's too hard that the level of abstraction is actually too high. And for some students, it's too exhausting. […] There are students with whom you can talk about this [QP interpretations] and who also see the added value. But for most of them, this year, it didn't work; there was no click. (Karim)

The provided *short written task* about the role of models was the least-used teaching strategy. Three teachers recognised the value of putting thoughts on paper and tried it in class, but only one teacher thought she was likely to use it again. The other teachers felt that organising and discussing the writing was too time-consuming.

In summary, those teachers who addressed NOS aspects in their lessons regarded the following teaching/learning activities (supported by the instructional material) as useful: introducing the NOS-related topic through narrative/explanation, explanatory videos or concept questions, and further elaboration of the topic through discussion in small groups (peer instruction) or together with the whole class (dialogic discourse).

5.3.3 Teachers' goals in QP lessons related to NOS aspects

For the conceptual understanding of QP, most teachers regarded it "inevitable" that they would devote lesson time to NOS topics such as the role of models (in the context of wave-particle duality) and believed that NOS aspects could also serve other teaching goals (see Table 5-4). In the following, we compile the goals teachers mentioned for each NOS aspect.

Role of models Most teachers (8/10) felt that it is crucial for students' understanding of QP concepts to actively discuss the role of scientific models.

> For me, the biggest benefit is that it [the discussion on the nature of electrons] revealed that we use models which co-exist and that you can explain different things with them, but that they are all useful scientific models. …. The students realised that it's a model you

> work with. That's new to most of them. Usually, they think: what you learn is how it is. (Liam)

Even in an "intellectually less engaged" class, it was possible to stimulate students' thinking and argumentation.

> There was a real discussion about that you can use one model for one situation and the other for another. […] It was about the double-slit experiment. The question was: how do you know whether it is a wave or a particle. [...] If you manage to make them look at their own arguments, then you will get a fruitful discussion. (Karim)

Tentativeness of scientific knowledge was considered useful by five teachers for achieving the goals to make students think, evoke their interest, or purely to explicitly address tentativeness as an important feature of scientific knowledge. Teachers found that tentativeness was easier to address in QP than in most other parts of the curriculum.

> Sometimes you feel like it [science] is finished, and then all of a sudden, you discover a new world behind it and that it's still happening. Students can see this in quantum physics. For other subjects, you don't talk about it that much because it's mostly classical physics. (Nina)

> A student said: "People in a hundred years' time may find our advanced models stupid and simple." It's nice when they realise this; it's very valuable. (Liam)

Controversies in science Five teachers believed that a discussion of controversies surrounding QP interpretations was a good way to evoke the curiosity and interest of "a certain kind" of students. While some students could enthusiastically philosophise about possible multiple universes, other students disengaged and preferred to be told what to learn. Only one teacher thought that it was essential for all students to address controversies as an inherent characteristic of science in the making:

> In QP, you must talk about different interpretations because otherwise, you don't give an honest picture of where we are right now. (Tim)

Human endeavour According to three teachers in our study, historical contexts and comprehensible human stories in QP are most suitable for evoking curiosity and interest. Several teachers mentioned that the physics textbook they used did not provide a link between the explanations of isolated QP concepts. Therefore, they assumed that understanding the development of theories and models as human endeavour would help students to make sense of new content and connect it to prior knowledge.

> It sticks better, I think. […] historical facts about how they thought or who discovered what give students a framework in which they can place their knowledge. (Daan)

> I think it might be even more important [than learning content knowledge] for them, for the future. This feeling: Science is a fascinating process for curious people [...]. That it's

sometimes nice when reality turns out to be different from what you thought, and perhaps only then they start to find it really interesting. (Ans)

Limits of science Two teachers saw an opportunity to address the fact that science cannot answer all questions. They wanted to provoke students' astonishment and stimulate their thinking by stating that there is no answer to the question of what an electron really is.

> In the past, I got the question: "What am I supposed to do with this? It is just old stuff." Well, now they see that we still can't explain everything. Students find this more exciting. (Tim)

Summarising, teachers' most important reason to address NOS aspects was to enhance students' understanding of QP concepts. The fragmented presentation of QP in physics textbooks was seen as problematic, and consequently, teachers felt that a more coherent narrative of scientists' struggles and wonder during the development of quantum theory is desirable. Teachers thought that this would not only arouse students' curiosity but also help them to relate QP to previously learned concepts and models. All participants mentioned additional educational goals, such as increasing students' self-efficacy and preparing students for the final exam, but teachers did not link these goals to addressed NOS aspects.

5.4 Discussion

A large number of studies in science education have found that NOS is rarely addressed in secondary physics lessons because teachers are not familiar with NOS teaching (Abd-El-Khalick et al., 1998; Galili, Igal & Hazan, 2001), find it irrelevant for students' physics learning (Dunlop & Veneu, 2019), find it too difficult to teach (Henke & Höttecke, 2015) or consider it not possible because of time restrictions and preparation for national exams (Abd-El-Khalick et al., 1998). In our research, in contrast, most teachers indeed chose to address NOS aspects – especially the role of models – in their QP lessons even though they had no specific NOS training and NOS is not mandatory in the curriculum, and even though the lessons took place a few months before the national final exam. This remarkable result requires an analysis of teachers' reasons for addressing NOS aspects in their lessons. But first, we will reflect on possible limitations to the significance of our research.

The literature regularly reports that when interviewed, teachers over-estimate their in-class instructional practices (Fitzgerald et al., 2020; Wubbels et al., 1992). In order to counteract this phenomenon, we observed several lessons to triangulate the interview results. These triangulations revealed no differences between actual and reported classroom activities. Moreover, the participants received the innovative QP learning materials without being specifically alerted to the embedded NOS aspects. Consequently, they had no reason to exaggerate their use of NOS. This is evident in the openness of the interviews. A telling example of this openness is the teacher who made no secret of not using a single NOS-related teaching activity. This attitude of the participants, together with the triangulation of the data, ensures the validity of our findings.

Nevertheless, there are two reasons why our results may not be representative of all physics teachers. First, all participants studied physics and graduated from teacher training programs in Dutch universities. Their master's degree in physics certifies broad academic subject knowledge. For countries where non-specialists teach physics at the upper secondary level, the situation is likely to be different. Second, we recruited our volunteers at conferences on physics education. Therefore, we have a self-selected sample of teachers: As conference participants, their interest in new ideas for physics lessons is likely to be above average. Additionally, they volunteered because they were dissatisfied, at least to some extent, with the way QP is covered in textbooks. On the other hand, this self-selection is unrelated to the extent to which teachers practice NOS instruction in general. The participating physics teachers were not familiar with the term NOS; it is not a common topic in Dutch teacher training or physics degree programs. Accordingly, we have no reason to believe that our participants had much experience with NOS teaching.

The finding that teachers found it worthwhile to address — at least some — NOS aspects in their QP lessons suggests that our ecological instructional material meets Doyle and Ponder's requirements of practicability; it provides concrete and directly usable classroom activities and is adaptable to teachers' instructional preferences and specific classroom settings. In the introduction, we argued that teachers address NOS aspects in physics lessons only when they consider it practical (Doyle & Ponder, 1977) and helpful in achieving their teaching goals (Westbroek et al., 2017). Therefore, we shall interpret the fact from this perspective.

We also explained in I.B.2 that teachers would develop their QP PCK develop their QP PCK with respect to Magnusson's first PCK subcategory, "knowledge and beliefs about the goals and purposes of subject teaching" (Magnusson et al., 1999). Thus, if teachers consider NOS as a learning goal in itself, their QP teaching will certainly be infused with NOS aspects. Indeed, research shows that teachers who want to integrate NOS into regular teaching often lack appropriate contexts and/or strategies (Leden & Hansson, 2019); our teaching materials provide both. The answer to our second research question (on teachers' goals) sheds light on whether the teachers in our study used QP primarily as a means to teach NOS or whether they used NOS aspects to achieve their goals in QP.

We identified five main goals that teachers have when addressing specific aspects of NOS in QP: (1) Enhancement of conceptual understanding, (2) Stimulation of thinking /argumentation, (3) Arousal of curiosity and interest, (4) Connection to prior knowledge and contexts, and (5) Indication of how science works. Only the latter is primarily a NOS-related teaching goal, and only three teachers mentioned it in the interviews. This seemingly low NOS awareness might appear disappointing at first sight, but it shows that teachers who are under pressure to prepare students for the final exam and working in a regular school system in which NOS is not examined have other priorities.

However, the encouraging finding of our study is that teachers discussed NOS aspects in class, not to pursue NOS as a goal in itself, but as a means of achieving other goals. This phenomenon is not mentioned in the literature on the teaching of other physics topics. As well as for students (Stadermann & Goedhart, 2020), it is likely that for teachers, the NOS-related topics are evident here because QP still contains many elements of science in the making. Issues such as the difficulty of finding a suitable model (for wave-particle duality) and the existence of controversies between scientists (on interpretations) do not appear in other topics in the physics curriculum. Teachers were certainly encouraged by the teaching materials to address NOS aspects in QP. Still, it is striking that many teachers in our study addressed NOS aspects that are not part of the final examination. Therefore, we believe the reason for the teachers' use of NOS in our study is likely to be due to their intentions to teach conceptual QP in a good way.

In addition to our findings on teachers' goals in QP lessons, the analysis of the teachers' preferred instructional strategies also provides important insights for NOS implementation in regular physics lessons. We found that dialogic discourse was the most commonly used activity (by 8/10 teachers) to address various NOS aspects in QP lessons. This classroom activity allowed teachers to engage students while moderating the discussion. Interestingly, in a recent review McComas, Clough, and Nour (2020) found that the most effective NOS instructions are "teacher practices that encourage students to be mentally engaged and think about NOS and that assist students in coming to more accurate conclusions" (p.70 emphasis in the original). While our study does not focus on the effect of instruction on students' NOS views, it is encouraging to notice that most of the participants chose a potentially effective NOS teaching strategy. In general, participants in our study were experienced teachers with a well-developed repertoire of topic-specific instructional strategies (part of PCK). These skills enabled them to use strategies like whole-class discussions or peer instruction, even for new, more challenging topics, such as philosophical discussions regarding QP interpretations.

The most popular practical tools for initiating dialogic discussions were the concept questions. The voting system prompted all students to think and decide on an answer. The engagement effect of concept questions (or clicker questions) is well-known in physics education research (Mazur, 1997a). However, in contrast to traditional clicker questions, several NOS-related concept questions had no defined correct answer (see *Figure 5-1*) but were intended to prompt discussion. Although previous research found that such uncertainty in QP classes can be unfamiliar and unsatisfactory for students (Bøe et al., 2018), many teachers in our study managed to encourage students to participate in the discussions. From the literature, it is known that for experienced teachers, NOS implementation and the use of thought-provoking questions for discussions go hand-in-hand (Herman et al., 2013). Again, the combination of teachers' general PCK (judging which concept questions are appropriate for discussion and skills to lead a group discussion) and the provided resources are likely to be responsible for this outcome.

Other frequently used instructional strategies for NOS aspects (used by 6/10 teachers) were narratives and explanations. Teachers' preferences for these traditional strategies concur with research on classroom practice in upper secondary schools' physics (Geelan, 2013). Narratives and explanations give learners guidance and context, especially for new and counterintuitive concepts such as those in QP. In fact, narratives based on the history of science combined with classroom conversations are reported as powerful NOS teaching strategies (Hansson et al., 2019; Kapsala & Mavrikaki, 2020; Williams & Rudge, 2019). Explanatory videos were an easy-to-use alternative. Teachers who considered introducing controversies about QP interpretations, but did not feel competent to explain them, appreciated the videos. This supports Kulgemeyer (2018), who states that explanatory videos have potential learning advantages for students and teachers. Teachers can learn from experts how to introduce complex concepts.

We would also like to discuss two outcomes that might be considered as partial failures of our approach. First, only three teachers discussed controversies surrounding interpretations with the whole class, even though this is arguably essential for conceptual QP. This is similar to what Dunlop and Veneu (2019) found: teachers regarded discussing controversies in science as suitable for "brighter" students only. Additionally, some teachers in our study mentioned that they felt uncomfortable because they knew little about different QP interpretations. Explanatory videos are a relatively successful way to support insecure teachers who want to address this challenging topic. Moreover, if we acknowledge the professionality of experienced teachers, it is reasonable that they can judge if a certain group of students is ready for philosophical discussions or not. This, indeed, indicates that an ecological intervention is beneficial. Second, one teacher, Milan, who holds a PhD in quantum physics, did not address any NOS aspect in his lessons. He thought that the only acceptable context for QP was mathematical formalism. This pragmatic attitude is shared by many theoretical physicists but arguably not helpful to introduce students to QP for the first time (Johansson et al., 2018). This again is a consequence of our ecological approach; if a teacher is convinced that the offered instructional materials do not serve any purpose, they will not use them. To get them to implement some NOS aspects in their lessons, it would take more than just offering new instructional materials; the teacher would have to change their beliefs as well. We tend to accept that teachers are different and that it is not possible for everyone to teach in the desired way.

5.5 Conclusions and Implications

We have argued that conceptual QP and NOS instruction can mutually support each other but that this approach is rarely implemented for various reasons. Our results show that experienced teachers – if provided with practical instructional material – find addressing specific NOS aspects beneficial for QP lessons.

5.5.1 Concept questions for discussing the role of models in QP

Our participants saw understanding the role of scientific models as critical for learning conceptual QP. To visualise quantum entities such as electrons or photons, they are sometimes modelled as classical particles and in other situations as waves. If students do not actively discuss the use and the function of models in QP, they are likely to be prone to various misunderstandings (Krijtenburg-Lewerissa et al., 2020; Krijtenburg-Lewerissa et al., 2017). The teachers in our study found concept questions that challenged students' ideas about models particularly purposeful and practical to address this topic. To facilitate activating teaching strategies such as peer instruction or whole-class discussions, more concept questions on this topic would be helpful.

5.5.2 NOS as a connection between QP concepts and QP as context for NOS

NOS aspects such as tentativeness, controversies, and science as a human endeavour had important roles in many of our participants' lessons: they served as contexts to introduce new QP concepts to students. Teachers who did not feel competent storytellers or those who lacked knowledge about these NOS aspects of QP felt supported by short videos that covered these aspects. In line with research on the connection between teachers' NOS implementation and their pedagogies and beliefs about science education (Bartholomew et al., 2004; Herman et al., 2017), teachers in our study used dialogic practices which stimulate students' reasoning to achieve goals concerning students' intellectual and emotional engagement. Many of our teachers reported that these goals are beneficial for QP learning, and they found that addressing NOS aspects of QP is necessary for students' understanding. Hence, NOS aspects could serve as a coherent framework for all QP concepts at secondary school level, and at the same time, be an ideal example of contextualised NOS instruction. QP might therefore deserve a prominent position in physics curricula.

5.5.3 Implications for supportive teaching materials

Educational research is often criticised for having little effect on instructional practice (Schneider, 2014). Westbroek, Janssen, and Doyle (2017) argue that educational reforms might be more successful (i.e., would be integrated into real classrooms) if the designers of the reform would focus on the goals of teachers. At the same time, they show that these core goals are situation- and teacher-specific. A one-size-fits-all pedagogy of educational reform will, therefore, never be successful. Our research shows that experienced teachers addressed NOS in different ways and to varying degrees, depending on their personal preferences and the perceived needs of their students. We believe that it is crucial to trust and acknowledge teachers' professionality. With this premise, our study shows that buffet-style materials in an ecological intervention can produce clear results because hard-to-change conditions such as curricula, lesson plans, access to digital devices, student populations, and the available teachers can be taken as they are.

We can conclude that any support for teaching conceptual QP – and probably other topics – should be practical, flexible, and adaptable to allow teachers to use it in different situations. In our view, teaching materials should, therefore, ideally serve as a database that supports various possible pedagogies from which experienced teachers can spontaneously create personalised lessons. We see particular potential for a collection of concept questions designed to spark discussions on NOS issues. Further research could show how best to develop and deliver buffet-style teaching materials and support teachers in working with them to prevent one-size-fits-all pedagogies.

5.5.4 Implications for further research on teacher views

There is considerable interest in students' difficulties in learning QP, and an increasing number of teaching approaches for secondary schools have been suggested and tested. However, little research has been performed on teachers' beliefs and practices, and the studies that do exist relate only to particular teaching situations (Bitzenbauer, 2021; Bøe et al., 2016; Bouchée, Thurlings et al., 2021). As teachers are the most important facilitators of learning, their perspective is crucial. Therefore, we suggest more studies on teachers' goals and needs for conceptual QP in different educational systems.

Chapter 6:

General conclusions and discussion

6.1 Introduction

The catalyst for this study was the introduction of qualitative QP into the Dutch upper secondary school (vwo) physics syllabus, which means that QP belongs to the topics that can be examined in the national school-leaving exam. For many teachers, teacher trainers, test developers, and textbook authors, the decision to make QP mandatory for all students in physics courses came as a surprise. Consequently, the introduction raised questions among many of those involved in Dutch physics education. These questions were expressed in lively debates in NVOX, the Dutch science teacher journal, and Dutch physics education conferences before and during the implementation of QP in the vwo curriculum (Biezeveld et al., 2011; Hoekzema, 2017; van Bemmel, 2011b). There were educators who felt that QP was only important for students who wanted to pursue a career in science. Some opponents of the introduction doubted that it was possible to learn QP by vwo students at all. Others disliked that geometrical optics had been removed from the syllabus to make room for QP. In their view, this was the exchange of a versatile, well-tried, well-known, and practical exam component with a new, allegedly abstract, difficult-to-test topic, with which most teachers had no teaching experience (Biezeveld, 2009).

Apart from the discussions about the reasons for teaching QP to pre-university students, there were, on a more concrete level, discussions about what should exactly be in the curriculum and questions from teachers about how QP can best be taught at this level. These issues are interrelated, as the answer to why QP should be taught influences the answers to the question of what and how it should be taught. Because there was little experience (only with motivated PMN teachers and students interested in physics-related university degree studies, see introduction 1.2.) of teaching QP in Dutch secondary schools, many decisions in the introductory phase had to be taken without knowing how they would work in practice. In general, there was a need for knowledge about QP teaching at secondary school level. To contribute to this knowledge, I specifically wanted to bring attention to an often underexposed factor in the teaching and learning of QP, namely learners' views and understandings of NOS.

In the introduction chapter of this thesis, I explained that many of the reasons why QP is considered difficult are related to uninformed or positivist views on aspects of NOS. Many researchers have proposed that there should be explicit attention to the role of models and interpretations in teaching QP (Baily et al., 2010; Bøe et al., 2016; Garritz, 2013; Greca & Freire, 2014a; Greca & Freire, 2014b; Henriksen et al., 2018; Kragh, 1992; Müller & Wiesner, 2002b; Myhrehagen & Bungum, 2016; Pospiech, 2003). However, teachers and educators experienced a lack of knowledge about practical aspects of integrating NOS into QP teaching. In the Netherlands, it was also unknown whether other countries had curriculum documents that emphasised the connection between QP and NOS aspects. Internationally, there was also little research on the assumed benefits of NOS in QP at secondary school level. In particular, it was not clear if students or teachers would perceive such an approach as useful. Therefore, the aim of this thesis was to address the issues discussed above by exploring the integration of NOS in QP teaching from different perspectives.

In the following sections, I summarise how my research goals were approached and which insights were gained. I link these insights to other research on the teaching and learning of QP in different educational settings and discuss how the findings of this PhD thesis contribute to the practice of QP teaching in Dutch secondary schools. Because essential parts of this PhD project are qualitative studies in which I had multiple roles (observer, interviewer, one of the coders, physicist with a background in quantum optics and physics teacher with a positive attitude towards QP), I reflect on my role as a researcher in section 6.4. In section 6.5, I discuss the theoretical and methodological contributions of my research. I reflect on implications for professional development for the topic of QP. Finally, the desiderata for research and the implications of this thesis for future research, teacher training, and teaching materials are presented in 6.5.

6.2 Results

6.2.1 The international curriculum perspective (Chapter 2)

To explore whether Dutch curriculum developers can learn from countries with more experience, I began my research by documenting the current situation of QP in secondary school curricula in different countries. I was especially interested in whether a connection between NOS aspects and QP is visible in the curricula and if curricula from these countries emphasise specific aspects of QP in secondary schools. This simple idea, when implemented, gradually led me into a jungle of national education systems with all their specifics in terms of authorities, school structures, and examinations. Finding and understanding national curricula was only possible with the help of 17 international experts who also helped to fathom characteristics of educational systems that are not written in official curriculum documents. Collecting, selecting, structuring, analysing, and comparing 23 official documents resulted in an overview of QP topics and NOS aspects in the physics curriculum documents of 15 countries. Further analysis yielded the following results:

- Seven of the 17 identified QP topics appeared in the majority of the analysed curricula: discrete energy levels (line spectra), interactions between light and matter, wave-particle duality/complementarity, matter waves with quantitative calculations (de Broglie wavelength), technical applications of QP, Heisenberg's uncertainty principle, and some account of the probabilistic or statistical predictions in QP measurements. This is the *international QP core curriculum* for secondary schools.
- In countries with more comprehensive QP curricula, it was possible to identify three different foci of the extra items: (1) Wave function and mathematical descriptions, similar to traditional university curricula, (2) Atomic theory, which enables a connection to the chemistry curriculum, and (3) Philosophical aspects related to NOS such as the discussion of thought experiments and different interpretations of QP. Only the Norwegian, the Italian, and six German curriculum documents explicitly mentioned NOS-related learning outcomes in QP.

- In contrast to common lists of mandatory test items for QP, NOS aspects were generally formulated as desiderata in the curricula. Explicit links between QP and the intended learning of NOS were scarce; nevertheless, they occurred in a few curriculum documents. These documents contained detailed intended achievement levels for students' ability to evaluate and communicate NOS aspects in the context of QP.

In summary, this research has produced many results that are relevant for various researchers and policymakers. For those educational experts in the Netherlands, who thought that QP is an extra-ordinary subject for pre-university education, this study shows that many countries include QP in their secondary school curricula. It should be noted that this study cannot prove that QP is learnable, as it did not examine what students can learn. It is also unknown what exactly is taught about QP in physics classrooms of different countries. However, this study has shown that many countries consider the topic so important that QP is included in the national curriculum. Indeed, not teaching QP would be an exception in Europe. It also became clear that many countries have years of experience with QP in the final exam.

Considering the initial motivation to learn from others in order to integrate NOS into QP, the main finding is that such an integration is far from commonplace. Nevertheless, some official curriculum documents indeed pay explicit attention to NOS aspects in QP. For policymakers in the Netherlands and countries that plan to introduce QP into their curriculum, the research offers a reliable overview of different possibilities that can help to make decisions (see 6.6. for practical implications).

6.2.2 Students' perspective (Chapter 3)

Having observed that it is not common, nevertheless possible, to include NOS aspects in the requirements of QP in secondary school macro level curricula[14], the next step was to investigate whether students with a sophisticated NOS view would indeed understand conceptual QP better. A mixed-methods approach seemed appropriate to test both students' understanding of QP concepts and their NOS views. A concept test is suitable for testing the level of QP understanding of many students in a quantitative study. However, nuanced NOS views can only be determined qualitatively with individual interviews. The study was conducted with students from different schools and teachers who had taught their regular QP lessons without special attention to NOS. The design of the study was as follows: 240 students were given a 20-item QP concept test especially developed for this study. The students were then divided into high-performing, medium-performing, and low-performing groupings according to the test results. Twenty-four students with different levels of QP mastery were selected for the NOS interviews. The interview questions were set in the context of QP. They covered the following NOS aspects: The role of scientific models, the tentativeness of scientific knowledge, creativity in science, subjectivity in science, and controversies in science.

[14] Van den Akker defines the macro level curriculum as the official intended curriculum written document on nation, system or state level, from which all lower-level curricula of that nation, system or state (for example on school level) are derived (van den Akker, 2010, p.175).

The surprising result of our study was that all students, even those who had answered only two or three questions correctly in the QP test, showed an informed understanding of the five selected NOS aspects in the interviews. This was not to be expected as these aspects were not addressed at all in their lessons. The finding also contradicts the literature, which indicates that only explicit and reflective teaching of NOS aspects leads to informed views. Therefore, the hypothesis that a better understanding of QP is related to more informed views on these NOS aspects could not be confirmed.

6.2.3 Teaching materials and teachers' perspectives (Chapters 4 and 5)

The results presented in Chapter 3 (students' informed NOS views) were obtained in interviews using targeted questions in QP contexts typically not covered in regular QP classes. This means QP contexts have the potential to prompt students to reflect on NOS aspects, and if asked, they indeed come to informed NOS views on their own. However, to enable *all* students to reflect on NOS in physics, teachers need to draw attention to these QP contexts with potential for NOS learning in regular lessons. Since textbooks offer little support for NOS teaching, I have developed QP teaching materials infused with NOS components, which are presented in Chapter 4.

Indeed, students will only benefit from the prompts to reflect on the NOS in these materials if teachers use the possibilities to address NOS in their lessons. Research has shown that teachers only use innovative teaching approaches if they contain concrete teaching/learning activities (*instrumentality*), if the approach fits their usual way of teaching (*congruence*), if it does not involve too much time and effort to implement the innovation (*low-cost*), and if teachers anticipate improvements in achieving their *teaching goals* (Doyle, & Ponder, 1977; Westbroek et al., 2017). The teaching materials have been designed to meet *instrumentality* and *low-cost* requirements by including ready-to-use explanatory videos, concept questions, and computer simulations of QP experiments in a slide presentation. To make the materials *congruent* to different teachers' preferred teaching styles, the materials are adaptable. Teachers can add or delete content, change the order of topics, and choose between different activities to teach QP concepts — explicitly addressing NOS concepts is one option.

Thus, the design of the teaching materials fulfils three of the four conditions mentioned above for the successful implementation of innovations. The fourth condition, that the innovation has to serve teachers main goals, could partly be anticipated. One of the leading teaching goals of all teachers is undoubtedly to prepare their students for the exam. The resources, therefore, offer teaching activities for all exam curriculum items. As NOS elements are not included in the examination programme, the question whether teachers would use NOS aspects to reach other teaching goals remained open. Especially because the participating teachers had not been trained to teach NOS, it cannot be expected that teachers have NOS as a teaching goal.

The participants had the possibility to use the materials in their regular pre-exam physics classes. As the NOS elements — just like all other parts of the materials — were optional, teachers could skip them and only use the QP concept teaching elements. They could even ignore materials and use the textbook instead, which would have been understandable if they had not seen any advantage in using the innovative resources. In Chapter 4, we explored whether teachers used the available NOS learning activities and, if so, what their goals were in doing so.

The findings of the study on teachers' perspectives were obtained through lesson observations and interviews with teachers after they had finished teaching QP for that school year. The results show that nine out of the ten teachers used teaching activities designed to address NOS aspects in reflective learning activities. Most teachers addressed the role of scientific models and discussed the use of wave and particle models in QP. When asked which goals they wanted to achieve, teachers most often mentioned that reflecting on the role of models is essential for students' comprehension of QP concepts, which is naturally the main teaching goal. The teachers who addressed the limits of scientific knowledge and the controversies surrounding the different interpretations of QP — which is not part of the Dutch curriculum — justified this decision with their desire to provide a realistic picture of the current state of physics. Several teachers also addressed the tentativeness of science and historical narratives to give physics a human face and make it more attractive than only working with "cold formulas". Using the NOS activities, most teachers found that students could make more connections between otherwise isolated curriculum items. Although some teachers are more attracted to the NOS aspects than others, the encouraging finding is that most teachers in our study acknowledged the value of some NOS aspects in teaching QP.

6.2.4 Summary of the main results

The international curriculum perspective (Chapter 2): In many, mainly European, countries, QP topics are taught in secondary schools. A cross-national comparison identified a common core curriculum consisting of QP phenomena, fundamental principles, and some technical applications of QP. Beyond this core curriculum, several national curriculum documents have extensions that indicate the thematic focus of a country. Some countries focus on mathematical descriptions of QP, while others emphasise the philosophical implications of QP or show the usefulness of QP for chemistry. In a few national curriculum documents, NOS aspects are also mentioned, thus having a philosophical focus. In these documents, NOS aspects are not included as tenets, but the documents describe the evaluation and communication skills students should acquire for topics such as models or scientific controversies in detail.

Students' perspectives (Chapter 3): In this study, students were asked about their views on the following aspects of NOS in QP: scientific models, tentativeness, creativity, subjectivity, and controversies in science. All students, regardless of their conceptual understanding of QP, expressed informed views on these NOS aspects. This was a surprising outcome because these NOS aspects had not been explicitly addressed in the participants' lessons.

Teaching materials (Chapter 4): QP teaching materials were developed to investigate teachers' views on addressing NOS in their QP lessons (Chapter 5). These teaching materials were designed as buffet-style resources to make them compatible with the instructional preferences of teachers and suitable for various educational settings. The resources use various teaching strategies from educational research on NOS learning and students' difficulties with QP. The adaptable materials offer several easy-to-implement NOS teaching strategies and are provided online and are freely available for teachers.

Teachers' perspectives (Chapter 5): Most participating teachers used a variety of reflective NOS teaching activities from the provided materials (Chapter 4). This depended on the educational setting and the personal preferences of the teachers. Nine out of ten teachers stressed that it is essential to discuss the role of models in QP to help students understand QP concepts such as wave-particle duality. Teachers also mentioned the following reasons for addressing NOS aspects: engaging students in argumentation and reasoning, connecting separate curriculum items, and making physics more "human".

6.3 Conclusions and Discussion

The central idea for this PhD project was the notion that QP is inherently linked to NOS aspects, which are usually rarely addressed in physics classes. A literature review showed that many researchers stress that this interconnectedness requires NOS aspects to be addressed in QP teaching. However, there is little knowledge about the actual use and practical benefits of such an approach.

The sobering assessment of the current state of teaching NOS in QP could be summarised as: Although the necessity to link QP and NOS aspects in teaching seems obvious in theory, in practice, only a few countries have clear NOS learning goals in the QP section of their official national curriculum documents. Consequently, in many countries (including the Netherlands), it is not supported in textbooks (Borin, 2021). Teachers rarely address NOS in their lessons, and most students do not, therefore, have the opportunity to engage with NOS-related questions while learning QP.

However, this PhD research has shown that integrating NOS with QP teaching offers promising results in practice. I will discuss the current situation first and then explain how my PhD research can contribute to the added value of QP in secondary education, also for pupils who will not continue in science or engineering.

6.3.1 The current situation of NOS and QP in the Dutch syllabus and textbooks

The Norwegian, the International Baccalaureate®, and some German macro level curriculum documents show that it is indeed possible to draw attention to NOS aspects in QP. I see two main reasons why NOS is currently not explicitly mentioned in the Dutch QP syllabus: the structure of the physics syllabus and the novelty of QP for curriculum designers and textbook authors. Because textbooks are based on official curriculum documents and are the most visible educational resources for teachers and students, I discuss their role together with the syllabus.

In the current structure of the Dutch vwo physics syllabus, the requirements of students' evaluation and communication skills are mentioned in *Domein A*, a separate chapter to those dealing with traditional physics content. Some NOS-related learning goals are given in this *Domein A* (College voor Toetsen en Examens, 2019, 2.2. Domein A), for example, "being able to evaluate models" (2.2. Domein A7.3) or "being able to distinguish between scientific arguments, normative societal considerations and personal opinions" (2.2. Domein A9.2). However, there is no direct connection to the specifications for QP (College voor Toetsen en Examens, 2019, 2.2. Subdomein F1). This could be justified since NOS-related learning goals are undoubtedly applicable for all topics in the physics curriculum. This PhD research showed, though, that students and teachers experience the need to address NOS aspects in QP more than in other topics. This is most likely because the QP topics in the curriculum show more elements of *science in the making* than others. Additionally, topic-specific NOS aspects emerging from the content (van Dijk, 2014) should be taught in contexts (McComas, William F. et al., 2020), and, therefore, a more explicit connection to NOS in the exam syllabus also seems necessary. I come back to possibilities to do so in the implications (6.5.4) of this thesis.

In addition, there had not been a long try-out for testing QP in the national exam. The first Dutch QP curriculum (Groen et al., 2014) was based on the experience of pilot curricula, which originated from the 1990s (see Introduction 1.2). Similar to physics courses in Sweden (Danielsson et al., 2020; Johansson et al., 2018), the academic physics background of the Dutch curriculum designers did probably not prepare them for a non-mathematical approach of QP. Also, multiple QP interpretations and other philosophical questions were probably not addressed when they followed academic physics courses. This pragmatic view of QP is reflected in the secondary school pilot curricula (PMN and NiNa). The curriculum designers managed to present QP learning goals without mathematical formalism, but addressing NOS aspects was avoided or simply did not occur to them. The same might be true for those authors who wrote QP chapters in Dutch textbooks. Most of these textbook authors were recruited from the participants of the NiNa project (see Introduction 1.2). They had some experience with teaching QP, but probably did not have much time to scrutinise the literature for different pedagogical ways to present QP. As a result, for example, most Dutch textbooks present the photoelectric effect as a compelling reason why light must be made up of photons. This claim is not only wrong from a physics point of view (Jones, D. G. C., 1991; Passon & Grebe-Ellis, 2015), but it also is historically incorrect (Klassen, 2011; Niaz et al., 2010) and conveys an undesired NOS view (Borin, 2021). Even if authors want to emphasise NOS aspects, research shows that in the interplay of authors, editors, and publishers of commercially produced textbooks, marketability factors can lead to an undesirable presentation of NOS (DiGiuseppe, 2014).

Thus, there is currently little attention for NOS aspects in the Dutch physics exam syllabus and textbooks. Even in the Dutch handbook of physics teaching, Dekker and Kortland write about

NOS: “As far as we know, this learning goal [Domain A] leads a rather dormant existence in physics textbooks.”[15] (Dekkers & Kortland, 2017, p.2). However, this situation could change. This research could contribute to this change as it has identified some good practice cases in the curricula of other countries (Stadermann et al., 2019). Additionally, the work of Borin (2021) shows that British textbooks contain several exemplary accounts of NOS in their QP chapters and that these could serve as inspiration for Dutch textbook authors. One prerequisite for such a change in curricula and textbooks is an awareness of the relevance of NOS in QP. In the following section, I discuss the results from my research that highlight the relevance of NOS in QP for students and teachers.

6.3.2 NOS and QP for students and teachers

This thesis does not provide direct evidence that QP lessons infused with NOS lead to a better understanding of QP among students. However, when exploring whether there is indeed a link between students’ understanding of NOS aspects and QP, another exciting insight emerged. In the research presented in Chapter 3, all students expressed well-informed NOS views regardless of their level of QP comprehension. In the context of QP, all interviewed students had no problem understanding and even appreciating, for example, that physics cannot explain everything and that human factors influence the course of science. This surprising but intriguing result demonstrates that QP could be an ideal vehicle for addressing NOS in physics lessons.

According to McComas et al. (2020), the most efficient development of informed NOS views is achieved if students regularly get highly contextualised, explicit NOS instructions with a high level of reflective learning. The history of science offers ample possibilities to show NOS in the development of science. However, it is often difficult for teachers to integrate authentic examples in their lessons because “history is more complicated than we often think. It is easy to give wrong messages: science makes steady linear progress; modern scientists are so much smarter than these old folks who got so much of it wrong.” (Dobson, 2000, p.1). The way of covering history in science teaching, as portrayed by Dobson, can be found regularly in textbooks. This *quasi-historical approach* (Kragh, 1992; Whitaker, 1979) might cause more problems than it solves for NOS teaching. Researchers found that even if NOS aspects, such as tentativeness of science and controversies in science, are correctly addressed in a historical context, it is difficult for students to “put on a different thinking cap”. Most young learners do not see the significance of historical, scientific debates because these questions were solved long ago, and the views of some historical figures might not seem scientific at all to students (Abd-El-Khalick & Lederman, 2000). Even if teachers receive training and resources for correct and engaging ways to address the history of science in their lessons, they experience the teaching of this as a disproportional burden (Höttecke et al., 2012).

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[15] Original text in Dutch: ‘Voor zover bekend, leidt deze eindterm [*Domein A*] in natuurkundemethodes een nogal sluimerend bestaan.’

Some researchers advocate including socioscientific issues (SSIs) in science teaching, which would make NOS more relevant and topical for students (Holbrook & Rannikmae, 2007; Khishfe, 2014). While SSIs avoid the conceptual distance of students to NOS concepts, it creates other challenges. The emotional involvement of students and teachers can lead to different complex conflicts between personal values, the urge for decision-making and human needs. Students' emotional proximity to a SSI also influences their ability to reason. Addressing these issues is undoubtedly valuable in secondary education; however, the goals of NOS teaching could become easily blurred with other unintended issues. Additionally, these topics put an even higher demand on teachers' background knowledge and pedagogical skills to handle potentially emotionally charged student discussions.

QP can also play an essential role in avoiding the difficulties of contextualised NOS teaching mentioned above. Although this research started with advocating the necessity of integrating NOS for students' understanding of QP concepts, I gradually realised that, conversely, QP could help develop a better understanding of NOS. The comprehensive discussion in Chapter 3 concludes that three main factors caused students to understand NOS aspects: (1) The student interviews as such were highly contextualised and reflective NOS learning activities. The students, for example, explained in their own words what they thought precisely happened in the double-slit experiment. Additionally, they were asked to give their opinion on different interpretations of QP to which they had briefly been introduced. (2) In contrast to historical examples of long-ago resolved controversies, the issue of explaining or interpreting the results of the double-slit experiment appealed to students in this study. They understood the problem and also appreciated why it had not been solved yet. (3) For students, the double-slit experiment was less emotionally charged, unlike many SSIs. They saw it more like a puzzle they wanted to resolve, and they could comprehend the main ideas of different QP interpretations.

Finally, the question remains whether teachers would see addressing NOS aspects as an extra burden in teaching QP. For this, the research described in Chapter 5 gave encouraging results because nine out of ten teachers voluntarily addressed NOS in their QP lessons. In the interviews, they explained that they did this because they thought that it was necessary to assist students' understanding of QP content and to develop scientific literacy. Certainly, one could argue that the teachers were supported with appropriate teaching materials, which tempted them to address NOS in their lessons. Good teaching materials are indeed helpful, or even a prerequisite, for teaching NOS. However, two years after I finished the study on teachers' perspectives, the resources were still used by teachers. Participating teachers also share the materials with colleagues, and I regularly receive emails from teachers with questions about the included NOS teaching activities from teachers. Therefore, the most important conclusion of the study on teachers' perspectives is that the teaching materials seem to have fulfilled a need of the participating teachers and others who have come into contact with them.

I started this discussion with a sombre description of the current situation of NOS in QP teaching. However, now the conclusion is that students might be deprived of the benefits from discussing NOS aspects of QP, *mainly* because teachers lack knowledge and strategies do address QP aspects that are not supported by teacher training or textbooks. In 6.6, I will suggest how this issue could be tackled.

6.4 Methodological reflections

Coming from a research background (25 years ago) in applied physics, experimental quantitative research was my frame of reference when I began this PhD research. Qualitative research is a completely new terrain for me, and developing procedures and making research decisions felt uneasy in the beginning. Well-known qualifiers from quantitative research such as validity, reliability, generalisability, and objectivity cannot be used in the same way in qualitative research. The very fact that, for example, an interview or a classroom observation can never be reproduced under the same conditions shows that qualitative research needs other criteria to prove its soundness. *Transparency* and *self-reflection* are the essential means to demonstrate qualifiers such as sincerity and credibility in qualitative research (Creswell & Miller, 2000; Tracy, 2010).

6.4.1 Transparency

In an attempt to be transparent, collaboration with other researchers and co-authors was crucial. For example, two additional researchers coded all of the interview data (in Chapter 3 and Chapter 5), which made clarifying coding categories necessary. The mere fact that there had been regular and detailed communication about decisions in the research planning and data analysis during the research process required openness and clarity between me and my co-researchers. Throughout the process of writing the research manuscripts, this mutual clarity was translated for the readers into *thick descriptions* (Geertz, 1973) in each of the articles (Chapter 2, 3 and 5). These thick descriptions include detailed explanations of the methods used, examples of original data (for example, extracts from interviews) and discussions of choices made in collecting and analysing data. Each chapter also contains detailed descriptions of the context of the study and limitations of the research, such as brief descriptions of the education system in the Netherlands (Chapter 2), students background knowledge and educational level (Chapter 3), and teachers' experience and their initial teacher training (Chapter 5). By making these data explicit, readers can decide about the transferability of the results to their own situation. More qualifiers are addressed separately in individual chapters of this dissertation. These chapters are published as research articles in peer-reviewed journals, with credibility criteria for the various studies' context and content explained in each article.

6.4.2 An account of the researcher's self

Another crucial aspect in this dissertation is the "lens of the researcher" (Creswell & Miller, 2000). In social sciences, where qualitative studies are common, researchers are naturally more aware of human and social influences on the interpretation of data. Tracy states that one criterion for excellent qualitative research is that it is characterised by "self-reflexity about subjective values, biases and inclinations of the researcher(s)" (Tracy, 2010, p. 840). In the same vein, Denscombe (2014) advises reflecting on the *researcher's self* and questioning the extent to which the research has been done with an open mind.

The intertwining of these two topics is especially evident in the research on teachers' perspectives, in which I had multiple roles: In the preparation of the study described in Chapter 5, I recruited the participating teachers, developed the teaching material, and explained the intended use of the material to the participants. During the study, I observed lessons, conducted teacher interviews and performed the central part of analysing data and writing the manuscript of the research paper. All of these roles require reflection, all the more so because I am a physics teacher myself; moreover, a physics teacher with interest, knowledge and enthusiasm for QP.

It could have been problematic for the participating teachers to speak openly about their own thoughts because they probably knew that I am in favour of introducing QP in Dutch secondary physics education. At the same time, I do not think that teachers were "afraid" of me or my judgement. There are many indications that show that they trusted me. For example, they allowed me into their classes, knowing that I would document and analyse their in-class behaviour. Also, interviews often became conversations between colleagues from different schools or even friends. In some interviews, my questions inspired teachers to talk about other topics; or a teacher asked about my opinion on something. Only thanks to a well-prepared interview guideline, I managed to get answers to all of the planned questions. Fortunately, the interviews were held after the lessons. Therefore, our conversations could not influence the course of the lessons which were part of the research. However, my position in this research has been far away from an objective distant interviewer. At the same time, my insider – or friend – role has advantages for the research. Interviewees told me about their problems and took the opportunity to reflect on their own teaching. Being a physics teacher, asking other physics teachers in an open and relaxed atmosphere might be the closest one can get to a nuanced understanding of teachers' perspectives.

6.5 Theoretical and methodological contributions

This dissertation combines the two research fields of QP teaching and NOS teaching. Although previous research has described the role of specific NOS aspects in teaching a QP topic (Baily et al., 2010; Niaz & Rodríguez, 2002), some researchers used the context of atomic models to assess students' NOS views (Lederman, N. G. & O'Malley, 1990), and a framework for definitions of NOS in Physics (including QP) has been proposed (Galili, I., 2019), there has not been a comprehensive exploration of the benefits of combining QP and NOS in teaching. This PhD project approaches the connection between conceptual QP and NOS aspects from different viewpoints. It contributes to the knowledge about QP and NOS in the official curriculum documents of different countries and gives insights into students' and teachers' views on NOS aspects.

Table 6-1Overview of NOS aspects in QP addressed in this thesis

NOS aspect (and origin)	Example of intended NOS views	Examples of how the NOS aspect can be visible in secondary school conceptual QP
Methodology (e.g., experiments and hypothesis) ***Int.***	Diverse methods (among others, experiments) are used to develop scientific knowledge. Hypotheses are tentative explanations for scientific problems based on currently accepted science and creative thinking. Empirical observations support rather than prove scientific theories.	The methods used in classical physics (relation between experiment and theory) apply as well in QP. Thought experiments were an essential means to discuss fundamental concepts in developing QP and eventually led to various quantum entanglement experiments.
The role of scientific models ***Int., Stu., Res., Tea.***	Scientific models are not a complete representation of reality, but they explain or predict certain aspects of natural phenomena.	Depending on the situation, either the wave model or the particle model is useful to describe electrons or light. Some properties of atoms can be illustrated with the Bohr model, but to explain the existence of atomic energy levels, we use the *particle in a box* model.
Tentativeness of scientific knowledge ***Int., Stu., Res., Tea***.	Scientific knowledge is, in principle, always open to development, warranted change and improvement.	It is not possible to explain these quantum phenomena with Newtonian physics.
Creativity in science ***Int., Res.***	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 ***Stu., Res.***	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 ***Int., Stu., Res., Tea.***	Discussions and disagreements about scientific ideas are essential in scientific development. Different interpretations may exist.	There is no consensus about the (need for) interpretations of quantum theory. Different scientists adhere, for example, to the Copenhagen, the pilot wave, or the many-worlds interpretation.

- Bold abbreviations indicate the chapter in which each NOS aspect is addressed:
  Int. = International curriculum perspective (Chapter 2), ***Stu.*** = Students' views (Chapter 3), ***Res.*** = Resources / Teaching materials (Chapter 4), ***Tea.*** = Teachers' views (Chapter 5).
- The content of the second and third columns might be slightly different in each chapter of this thesis.
- The aspect "Methodology" was only part of the first study in which intended NOS views (second column) are not in the table. To make the here presented table complete, the text in square brackets has been added.

6.5.1 Theoretical contributions

The empirical contributions of this thesis concern, first of all, the link between QP and NOS. I analysed the literature on both students' conceptual difficulties in QP and teaching approaches that include elements of the philosophy and history of science to address these difficulties.

Then, I connected characteristic conceptual QP items with aspects of NOS. These connections formed the theoretical framework of all three empirical studies (Chapters 2, 3 and 5) on different perspectives on teaching NOS aspects in QP. Each chapter that describes a component of this PhD project contains a table that clearly shows the link between QP and the NOS aspects under investigation. Table 6-1 is a compilation of all of these tables.

Certainly, there are more or different connections between secondary school QP and NOS aspects possible. However, I focussed on NOS aspects that are underrepresented in other parts of the secondary school curriculum. These aspects mainly stem from the clusters "Human elements of science" and "Domain of science and its limitations" in the McComas (2020) diagram of NOS aspects, shown in *Figure 6-1*. The overview in Table 6-1 is neither static nor does it show the only existing connections between NOS and QP. However, this example of linkages between NOS and OP can be helpful as a framework for further research (see 6.5.3). Indeed, it already has been used in a study of the representation of NOS on QP in secondary school textbooks in different countries (Borin, 2021).

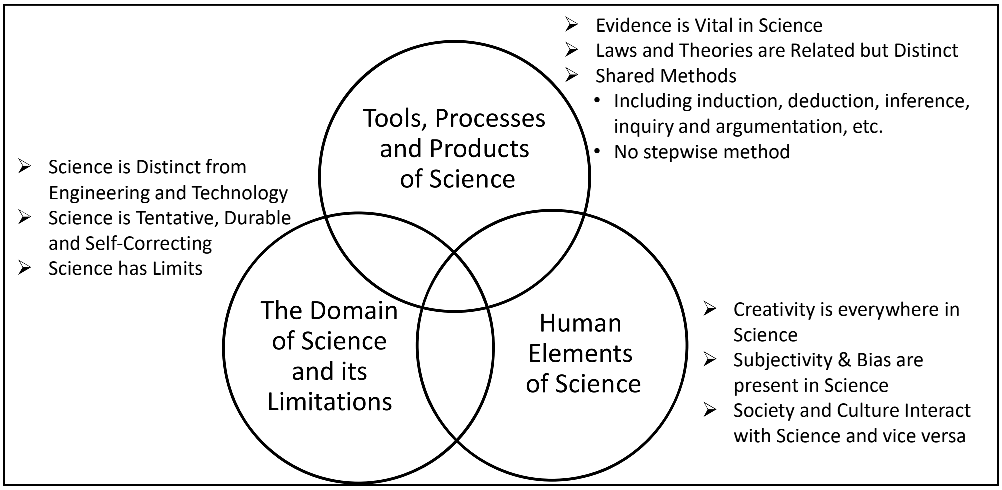

Figure 6-1 The major sub-elements or key NOS aspects often recommended for inclusion in science instruction, arranged in three related clusters (according to McComas, W. F., 2020). (This figure has been introduced as Figure 1-7. In the introduction of this thesis.)

Subsequently, a new construct has been developed from the study on international secondary school curricula: the common core curriculum for QP. The core curriculum represents the currently most commonly mentioned QP topics in the investigated countries. This construct of a core curriculum has gained more substance by analysing several possible extensions of the core curriculum. These extensions represent different perspectives on teaching QP and can be used and extended in future research.

6.5.2 Methodological contributions

Chapter 5 of this thesis offers an innovative methodological approach to test and develop the practicality of educational innovations: the ecological approach. 'Ecological' in this context is borrowed from psychology. 'Ecological psychology' encompasses several psychological approaches in which the interaction between a person and a context, often referred to by the term ecology, is central. In general, an ecological approach acknowledges how the structure of a context both limits and opens up possibilities of action and how a person in purposeful interaction with that context can discover and realise possibilities of action. Elements from ecological psychology have been used to describe and support teachers in educational innovations (Barker, 1968; Doyle, 1977a; Janssen et al., 2013).

In this framework, different school classes form different environments, and in combination with different teachers, they create different ecologies. A teacher will experience different possibilities (or affordances) for action in different environments. Experienced teachers will try to take the whole teaching ecology into account: limited lesson time and technical equipment, classroom atmosphere, curriculum requirements, the assumed interest and intellectual level of the students. Teachers might, for example, discuss a thought-provoking philosophical question with interested students in one class but will only teach topics that are covered in the curriculum in another class. This person- and situation-dependent behaviour is supported by the adaptable teaching material (discussed in Chapter 5).

While, at first sight, such an ecological teaching intervention has mostly practical advantages in a classroom setting, it also offers methodological possibilities for research. Educational studies often show that certain innovative teaching methods work well in principle. However, it all too often transpires that not much is left of the original, innovative idea in everyday teaching. Recent educational research acknowledges that many innovations fail in the reality of everyday school life because the innovations might be well-grounded in learning theories but are not practical for teaching (Breuer, 2021; Westbroek et al., 2017). It is expensive, inefficient and frustrating to develop innovations such as theoretically-sound learning strategies or socially-desirable learning objectives if they are finally not used in the classroom. An ecological teaching intervention could help researchers filter out which part of an innovation has the potential to be accepted by teachers. After an initial practicality check, the research could concentrate on improving the most practically-promising elements of an innovation.

6.6 Practical implications of this thesis

This PhD project explored the advantages and possibilities of teaching NOS aspects in conceptual QP teaching. As the studies in this thesis cover a broad spectrum of perspectives on NOS in QP teaching, there are various potential and actual implications.

6.6.1 Implications for physics education research

Before discussing the implications arising from the thesis as a whole, I would like to turn to the study presented in Chapter 2 (Stadermann et al., 2019). To my knowledge, Chapter 2 provides the first in-depth comparison and analysis of secondary QP curricula in different countries, and it seems to have filled a knowledge gap internationally. This study has already received some academic attention in international physics education research (20 citations during the first two and a half years since publication, according to the bibliographic database Scopus). Additionally, I have received positive feedback at international physics education conferences (GIREP 2017 and 2019) from policymakers, researchers and physics educators. For various reasons, the results of the research appear to be relevant for different groups:

- Secondary education curriculum developers because there was previously no overview of the content of advanced physics courses in different countries. The research shows which topics are commonly taught on this level and might inspire countries that do not currently have QP in their curriculum to include it.
- College or university lecturers who teach first-year physics students as they can get an idea of what prior knowledge can be expected from students enrolling from different countries.
- College or university lecturers who teach courses on introductory quantum physics for non-science majors. The analysis of secondary school curricula might give them an overview of the possibilities for a QP course without mathematical formalism. Depending on the intended character of the course, lecturers could, for example, choose the topics of the core curriculum (see 2.5.1) or items from the 'philosophical extension' (see 2.5.2).
- Science education researchers, because the study shows interesting trends for teaching quantum physics on a conceptual basis, which might open new research fields.

In Chapter 2, 17 QP curriculum items were identified and categorised in five themes: fundamental QP principles, phenomena and applications, atomic theory, wave function or other mathematical representations, and philosophical aspects of QP. These themes are useful for follow-up research. They have been used, for example, to develop categories of physicists' associations with QP in a mind map study (Winkler et al., 2021). The above-mentioned themes will also be used to create a database of QP curriculum items from all countries that participate in the European flagship project QTEdu. (Anonymous 2021).

It must be said that most of the interest in the publication in Chapter 2 is in the overview and comparison of QP in secondary school curricula. Only a few of the articles which cite the paper (Bouchée et al., 2021; Bouchée, de Putter - Smits, L. et al., 2021; Onorato et al., 2021; Pereira & Solbes, 2021; Scotti di Uccio et al., 2020) pay attention to the focus on NOS in QP.

The thesis as a whole has shown, most importantly, that there is considerable potential in combining QP and NOS in secondary school physics lessons. To explain what this could mean for secondary education, I return to the critical report by Osborne and Dillon (2008) on education in Europe, from which I quoted in section 1.4 of the Introduction. The authors also formulate a vision of a desirable school science curriculum:

> Such a curriculum – which serves the needs of developing a scientifically literate public – would be significantly different from that currently offered throughout most of Europe. It would recognise that, for the overwhelming majority, their experience of learning science in school will be an end-in-itself – a preparation for living in a society increasingly dominated by science and technology and not a preparation for future study. Its content and structure could then only be justified on this basis. It would represent an introduction to the cultural capital offered by science, its strengths and limitations, and develop an understanding, albeit rudimentary, of the nature of science itself. Our view is that all students, including future scientists, need this form of education at some stage of their school career.
>
> However, the content of the science curriculum has largely been framed by scientists who see school science as a preparation for entry into university rather than as an education for all. No other curriculum subject serves such a strong dual mandate. The result for teachers is that they must work with the tension that exists between these twin goals – the needs of future scientists and the need of the future non-scientists. As we have argued earlier, different goals require different approaches. (Osborne & Dillon, 2008, p.21)

Currently, many countries consider it important that young students learn about quantum physics, and there is much research on innovative QP teaching approaches. However, many innovations seem (again) to be created by scientists for future scientists. Regularly, QP is seen as a topic accessible only for “nerdy” students (Johansson, 2018), or the goal of an educational initiative is explicitly to prepare a future quantum workforce (Plunkett et al., 2020). This PhD research has highlighted a rather different facet of QP. It seems very much worth investigating further what the connection between QP and NOS can offer for all students. There are, for example, some approaches to introduce QP to younger students (Kaur, Blair, Moschilla, & Zadnik, 2017; Schorn & Wiesner, 2008). The question arises whether it would be feasible for younger students to reflect on NOS aspects in QP.

Some teachers who participated in this research mentioned that philosophical discussions fascinated students who would not normally be interested in physics. This anecdotal observation could be further investigated to ascertain whether NOS aspects of QP attract a more diverse group of students to science.

Finally, the research in Chapter 5 revealed that the participating teachers felt that in order to have a good understanding of QP, it was necessary to discuss some NOS aspects in class. When more teachers explicitly address NOS in their QP lessons, it will be possible to investigate whether this leads to a better understanding of QP content.

6.6.2 Implications for the Dutch physics curriculum

While some countries’ curriculum documents contain explicit descriptions of NOS aspects in QP, this is not the case in the Netherlands. It would be helpful if the Dutch vwo curriculum for QP would integrate explicit learning outcomes that stimulate reflections on NOS aspects. The role of models in QP and the existence of different QP interpretations should be integrated into the final exam requirements. Therefore, I recommend integrating these NOS aspects into the Dutch upper secondary physics syllabus. There are two main reasons for this recommendation.

First, this PhD research (see Chapter 3) demonstrates that QP is a valuable context to reflect on students' views on NOS aspects that are less obvious in other parts of the physics curriculum. For example, addressing different interpretations of QP can demonstrate science controversies. Likewise, discussing the reasons for different models of light and matter can serve as examples for the tentative character of scientific knowledge. If teaching NOS is to be a goal for secondary school physics education — as I think it should be — it must be visible in the official learning goals.

Second, almost all participants in my study on teachers' views on NOS in QP (Chapter 5) thought it was essential to address some NOS aspects while teaching QP. Students must understand the role and limits of scientific models in QP, especially because we use wave- and particle models for quantum entities. If such NOS aspects are not explicitly mentioned in the syllabus, there is a strong likelihood that NOS will also be neglected in the textbooks and that most teachers will therefore not think of addressing NOS aspects in class.

The overview of international documents in Chapter 2 can serve as a source of inspiration for curriculum developers. Concerning the integration of NOS learning goals in QP, the curriculum document from North Rhine-Westphalia (Ministry of Education of the state of North Rhine-Westphalia. 2014). could serve as a good example, also for the Netherlands. This curriculum document envisages, as a desired learning outcome, that students will be able to give examples of the limitations of wave and particle models for light and electrons. Students should also describe and discuss the controversy surrounding the Copenhagen interpretation and the wave-particle duality.

6.6.3 Implications for textbooks

This research showed (see Chapter 5) that teachers — if they get a chance — are happy to use teaching materials in which QP and NOS learning are intertwined. The participants found that understanding the role of models is essential for learning QP. Some also stated that the existence of different controversies highlights the current state of research on the foundations of QP and offers the opportunity to discuss subjectivity, tentativeness, controversies, and creativity in science in the making. Others explained that addressing this 'soft side' of physics would make the subject more attractive to diverse students.

Therefore, appropriate teaching materials should be available to enable teachers to make their own choices. For example, different interpretations of QP should be addressed in textbooks. Additionally, instructional materials should be available to support teaching activities that engage students in reflective thinking and argumentation with and about models. Ideally, teaching resources should be adaptable to individual teaching environments without much effort.

6.6.4 Implications for teacher training and professional development programs

Interviews with teachers (see Chapter 5) revealed that they were unaware of the existence of the term NOS, but several felt that it would help to discuss historical, philosophical and epistemological issues in QP. To make student teachers aware of the importance of NOS, teacher training at all Dutch institutions should prepare students for teaching NOS aspects in QP and other science topics.

Professional development training should be provided for in-service teachers who do not have sufficient background knowledge and PCK of conceptual QP. A very important criterion to make such training successful is practicality. Teachers should receive instructional materials and suggestions for teaching strategies that can be directly implemented in various classroom ecologies.

During the development of the teaching materials (see Chapter 4) and in teacher interviews (see Chapter 5), I noticed that teachers like to talk about their own method of teaching and have many ideas to improve existing teaching materials. This could be an inspiration for the format of teacher development training. Teacher development teams at some universities already come together regularly to develop instructional materials. To do this from scratch might be too challenging for a relatively new and allegedly complex topic. Therefore, it could be helpful if such teacher development teams get appropriate instructional materials as a basis to develop their own materials. Additionally, they should have the possibility to discuss difficulties with an expert.

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Appendices

Appendix 2-A: references to the analysed curriculum documents

Country	Curriculum document
	(Websites were accessed in the period 01-01-2018 to 11-11-2018)
UK (England,)	English Office of Qualifications and Examinations Regulation. (2017). GCE subject level conditions and requirements for science (biology, chemistry, and physics). Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/600864/gce-subject-level-conditions-and-requirements-for-science.pdf
	AQA Education. (2017). AS and A-level physics. Retrieved from https://filestore.aqa.org.uk/resources/physics/specifications/AQA-7407-7408-SP-2015.PDF
UK (Scotland)	Scottish Qualifications Authority. (2015). Advanced higher physics Course/Unit support notes. Retrieved from https://www.sqa.org.uk/files_ccc/AHCUSNPhysics.pdf
Netherlands	National Board Of Examination CvTE. (2017). Natuurkunde vwo | syllabus centraal examen 2019. Retrieved from https://www.examenblad.nl/examenstof/syllabus-2019-natuurkunde-vwo/2019/vwo/f=/natuurkunde_2_versie_vwo_2019.pdf
International Baccalaureate	International Baccalaureate Organisation. (2014). Diploma programme physics guide: First assessment 2016. Cardiff, Wales: International Baccalaureate Organisation (UK) Ltd. http://www.holyheart.ca/wp-content/uploads/2016/10/IB-Physics-Guide-2016.pdf
Denmark	Danish Ministry of Education. (06-2013). Fysik stx. Retrieved from https://www.retsinformation.dk/forms/r0710.aspx?id=152507#Bil23
	English translation (Current STX curriculum) in: The Danish Evaluation Institute. (2009). The subject of Physics from an international perspective. Retrieved from https://www.eva.dk/sites/eva/files/2017-08/Physics from an international perspective.pdf
Norway	Norwegian Directorate for Education and Training. (valid from 01.08.2006). Physics - program subject in programs for specialisation in general studies (FYS1-01). Retrieved from https://www.udir.no/kl06/FYS1-01?lplang=eng
Finland	National Board of Education. (2015). Lukion opetussuunnitelman perusteet 2015 (the basics curriculum 2015) 5.9 fysiikka. Retrieved from http://www.oph.fi/download/172124_lukion_opetussuunnitelman_perusteet_2015.pdf
	Older version in English: Finnish National Board of Education. (valid from 01-08-2005). National core curriculum for general upper secondary education. Retrieved from http://www.oph.fi/download/47678_core_curricula_upper_secondary_education.pdf

Germany	The Standing Conference of the Ministers of Education and Cultural Affairs of the Länder in the Federal Republic of Germany. (2004). Einheitliche Prüfungsanforderungen in der Abiturprüfung Physik. Retrieved from https://www.kmk.org/fileadmin/veroeffentlichungen_beschluesse/1989/1989_12_01-EPA-Physik.pdf
Germany (Baden Württemberg)	Ministry of Culture, Youth and Sports Baden-Württemberg. (2016). Bildungsplan des Gymnasiums Physik. Retrieved from http://www.bildungsplaene-bw.de/site/bildungsplan/get/documents/lsbw/export-pdf/depot-pdf/ALLG/BP2016BW_ALLG_GYM_PH.pdf
Germany (Lower Saxony)	Lower Saxony Ministry of Education. (2017). Kerncurriculum für das Gymnasium Physik. Retrieved from http://db2.nibis.de/1db/cuvo/datei/ph_go_kc_druck_2017.pdf
Germany (North Rhine–Westphalia)	Ministry of Education of the state of North Rhine-Westphalia. (2014). Kernlehrplan für die Sekundarstufe II Gymnasium/Gesamtschule in Nordrhein-Westfalen Physik. Retrieved from https://www.schulentwicklung.nrw.de/lehrplaene/upload/klp_SII/ph/KLP_GOSt_Physik.pdf
Germany (Hesse)	Hessian Ministry of Education and Religious Affairs. (2010). Lehrplan Physik gymnasialer Bildungsgang gymnasiale Oberstufe. Retrieved from https://kultusministerium.hessen.de/sites/default/files/media/go-physik.pdf
Germany (Saxony)	Saxon State Ministry of Culture. (2011). Lehrplan Gymnasium Physik. Retrieved from https://www.schule.sachsen.de/lpdb/web/downloads/lp_gy_physik_2011.pdf?v2
Germany (Bavaria)	Bavarian State Institute for School Quality and Education Research ISB. (2009). Gymnasium Lehrplan für Physik Jahrgangsstufe 6 bis 12. Retrieved from http://www.isb-gym8-lehrplan.de/contentserv/3.1.neu/g8.de/index.php?StoryID=27147
France	French National Ministry of education. (2014). Repères pour la formation en physique-chimie au cycle terminal scientifique. Retrieved from http://cache.media.eduscol.education.fr/file/PC/45/7/reperes_formation_filiere_S_380457.pdf
Italy (Liceo Scientifico)	Italian Ministry of Education, University and Research. (2015). Quadro di riferimento della II prova di fisica dell' esame di stato per i licei scientifici. Retrieved from http://www.miur.gov.it/il-quadro-di-riferimento-della-seconda-prova-di-fisica-per-gli-esami-di-stato-dei-licei-scientifici
Portugal	Ministry of Education and Science. (2014). Metas curriculares de fisica 12.º ano curso científico-humanístico de ciências e tecnologias. Retrieved from http://www.dge.mec.pt/sites/default/files/Secundario/Documentos/Documentos_Disciplinas_novo/Curso_Ciencias_Tecnologias/Fisica/metas_curriculares_fisica_12_ano.pdf
Sweden	Swedish National Agency for Education. Physics - aim and courses (Fysik Gymnasieprogrammen, 2013). Retrieved from

	https://www.skolverket.se/download/18.189c87ae1623366ff374c3/1521539980000/Physics-swedish-school.pdf
Germany (Rhineland Palatina)	Ministry of Education Rhineland-Palatinate. (2014). Lehrplan Physik der gymnasialen Oberstufe. Retrieved from https://lehrplaene.bildung-rp.de/no-cache.html?tx_pitsdownloadcenter_pitsdownloadcenter%5Bcontroller%5D=Download&tx_pitsdownloadcenter_pitsdownloadcenter%5Baction%5D=forceDownload&tx_pitsdown-loadcenter_pitsdownloadcenter%5Bfileid%5D=9iBBxB07W%2By%2BUjfMWG5gHg%3D%3D
Belgium (Flemish community)	Flemish Confederation of Catholic Secondary Education. (2014). Fysika, derde graad ASO, leerplan secundair onderwijs VVKSO. Retrieved from http://ond.vvkso-ict.com/leerplannen/doc/Fysica-2014-015.pdf
Austria	Austrian Federal Ministry of Education, Science and Research. (2018). Gesamte Rechtsvorschrift für Lehrpläne – allgemeinbildende höhere Schulen, Gymnasium Physik. Retrieved from https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=10008568 Older version with more details: www.physikunterricht.at - Das Portal für Physiklehrer/innen. (2004). Lehrstoff physik-oberstufe. Retrieved from http://www.physikunterricht.at/Unterricht/Physik8Klasse/Lehrstoff_Oberstufe.doc
Spain	Ministry of Education, Culture and Sport, Spain. (2015). Real decreto 1105/2014 currículo básico de la educación secundaria obligatoria y del bachillerato. Retrieved from https://www.boe.es/boe/dheisenias/2015/01/03/pdfs/BOE-A-2015-37.pdf
Australia	Australian Curriculum and Assessment Reporting Authority (ACARA). (2015). Physics - The Australian Curriculum Version 7.5. Retrieved from https://www.australiancurriculum.edu.au/senior-secondary-curriculum/science/physics/ or as pdf: https://www.australiancurriculum.edu.au/umbraco/Surface/Download/Pdf?subject=Physics&type=SS
Canada (Ontario)	Ministry of Education. (2008). The Ontario curriculum grades 11 and 12 science. Retrieved from http://www.edu.gov.on.ca/eng/curriculum/secondary/2009science11_12.pdf

Appendix 2-B: Background information about educational contexts

Educational system	Course in which QP is given	Students who may take QP	Final exam (as part of the school leaving qualifications)	Additional information
UK (England)	Advanced level physics' is an elective two-year course in the last two years of secondary school	Students preparing for A-level exams in England or Wales, age 17-18.	Written A-level exam as part of the school leaving qualification offered by the educational bodies.	The examination for British A-Levels is executed by independent examination boards*
UK (Scotland)	'Advanced Higher Physics' is an elective course in the not compulsory sixth year of secondary school.	Students preparing for progressing to further and higher education, age 17-18.	Written exam as part of the Scottish National Qualification.	The exam is set and marked by the Scottish Qualifications Authority (SQA).
Netherlands	*'Natuurkunde'* is an elective physics course, but compulsory for students in the nature and technology stream.	Students attending pre-university high school (*vwo*), age 17-18.	Written national final exam (*Centraal Schriftelijk VWO eindexamen*).	Exams are set by a national commission and marked by the own teacher and an independent second teacher.
Intern. Baccalaureate (IB)	The Higher level (HL) physics course is an elective course in the Diploma Programme.	Students, preparing for the pre-university IB Diploma Programme, age 17-19.	Written exam as part of the IB Diploma Programme.	The written exam is externally set and marked.
Denmark	Physics (*Fysik)* A in is an elective course in upper secondary schools on STX-level.	Students attending pre-university upper secondary school (*STX* or *gymnasium*), age 18 -19.	Oral, practical and written final exams. A central exam commission composes the written exams.	Every year the ministry of education announces a theme from '21st century physics' as part of the exam.**
Norway	Physics (*Fysikk)* 1 and 2 are consecutive elective courses in the upper secondary school, leading to higher education entrance qualifications.	Physics 1 is given in grade 12 (students age 17-18) and is a prerequisite for the optional higher-level course, given in grade 13 (age 18-19).	National written exam in Physics 2.	Physics 1 has an oral exam for a sample of students each year.
Finland	Physics (*fysiikka*) 1is a compulsory course. QP is taught in physics 7 'Matter and Radiation' which is one of the seven elective specialisation courses in physics.	QP is taught in schools for General Upper Secondary Education (*Lukiokoulutus*) which is not compulsory to students age 17-19.	Students can choose to take the national written matriculation exam for physics (*Ylioppilastutkinto*).	The matriculation exams are executed by the National Matriculation Examination Board.

Germany	In most federal states QP is part of the elective physics course (*Physik*). Students can choose between two different course levels. ***	Students attending upper pre-university secondary school (Sekundarstufe II, *Gymnasiale Oberstufe*), in general, 17-19 years old. Exception in Bavaria. ***	Students take a written final exam (*Abiturprüfung*). In some states, students can choose to do an additional oral exam.	The written exam is a federally set exam in 15 of the 16 states. Only in Rhineland-Palatinate, the written exams are locally set but still under strict federal control.
France	Chemistry and Physics (*Physique-Chimie*) in French upper secondary schools is an elective course. ****	Students following the science stream in the pre-university upper secondary school (*lycée général*), age 16-18.	Written national final exam '*Baccalauréat général série scientifique*'.	The course *Physique-Chimie* contains items that in other countries would be in the chemistry curriculum.
Italy (Liceo Scientif-ico)	Physics (*Fisica*) is a compulsory subject in *Liceo Scientifico,* one form of upper secondary school, specialised in science subjects. QP is taught in the fifth year and final year of upper secondary school.	Students in final year of the pre-university secondary school with a focus on science (*Liceo scientific)*, age 18-19.	Oral or teacher-set written final exams (*Esame di Stato)* are common. A national written final exam (*seconda prova*) is possible.*****	The Ministry of Education announces every year if the *seconda prova* is in mathemat-ics or physics.
Portugal	The elective physics course (*Física*).******	Students in grade 12 of the science and technology track of pre-university upper sec-ondary school (*Científico-humanístico*), age 17-18.	For physics, there are oral examinations and locally set written exams.	In lower years physics and chemistry form an integrated subject.
Sweden	Physics (Fysik) 2 and 3 are consecu-tive elective courses in the not compulsory upper secondary school (*Gymnasieskola*)	Students following a national university preparatory pro-gram for natural sciences or technology, age 17-19.	There is no external centrally set exam for physics. Teach-ers follow an official curriculum and grading system.	For physics 2, teachers can voluntarily use an exam pro-vided by the Swedish National Agency for Education.
Belgium (Flemish com.)	An optional module in the elective physics course (*Fysica*) in the final year of general secondary educa-tion. The physics teacher decides if this module is given.	Students, who are attending pre-university secondary schools (*ASO*), age 17-18.	All exams (oral or written) are organised locally on school level.	The structure of Belgium secondary education yields a several variations of curricula. *******

Austria	The elective course Physics (*Physik*) in upper secondary schools.	Students attending pre-university secondary schools (*AHS* or *BHS*), age 17-19.	The written final exam for physics is locally set according to national guidelines. Students can choose to take an oral exam.	While the written exam is set by the own teacher, the grading has to be confirmed centrally.
Spain	The elective physics course of the last year of scientific high school.	Students in the last two years of high school (*Bachillerato*) which are not compulsory.	No national written school leaving exam.	Universities require a standardised higher education entrance exam. ********
Australia	The elective physics course of Senior secondary school Unit 4: Revolutions in modern physics.	Students in Senior Secondary School year 12; students age 17-18.	Centrally (on state level) set written examination.	Each Australian state writes its own curriculum with about 90% of the content of the Australian Physics curriculum.
Canada (Ontario)	The elective high school physics course: Physics, Grade 12 University Preparation SPH4U	Students in the last year of high school (grade 12), age 17-18.	No provincial or national final exam in physics.	

*United Kingdom (England): The national curriculum for upper secondary physics (GCE subject level conditions and requirements for science) is not very specific because independent examination boards execute the examination for British A-Levels. These examination boards on their term have very detailed exam syllabi to define precisely which content and what kind of questions students can expect in the written exam. The data for the comparison in were taken from the specifications of the Assessment and Qualifications Alliance (AQA), the largest of the five main examination boards for British A-Levels. More detailed information about NOS aspects in British science education can be found in the National Curriculum in England: science programmes of study (UK Department for Education, 2015). Since this document does not cover any aspects of our definition of QP, it has not been included in this research.

**Denmark: Physics A is required to include ‘Physics of the 21st Century’. The subject is a window to the current physics. The course will vary from year to year and the contents will be announced every year. In recent years the subjects were: medical physics, plasma physics, fusion energy, modern particle physics, astronomy. In Table 2-4 we indicate technical applications of QP as optional because it is likely that these are treated in ‘Physics of the 21st Century’. Additionally, the core material of the curriculum must fill approx. 70% of teaching time. The last approx. 30% must be used for optional (supplementary) subjects. Current events, such as significant natural phenomena and research findings in the media, can thus be included in the teaching.

***Germany: QP has a long tradition in secondary schools in Germany. Starting from 1945 it was taught in physics courses of the final two years at the pre-university level (Gymnasium)(Müller, 2006). Depending on the federal state this is grade 11 and 12 or 12 and 13; students are usually 17 to 19 years old. Physics is an elective course of two years at these grades. Students can choose between two different levels: G (Grundkurs), a more basic general physics course or L (Leistungskurs), a specialised course which typically has more lesson time, offers more depth and might require a high level of mathematics. QP is a compulsory part of both courses but offered with different depth and mathematical complexity. In Germany, a general national examination document (Einheitliche Prüfungsordnung, 2004) gives overall learning objectives. Within the guidelines of this national document, each of the 16 federal states is responsible for the school system of the individual state, examination, and related detailed syllabuses (Lehrplan). Since all states have to comply with the same national directive, they show many similarities, but still, there are significant regional differences regarding examinations, chosen topics and intended learning outcomes. To give a representative overview of Germany's variety of curricular documents we took into account the individual curricula of the seven most populated German states.

The curriculum of Bavaria has a notable specialty: students in this federal-state already learn some central QP concepts at the age of 15. At that age, physics is a compulsory subject for all Gymnasium (pre-university secondary school) students. The developers of this curriculum consider QP as so crucial for our modern worldview that every student – even if they do not choose physics in their final years – should know some fundamental properties of QP (Müller, 2006).

****France: Chemistry and Physics are integrated into one subject in French upper secondary schools, and there is a national curriculum for this subject. While aspects of QP were taught in French upper secondary schools before 1995, this topic disappeard in a curriculum reform. In the curriculum from 1995 selected items were more real-world related and less mathematical, and as a consequence, QP was not mentioned anymore in the intended learning outcomes (Crastes, 2017). However, in 2012 several QP items were reintroduced in the national curriculum (Annexe: Programme de l'enseignement spe´cifique et de spe´cialite´ de physique-chimie, classe terminale de la se´rie scientifique.2011).

*****Italy: The final exam on a Liceo scientifico consists of three written and one oral exam, only the first two written exams are national exam: one in Italian language and the second one in Mathematics or physics. In the beginning of each year the ministry of Education announces which of the two subjects will be examined in the national exam of that year.

******Portugal: In Portugal, physics and chemistry are taught as a combined subject for higher years of secondary school (students age 15 to 18). Physics can only be chosen as a separate subject in the final year (grade 12) of the science and technology upper secondary academic track. The connection between the two subjects is intense, and QP items related to atomic models and the periodic table (e.g., the Pauli Exclusion Principle) are taught in chemistry lessons. Consequently, this is not visible in the comparison of physics curriculum documents of Table 2-4.

*******Belgium: We analysed the curriculum of the senior secondary general education (ASO) of the Catholic Education Flanders (VVKSO) 3, which is the largest school board in Belgium. Belgium has a complex structure of the educational system. First of all, there are three different language communities (Flemish, French, and German-speaking) with different educational systems and secondly, three different school boards have their own curriculum and school leaving exam. QP is one of 8 possible choice modules. The teacher chooses at least two of these modules in the last two years of secondary school.

********Spain: Spanish upper secondary schools do not have a high-stake leaving exam. However, students who want to enter university have to take a national university entrance test (Prueba de Acceso a la Universidad, PAU), which can be regarded as equivalent to final exams in other countries. These PAU exams are set by the Public Universities, and the content of the exam is not exactly the same as the high school curriculum. During recent years there have not been any questions about QP in the PAU. In practice, this can make QP to an underestimated topic in high school, and teachers occasionally skip it in order to have more lesson time for tested topics (Vázquez, 2017).

Appendix 2-C: Examples of curriculum texts concerning the role of scientific models

Denmark (Current STX curriculum – Physics B)

"Through their work with experiments and theoretical models, the pupils will gain knowledge of how physics models are set up and used as a means to qualitatively and quantitatively explain phenomena and processes". (Purpose, p. 55)

Italy (Framework of the Second Physics exam of the State Exam for the Licei Scientifici, translated by the author)

"[At the end of the high school career the student will have the following general competencies:]

- Being able to examine a physical situation by formulating explanatory hypotheses through models or analogies or laws; …
- Being able to interpret and / or process data, also of an experimental nature, verifying their relevance to the chosen model. …" (General competences of Physics, p.3)

Lower Saxony, Germany I (Core curriculum for upper secondary *Gymnasium* education, Physics)

"Working with models

Physical problems are made accessible by modelling and certain idealisations of processes. Models can be representational, iconic, graphical or mathematical or they use analogies. Examples from lower secondary education are the core-shell model of the atom, the model of elementary magnets and the particle model introduced in chemistry classes as iconic models, energy flow diagrams as graphic models. In upper secondary education, mathematical models also include phasor diagrams. In examples, the students recognise the capacity of models to make predictions and they understand the limits of models. Only advanced learners are able to reflect on the differences between model and reality."

At the end of lower secondary education, the students …

- show relationships in the form of graphical representations.
- check hypotheses on selected examples by self-designed experiments.
- use models as a tool for solving problems and formulating hypotheses.
- describe idealisations in different situations.
- distinguish between models and reality.

Additionally, at the end of upper secondary education, the students ...

- represent relationships in the form of function equations.
- only advanced level: model simple processes with differential equations.
- explain the model of the potential well and use it as a heuristic tool for problem solving.
- Use the phasor representation or other appropriate representation to solve problems in wave physics or quantum physics.

- recognise structural equalities and use them to transfer existing knowledge to other situations.
- distinguish between model presentation, iconic representation and reality."

(Process related competencies, p. 19, translated from German)

England (AQA Education, specifications AS and A-level physics)

"Understanding of How Science Works is a requirement … and is set out in the following points which are taken directly from the GCE AS and A Level subject criteria for science subjects. Each point is expanded in the context of Physics. The specification references given illustrate where the example is relevant and could be incorporated.

A. Use theories, models and ideas to develop and modify scientific explanations

Scientists use theories and models to attempt to explain observations. These theories or models can form the basis for scientific experimental work.

Scientific progress is made when validated evidence is found that supports a new theory or model.

Candidates should use historical examples of the way scientific theories and models have developed and how this changes our knowledge and understanding of the physical world.

Examples in this specification include:

- Galileo deduced from his inclined plane experiment that falling objects accelerate. Newton later explained why and showed that freely-falling objects have the same acceleration. The kinetic theory of gases explains the experimental gas laws. "

(How Science Work, p.36-37)

Australia (ACARA | The Australian Curriculum | Version 7.5)

"Physics uses qualitative and quantitative models and theories based on physical laws to visualise, explain and predict physical phenomena. Models, laws and theories are developed from, and their predictions are tested by making, observations and quantitative measurements." (Rationale, p.4)

"Physics aims to develop students' understanding of the ways in which models and theories are refined and new models and theories are developed in physics; and how physics knowledge is used in a wide range of contexts and informs personal, local and global issues." (Aims, p.4)

"As science involves the construction of explanations based on evidence, the development of science concepts, models and theories is dynamic and involves critique and uncertainty. Science concepts, models and theories are reviewed as their predictions and explanations are continually re-assessed through new evidence, often through the application of new technologies." (Science as a Human Endeavour, p.7)

"Science understanding is evident when a person selects and integrates appropriate science concepts, models and theories to explain and predict phenomena, and applies those concepts, models and theories to new situations. Models in science can include diagrams, physical replicas, mathematical representations, word-based analogies (including laws and principles) and computer simulations. Development of models involves selection of the aspects of the system/s to be included in the model, and thus models have inherent approximations, assumptions and limitations. The *Science Understand-*

ing content in each unit develops students' understanding of the key concepts, models and theories that underpin the subject, and of the strengths and limitations of different models and theories for explaining and predicting complex phenomena." (Science understanding, p. 8)

"By the end of this unit, students … understand how scientific models and theories have developed and are applied to improve existing, and develop new, technologies." (Learning outcomes, p.13)

"For the physical systems studied, the student…

- applies theories and models of systems and processes to explain phenomena, interpret complex problems, and make reasoned, plausible predictions in unfamiliar contexts.
- analyses the roles of collaboration, debate and review, and technologies, in the development of physical science theories and models"

(Achievement Standard A, B and C, p.28)

"For the physical systems studied, the student…

- identifies aspects of a theory or model related to the system; describes phenomena, interprets simple problems, and makes simple predictions in familiar contexts.
- describes the roles of communication and new evidence in developing physical science knowledge; describes ways in which physical science has been used in society to meet needs,"

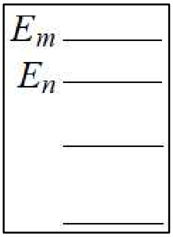
(Achievement Standard D and E, p.28)

Appendix 3-A: Secondary School Students' Views of Nature of Science in Quantum Physics

Translated questions of the QP concept test for the Dutch upper secondary physics exam syllabus.

Students in our research answered the teat on their own these digital devices. The 20 questions were presented in a random order (without the question number) for each student.

Q1 The figure on the right shows a part of the energy level scheme of an atom.

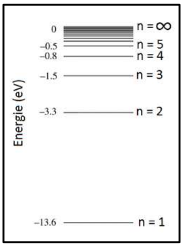


An electron is in an energy state (= level) E_m.

When this electron changes to state E_n light is released. The larger the energy difference between E_m and E_n...

A ... the more photons are emitted.
B ... the brighter the transmitted light (higher intensity).
C ... the longer the wavelength of the emitted light.
D ... the shorter the wavelength of the emitted light.
E More than one of the above answers are correct.
F I don't know.

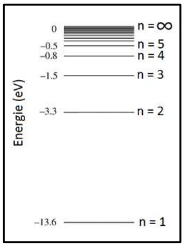
Q2 The figure on the right shows the energy level diagram of a hydrogen atom. The atom is in its ground state.



Can this atom absorb a photon with 3.3 eV of energy?

A Yes
B No
C I don't know

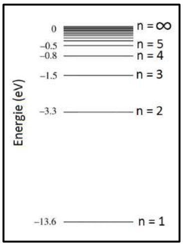
Q3 The figure on the right shows the energy level diagram of a hydrogen atom. The atom is in its ground state.



Can this atom absorb a photon with 13.1 eV of energy?

A Yes
B No
C I don't know
D

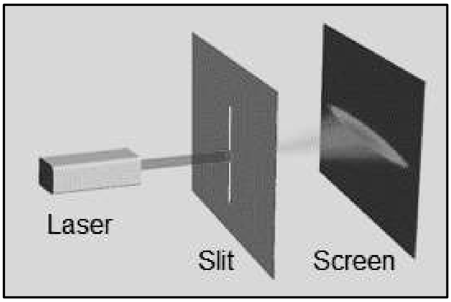
Q4 The figure on the right shows the energy level diagram of a hydrogen atom. The atom is in its ground state.



Can this atom absorb a photon with 13.8 eV of energy?

A Yes
B No
C I don't know

Q5 When laser light is passed through a narrow slit, the light diffracts, see figure.



Why does diffraction occur? Choose the best answer.

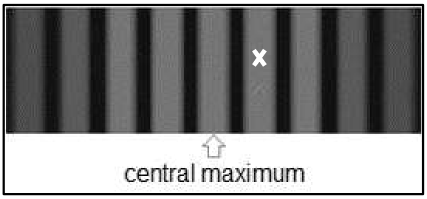
A The slit is very narrow; its width is close to the wavelength of the light. The narrower the gap, the more diffraction of the light waves is visible.

B Because the photons pass through a narrow space, their lateral position is determined accurately. The spread of the lateral momentum of the photons is therefore large so that they end up in different places.

C Depending on which model ('light as a wave phenomenon' or 'light consisting of photons') is used, both A and B can be reasonable explanations for the diffraction of light.

D None of the above answers is correct.

Q6 Laser light (monochromatic, with wavelength λ) passes through a pair of vertical slits. An interference pattern appears on a screen behind it, see figure. A specific spot on the screen is marked with a cross.



What can you say about the location of this spot?

A This spot is as far away from the right as from the left slit.

B This spot is ½ λ further away from the left slit than from the right slit.

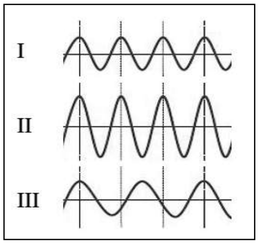
C This spot is exactly one wavelength further away from the left slit than from the right slit.

D This spot is exactly 2λ further away from the left slit than from the right slit.

E I don't know.

Q7 Three electrons move in the same direction. The image shows the de Broglie waves associated with these three electrons.

How do the velocities of the electrons (I, II and III) relate to each other?



A $v_{II} > v_I > v_{III}$

B $v_I = v_{II} > v_{III}$

C $v_{II} > v_I = v_{III}$

D $v_{III} > v_{II} = v_I$

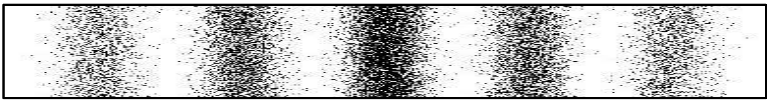
E $v_I = v_{II} = v_{III}$

F I don't know.

Q8 An electron and a proton move at the same speed. What can you say about their de Broglie wavelength?

- A $\lambda_p > \lambda_e$
- B $\lambda_p < \lambda_e$
- C $\lambda_p = \lambda_e$
- D You cannot say anything about their de Broglie wavelength.
- E I don't know.

Q9 A researcher carries out the double-slit experiment. First, she sends electrons through the double slit and looks where they end up on the screen. An interference pattern occurs as shown below.

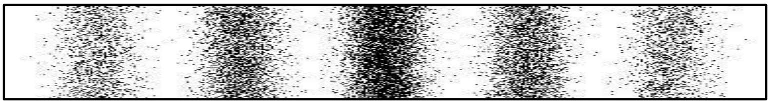


What will change in the interference pattern if the electrons have a higher velocity?

- A Nothing.
- B The minima/maxima come closer together.
- C The minima/maxima are further apart.
- D The interference pattern disappears, two maxima arise directly behind the gaps.
- E I don't know.

Q10 A researcher carries out the double-slit experiment. First, she sends electrons through the double slit and looks where they end up on the screen. An interference pattern occurs as shown below.

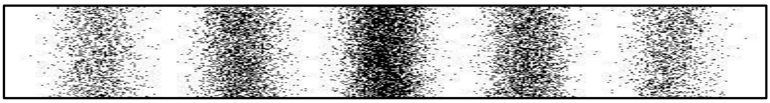
What will change in the interference pattern if the researcher does not use electrons but particles with a slightly



larger mass and equal speed?

- A Nothing.
- B The minima/maxima come closer together.
- C The minima/maxima are further apart.
- D The interference pattern disappears, two maxima arise directly behind the gaps.
- E I don't know.

Q11 A researcher carries out the double-slit experiment. First, she sends electrons through the double slit and looks where they end up on the screen. An interference pattern occurs as shown below.



What will change in the eventual interference pattern if the researcher then lets the electrons go through the double-slit one by one?

- A Nothing.
- B The minima/maxima come closer together.
- C The minima/maxima are further apart.
- D The interference pattern disappears, two maxima arise directly behind the gaps.
- E I don't know.

Q12 Why can we use the photoelectric effect as an argument for the particle character of light?

A Because the speed of the emitted electrons depends on the total intensity of the light and not on the wavelength.
B Because the number of electrons that are released depends on the total intensity of the light and not the wavelength.
C Because a minimum amount of light energy is required to release electrons from a metal.
D Because it depends on the frequency of the light if electrons are released or not.
E Because it depends on the total intensity (=power) of the light if electrons are emitted or not.
F I don't know.

Q13 The uncertainty relationship of Heisenberg is described by the following inequality:

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

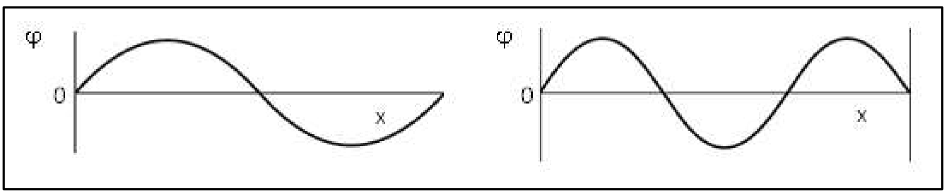
What does Δ represent in this comparison?

A The measurement error in x and p.
B The spread in the possible measurement values of x and p.
C The change of x and p.
D I don't know.

Q14 Heisenberg's uncertainty relationship is mainly used for small objects such as electrons and protons. Why is the uncertainty relationship not used for larger objects, such as cars and tennis balls?

A The uncertainty relationship does not apply to large objects, because we can precisely measure the position and speed with our measuring equipment on this scale.
B The uncertainty relationship does not apply to large objects because they behave according to Newton's laws.
C The uncertainty relationship also applies to large objects, but the uncertainties are so small that we cannot perceive them.
D I don't know.

Q15 Below you see a quantum model of two identical particles in a one-dimensional energy well. The scale in both figures is the same.



What can you say about the energy state of these particles?

A The energy state is the same for both particles.
B The energy of the particle in the left diagram is higher.
C The energy of the particle in the right diagram is higher
D We don't have enough information to say anything about the energy of the particles.
E I don't know

Q16 Consider the quantum model of a particle in a one-dimensional energy well; what is a measure of the energy of this particle?

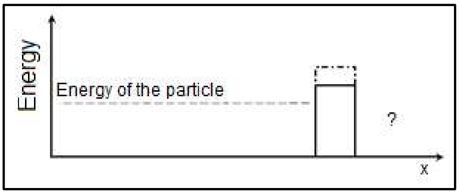
- A The amplitude of the wave function.
- B The area under the graph.
- C The level of the equilibrium state.
- D The number of nodes and antinodes.
- E I don't know.

Q17 Consider the quantum model of an atom.

An electron in the atom is excited and goes from energy level E_1 to E_2. Below are 3 statements for this situation. Which statement is true?

1. The electron has in E_1 a smaller distance to the nucleus than in E_2.
2. The electron travels in both energy levels along a sinusoidal orbit.
3. There is a chance that the electron can be found in the same location before and after the excitation.
4. I don't know.

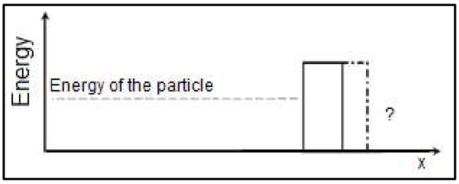
Q18 A particle with a certain amount of energy has a small chance to tunnel through a barrier. Then the barrier is made higher.



What is the effect of raising the barrier?

- A The energy of the transmitted particle becomes smaller.
- B The chance of tunnelling decreases.
- C Statements A and B are both true.
- D None of the above answers is correct.
- E I don't know.

Q19 A particle with a certain amount of energy has a small chance to tunnel through a barrier. Then the barrier is made wider.



What is the effect of widening the barrier?

- A The energy of the transmitted particle becomes smaller.
- B The chance of tunnelling decreases.
- C Statements A and B are both true.
- D None of the above answers is correct.
- E I don't know.

Q20 An electron tunnels through a barrier. What can you say about the total energy of this electron after it is tunnelled?

- A It is larger than the total energy before tunnelling.
- B It is equal to the total energy before tunnelling.
- C It is smaller than the energy before for tunnelling.
- D I don't know.

Appendix 3-B: Secondary School Students' Views of Nature of Science in Quantum Physics

INTERVIEW PROTOCOL (NOS in the context of QP)

Phase 1: Introduction

DEMOGRAPHICS AND BACKGROUND INFORMATION

Name of teacher, school, date of QP course

Do you think physics, in general, is easy or difficult? Why?

Do you think that QP is interesting or not?

Do you think QP is easy or difficult? Why?

Do you know anything about the philosophy of science? If yes, how do you know it?

Phase 2: Conceptual understanding

2 a) CONCEPTIONS OF ELECTRONS AND ATOMS

What are the properties of an electron? Tell me as many as possible.
Possible follow up question:

- Is this an electron in an atom or a free electron?
- Is there anything else you know about electrons?

How do scientists describe an atom?

Possible follow up questions:

- Can you draw it?
- What does your drawing represent?
- Do different models exist?
- Is this a complete model?

2 b) DOUBLE SLIT EXPERIMENT

Describe the setup for the double-slit experiment.

Possible follow up questions:

- What is observed?
- Can the experiment be run with both light and electrons?
- What is observed when only single quanta at a time pass through?
- What happens if you block one of the slits?
- How do you explain the fringe pattern?

2 c) STUDENTS' CONCEPTION OF WAVE-PARTICLE DUALITY

Watch the double-slit experiment simulation[16] on the computer:

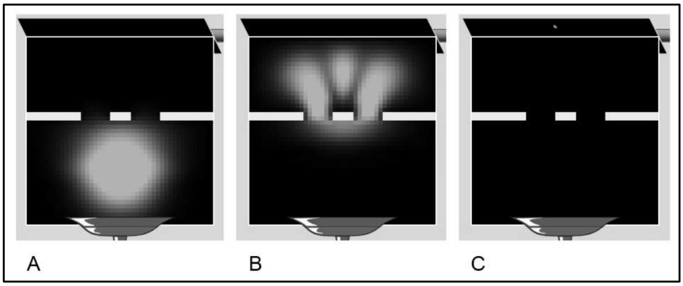


Figure 3-1 Simulation of double-slit experiment with single electrons. A:Electron just released; B:Electron passes double slit; C: Electron is detected as one spot on the screen.

The interviewer explains that other students made the following statements when they discussed the Quantum Wave Interference simulation (as depicted in Fig.1).

The interviewer asks students to read each statement one at a time and respond before moving on to the next statement.

Student 1: The area of the probability density is so large because we don't know the true position of the electron. Since only a single dot at a time appears on the detecting screen, the electron must have been a tiny particle, travelling somewhere inside that blob, so that the electron went through one slit or the other on its way to the point where it was detected.

Student 2: The blob represents the electron itself since an electron is described by a wave packet that will spread out over time. The electron acts as a wave and will go through both slits and interfere with itself. That's why a distinct interference pattern will show up on the screen after shooting many electrons.

Student 3: Quantum physics is only about predicting the outcomes of measurements, so we really can't know anything about what the electron is doing between being emitted from the gun and being detected on the screen.

Possible follow up questions if the student responses are not consistent with his/her earlier descriptions of electrons:

- Are you aware of the inconsistencies with your previous statements?
- Can you explain this?

[16] https://phet.colorado.edu/en/simulation/quantum-wave-interference

Phase 3: NOS views

STUDENTS' NOS VIEWS IN THE CONTEXT OF QP

Introduction, to make sure that the main question about QP interpretations makes sense for the interviewed student or if the student first needs more information

- Do you know different interpretations of quantum physics?
- Can you name any of them or describe their features?

If the student is unfamiliar with interpretations of QP. Explain briefly the main features (see Table Appendix 3-B) of the following three interpretations: Copenhagen, Pilot Wave, Many Worlds for the context of the double-slit experiment. (Table Appendix 3-B is not intended for students, and they are certainly not expected to understand it in detail, but they should realise that there are different interpretations.)

Table Appendix 3-B Information for students about some features of three QP interpretations

Name of the interpretation (proponents)	**Completeness of quantum theory and relation to reality**	**The role of measurement and relation to reality**
Copenhagen Interpretation (Bohr, Heisenberg, Dirac)	The state of a system is entirely described by the mathematical QP formalism, which is only an instrument to calculate possible outcomes of an experiment. It does not describe any real physical quantity.	As long as we do not make any measurement, a quantum particle exists in a superposition of all possible outcomes. By measuring, we determine (create) a specific outcome. Before measuring it does not make sense to talk about the position of a particle, it does not have one.
Pilot wave interpretation (de Broglie, Bohm, Bell)	Quantum theory is not complete. To describe the state of a quantum entity completely, we need extra variables and equations. If we would know these additional variables, we could calculate the exact outcome of each experiment.	A quantum particle always has a well-defined (but unknown) position. Its motion is guided by a pilot wave which can be described by the mathematical formalism of QP. Measurement is just a way to make the existing position visible.
Many worlds interpretation (Everett, DeWitt)	Quantum theory is complete and describes the state of a quantum entity in many parallel universes (many worlds) simultaneously of which we only see one. These multiple universes exist whenever the theory allows more than one possible state of a system.	As in this interpretation, reality continuously extends into many parallel universes. A quantum particle always has a defined position, which can be different in each universe. We can see only one branch of reality; thus, the concrete outcome of a position measurement cannot be considered as reality but is just a delusion in the limited mind of an observer.

Main question: Ask students to read each statement one at a time, and respond before moving on to the next statement.

Student 1: QP does not need an interpretation. As long as we can calculate with it and can build devic-es that work with it, we don't need an interpretation of QP. Interpretations are not science and physicists should not waste their time on it.

Student 2: Physicists should come to an agreement about which interpretation they want to use as they did for international measurement standards. If everybody sticks to his/her own interpretation, we only get a lot of useless discussions.

Student 3: At this moment, we cannot explain why electrons behave the way they do. But if scientists want to find out, they need a lot of creativity to find an explanation. That is how the interpretations are developed. That is part of science.

Possible follow up questions if the student did not cover the NOS aspects in the answer:

- How is it possible that different physicists have different ideas about what an electron is?
- Why do physicists have different interpretations?
- Is there a right interpretation?
- How can physicists find out which interpretation is the right one?

Appendix 3-C: Secondary School Students' Views of Nature of Science in Quantum Physics

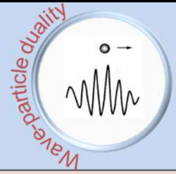
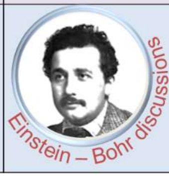
DEMOGRAPHICS AND SUMMARY OF STUDENT ANSWERS PHASE 1

Most students regarded QP as relatively difficult. From the 15 (out of 24) interviewed students who found QP interesting or very interesting six rated it difficult or very difficult.

Table: Demographics of interviewed students. This overview is arranged according to their scores on the QP test.

Achieving level on QP test	Student number, m/f		Teacher (m/f)	Score QP test	Is physics easy/difficult?	Is QP interesting or not?	Is QP easy/difficult?	Do you know the philosophy of science?
Low achieving	1	m	A (m)	0	neutral	neutral	difficult	yes
	2	f	F (f)	2	neutral	neutral	easy	no
	3	f	F (f)	3	neutral	neutral	difficult	no
	4	m	F (f)	3	neutral	not interesting	very difficult	no
	5	f	B (f)	5	very difficult	very interesting	very difficult	no
	6	m	C (m)	5	neutral	neutral	difficult	no
Medium achieving	7	f	C (m)	6	very difficult	not interesting	very difficult	no
	8	f	G (f)	6	very difficult	very interesting	difficult	yes
	9	f	A (m)	8	difficult	not interesting	difficult	no
	10	m	E (m)	8	difficult	very interesting	very difficult	no
	11	f	D (m)	8	easy	interesting	neutral	no
	12	m	B (f)	9	difficult	very interesting	difficult	no
	13	f	B (f)	9	neutral	very interesting	very difficult	no
	14	m	D (m)	11	easy	very interesting	neutral	no
	15	m	G (f)	11	neutral	not interesting	neutral	yes
	16	f	A (m)	11	difficult	not interesting	difficult	no
	17	f	D (m)	11	difficult	not interesting	difficult	no
	18	m	E (m)	12	difficult	interesting	very difficult	no
	19	m	C (m)	12	difficult	very interesting	neutral	yes
High achieving	20	m	C (m)	13	very easy	very interesting	easy	yes
	21	f	G (f)	14	difficult	interesting	neutral	no
	22	m	G (f)	15	very easy	very interesting	neutral	yes
	23	f	F (f)	15	easy	very interesting	difficult	no
	24	m	G (f)	17	easy	very interesting	easy	no

Appendix 4-A Classroom poster

NOS aspect	Example of the NOS aspect in Quantum Physics
The role of scientific **Models**	 Depending on the situation, either the wave model or the particle model is useful to describe electrons or light.
Tentativeness of scientific knowledge	Although Newton's laws of motion have formed the undisputed basis of classical physics for hundreds of years, it is not possible to understand quantum phenomena with Newtonian physics. 
Creativity in science	 The development of Quantum Physics (QP) was only possible through applying new mathematics to unsolved problems, out-of-the-box thinking, and creative (thought) experiments.
Subjectivity in science	Depending on personal preferences, some physicists are content with QP purely as a tool to describe and predict phenomena, whereas others are searching for a underlying meaning of the QP formalism for reality. (⇒ Interpretations of QP) 
Controversies in science	 Discussions between physicists 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.

H.K.E.Stadermann 2021

Appendix 4-B: Slide presentation, selected translated examples

Editable instructional material.
This is a semi-finished product. Please, use, change,
Rearrange or edit it to make it fit into your classroom.
The directory on the side line of the slides is 'clickable'.

Quantum Physics triggers questions

What is light? What is an electron? Is science able to answer these questions? How do we get answers? Why do we need quantum physics? Is classical physics wrong? What does the double slit experiment say about reality? Do all scientists agree on the interpretation? If not, is that a problem? Why are there different interpretations? Who is right? Are interpretations of quantum physics really science? Can science answer all questions? What are models good for? Can we choose whatever model we want? Can I make my own model? Why don't we choose the best model? Does this mean that everything could happen? Could I tunnel through a wall? Am I made of waves? Is there a universe where quantum physics does not exist?

about the Nature of Science.

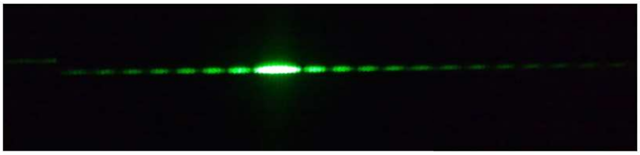
Enjoy it!

Nature of Science in Quantum Physics 2

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

Interference of waves

Laser light (can be demonstrated with a laser pen)



Video about the double-slit experiment:

Veritasium https://www.youtube.com/watch?v=Iuv6hY6zsd0

© Derek Muller, Veritasium via YouTube, 2013

Nature of Science in Quantum Physics Demonstration or explanatory video 3

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
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- Atomic models
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- Applications
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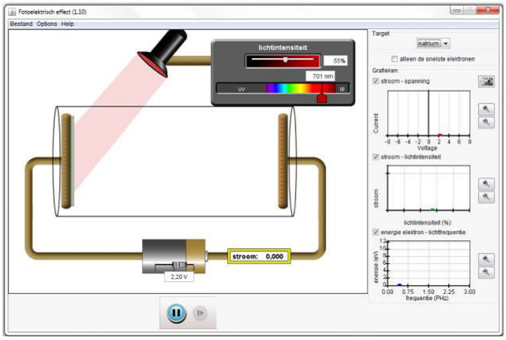
- Quackery
- Quiz

The photoelectric effect simulation



https://phet.colorado.edu/nl/simulation/photoelectric

DIY:
PhET simulation of photoelectric effect

Alternative:
Watch explanation

https://www.youtube.com/watch?v=EGwWSY2vTCk

PhET Interactive Simulations
University of Colorado Boulder
https://phet.colorado.edu/nl/simulation/photoelectric

- Intro
- Particles
- Waves
- Superposition
- Interference
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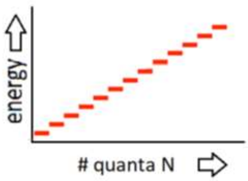
- Quackery
- Quiz

The energy of light is quantized: photon

You switch on a sodium light. If you could measure the emitted energy, it would not rise smoothly;

the energy of light comes in steps:

© James Cridland



The energy of light is determined by the frequency, f, and the number of photons, N.

$$E = N \times hf$$

Quantum of light: a photon

Speed in vacuum: $c = 299792458 \frac{m}{s} \approx 3{,}00 \cdot 10^8 \frac{m}{s}$

Wavelength: $s = v \cdot t \rightarrow \lambda = \frac{c}{f}$

Energy of a photon: $E_p = h \cdot f = \frac{h \cdot c}{\lambda}$

Planck's constant: $h = 6{,}626068 \cdot 10^{-34} Js$

- Intro
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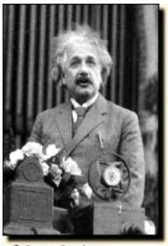

© Brown Brothers, Sterling, PA.

Einstein (1917)
Light (wavelength, λ) has a momentum *p*.

$$p = \frac{h}{\lambda}$$

© unknown, via Wikipedia

De Broglie (1923)
Particles of matter have a wavelength λ.

$$\lambda = \frac{h}{p}$$

- Intro
- Particles
- Waves
- Superposition
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- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
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- Applications
- Schrödinger's cat
- Quackery
- Quiz

Double-slit experiment

DIY: Phet simulation 'Double-slit experiment'
https://phet.colorado.edu/sims/cheerpj/quantum-wave-interference/latest/quantum-wave-interference.html?simulation=quantum-wave-interference

Fire single particles towards a double slit.

Alternative:
Watch Dr. Quantum 'Double-slit experiment'
https://www.youtube.com/watch?v=NvzSLByrw4Q&t=28s

from 0.28 s to 4.05 s

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

What is going on here? And why?

Task (5 minutes):

Discuss in pairs what you imagine an electron to be.

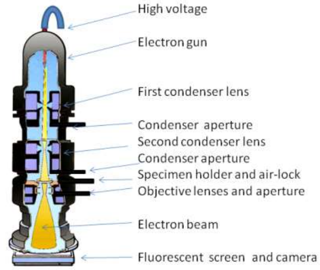
1. What did you see?
2. Why is this happening?
3. What kind of wave did you see?
4. How does this affect your idea of particles?

Write down what you think an electron is.

Electron as a wave

Electron microscope

Calculate the wavelength of the electrons if you use an accelerating voltage of 100 kV.



Transmission Electron Microscope

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

Electron as a wave

In an electron microscope, the accelerating voltage is doubled. The velocity of the electrons increases, but does not come close to the speed of light.

How does the wavelength, λ change?

A. λ becomes 4 times as large.

B. λ becomes twice as large.

C. λ becomes twice as small.

D. λ becomes 4 times smaller.

E. None of the above is correct.

DeBroglie wavelength

Two quantum particles (A and B) move through the universe. The deBroglie wavelength of particle A is shorter than that of particle B.

Which particle has the higher velocity?

A. A

B. B

C. They have the same velocity; quantum particles always move at the speed of light.

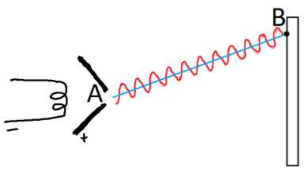
D. There is not enough information to answer.

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

Electron as a quantum particle

An electron is emitted by a source at position A.

After some time, the electron is observed on a detection screen at position B.



How did the electron reach position B?

A. In a straight line (like the blue straight line).

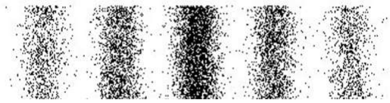
B. Along a sinusoidal path (like the red wavy line).

C. Impossible to tell.

Double-slit experiment

Instead of electrons, we can also use bigger particles in the double-slit experiment.

What changes do we see in the interference pattern if we use hydrogen atoms (at the same speed) instead of electrons?



A. No changes.
B. The maxima and minima are closer together.
C. The maxima and minima are further apart.
D. The interference pattern disappears and two maxima appear directly behind the slits.

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

Wave-particle duality in the Copenhagen interpretation

Watch 3:05 minutes of the video 'The Interpretations of Quantum Mechanics', starting at 0:32
https://www.youtube.com/watch?v=mqofuYCz9gs

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or

Watch 4:10 minutes of the video 'NOVA The Fabric of The Cosmos: Quantum Leap', starting at 16:24
https://www.youtube.com/watch?v=4Z8Ma2YT8vY

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

The Copenhagen interpretation

- It was **Niels Bohr's** favourite interpretation.
- It does not tell us what an electron really **is**.
- It does not tell us **where** the electron is during an experiment.
- Asking for the position of the electron is meaningless because it does not have the property of 'position'.
- It says nothing about **why** an electron arrives (=is measured) at a certain place.
- It can predict exactly how big the **chance** is that the electron is measured at a certain place.

Niels Bohr

© unknown, via Wikipedia

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

The Copenhagen interpretation

'If I were forced to sum up in one sentence what the Copenhagen interpretation says to me,
it would be '**Shut up and calculate**!'

(David Mermin)

Mermin, N. D. (2004). Could Feynman have said this. *Physics Today*, *57*(5), 10.

Why does Mermin say this?

Alternative interpretation 1

Many Worlds interpretation:

- can also explain all quantum phenomena;
- comes to the same results;
- but it is allowed to ask where the electron is

Many Worlds interpretation (in less than two minutes, from 3:53 to 5:40, or start from the beginning for also the Copenhagen interpretation):

https://www.youtube.com/watch?v=mqofuYCz9gs&ab_channel=DoS-DomainofScience

Alternative interpretation 2

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

Pilot Wave interpretation (7:40 min):

- can also explain all quantum phenomena;
- comes to the same results;
- the electron is **always** a particle;
- we just do not know where it is.

https://youtu.be/WIyTZDHuarQ

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

Alternative interpretations 3 to18

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Article Talk

Interpretations of quantum mechanics

4.1 Classification adopted by Einstein
4.2 Copenhagen interpretation
4.3 Many worlds
4.4 Consistent histories
4.5 Ensemble interpretation
4.6 De Broglie–Bohm theory
4.7 Relational quantum mechanics
4.8 Transactional interpretation
4.9 Stochastic mechanics
4.10 Objective collapse theories
4.11 Consciousness causes collapse (von Neumann–Wigner interpretation)
4.12 Many minds
4.13 Quantum logic
4.14 Quantum information theories
4.15 Modal interpretations of quantum theory
4.16 Time-symmetric theories
4.17 Branching space-time theories
4.18 Other interpretations

- Intro
- Particles
- Waves
- Superposition
- Interference
- Light
- Photoel. Effect
- Photon
- De Broglie
- Double slit
- Electron as wave
- Interpretations
- Atomic models
- Particle in a box
- Tunnel effect
- Uncertainty
- Applications
- Schrödinger's cat
- Quackery
- Quiz

Electron in an atom

Atomic models

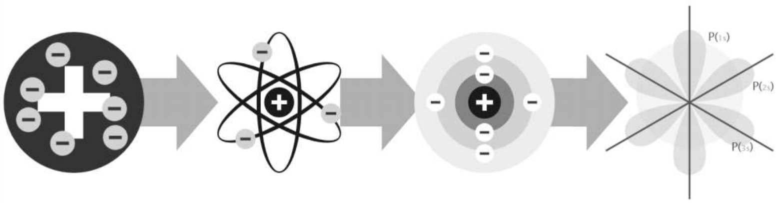

image credit: Ville Takanen
https://commons.wikimedia.org/wiki/File:Evolution_of_atomic_models_infographic.svg

The Bohr model and spectral lines

- How does the Bohr model explain spectral lines?
- Why are there only certain stable orbits in the Bohr model?

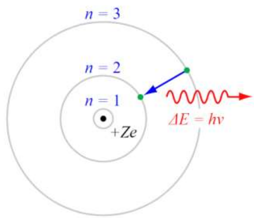

image credit: JabberWok at English Wikipedia

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Why are there only certain stable orbits in the Bohr model?

- Nobody knows;
- not even Niels Bohr.
- But we get nice pictures of it ☺.

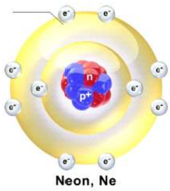


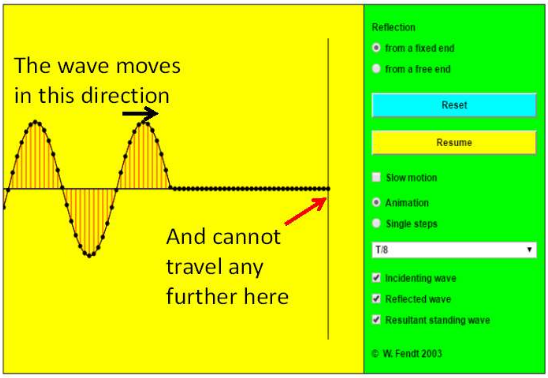
image credit: BruceBlaus 2014 Wikipedia

- Chemists can explain a lot with it.
- The only problem: Electrons are no marbles!

- **A model is not the reality!**

• Intro
• Particles
• Waves
• Superposition
• Interference
• Light
• Photoel. Effect
• Photon
• De Broglie
• Double slit
• Electron as wave
• Interpretations
• Atomic models
• Particle in a box
• Tunnel effect
• Uncertainty
• Applications
• Schrödinger's cat
• Quackery
• Quiz

The wave model of an electron: What happens when we trap the electron?



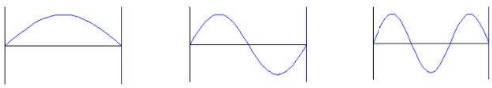
http://www.walter-fendt.de/html5/phen/standingwavereflection_en.htm

• Intro
• Particles
• Waves
• Superposition
• Interference
• Light
• Photoel. Effect
• Photon
• De Broglie
• Double slit
• Electron as wave
• Interpretations
• Atomic models
• Particle in a box
• Tunnel effect
• Uncertainty
• Applications
• Schrödinger's cat
• Quackery
• Quiz

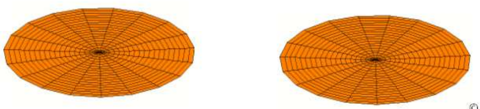
Particle (or wave?) in a box

Stranding wave:

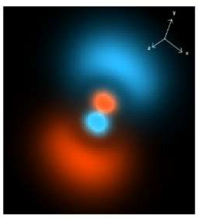
1 dimension



2 dimensions



3 dimensions (that is tricky!)



Samenvatting

Verbanden tussen Quantumfysica en de Aard van de Natuurwetenschappen in het vwo

Mogelijkheden en uitdagingen in curriculumontwerp, lesgeven en leren

Introductie

Bij een herziening van het Nederlandse curriculum natuurkunde voor het vwo in 2014 werd het subdomein 'Quantumwereld' in het verplichte deel van het Centraal Schriftelijk Examen (CSE) opgenomen. De introductie van dit nieuwe onderwerp was omstreden. Er waren docenten, vakdidactici en schoolboekauteurs die zich op docentenconferenties en in vakbladen fel tegen quantumfysica als onderdeel van het examen uitspraken. Deze tegenstanders van deze curriculumvernieuwing twijfelden aan het nut van dit examenonderdeel. Zij vreesden dat quantumfysica voor vwo-leerlingen niet leerbaar zou zijn en dat hun hooguit enkele trucjes geleerd zouden kunnen worden om quantumvraagstukken te beantwoorden. In 2016, het jaar waarin vwo-examenkandidaten voor het eerst opgaven uit de 'quantumwereld' in hun CSE kregen, begon ik met mijn promotieonderzoek.

Ik was geïnteresseerd in dit onderwerp omdat de quantumfysica in mijn beleving juist een onderdeel van de natuurkunde is, waar je met trucjes niet verder komt. Het begrijpen en toepassen van quantumfysische inzichten vergt een gefundeerd begrip van wat wetenschap kenmerkt, hoe een wetenschappelijke theorie tot stand komt en wat de rol van wetenschappelijke modellen is. Onderwerpen als deze behoren niet bij de inhoudelijke kennis van natuurkunde, maar gaan over de *Aard van de Natuurwetenschappen*, of in het Engels de *Nature of Science* (NOS). NOS is een centraal begrip in de didaktiek van de bètawetenschappen en vormt naast de quantumfysica de basis van mijn onderzoek. Hoewel quantumfysica en NOS intrinsiek en onlosmakelijk aan elkaar verbonden zijn, bestaan er weinig publicaties die het expliciet het verband leggen tussen het leren van quantumfysica en NOS.

Quantumfysica

De wiskundige beschrijving van quantumfysica vormt sinds meer dan honderd jaar de basis voor indrukwekkende wetenschappelijke en technologische ontwikkelingen. Tegelijkertijd zijn er ook al net zo lang onbeantwoorde vragen over wat de quantumfysica over de werkelijkheid zegt.

Quantumobjecten, zoals elektronen of lichtquanten, vertonen eigenschappen die elkaar in de klassieke natuurkunde uitsluiten en voor een deel alleen aan golven en voor een ander deel alleen aan deeltjes kunnen worden toegeschreven. Deze zogenoemde golf-deeltjedualiteit staat ook genoemd in de vwo-examensyllabus voor natuurkunde. Pogingen om de onomstreden wiskundige beschrijving van de quantumfysica met de waarneembare fenomenen te verbinden worden interpretaties van de quantumfysica genoemd. Met deze interpretaties kunnen de schijnbaar strijdige eigenschappen van quantumobjecten verklaard worden. De Kopenhaagse interpretatie, bijvoorbeeld, beschrijft met het zogenoemde complementariteitsbeginsel dat waarneembare eigenschappen van quantumobjecten niet alleen kunnen worden toegeschreven aan het quantumobject, maar ook afhankelijk zijn van de gebruikte meetapparatuur. Daarom vertoont volgens deze interpretatie een elektron golfgedrag, zolang er geen meting gedaan wordt. Zodra men echter meet waar een elektron is, zal men het nooit verspreid over een groot gebied (als een golf) vinden, maar altijd precies op één plaats, en lijkt het elektron dus op een klassiek deeltje.

Niet alle natuurkundigen vinden deze Kopenhaagse interpretatie zinvol, en er zijn ook interpretaties waarin elektronen wel degelijk altijd een gedefinieerde plaats hebben, ook als er geen meting plaatsvindt. Volgens deze interpretaties gedragen quantumobjecten zich veel meer zoals we het van deeltjes in de klassieke natuurkunde gewend zijn. Om waarneembare fenomenen te duiden, moeten in deze interpretaties andere - vaak moeilijk voorstelbare - aannames gemaakt worden. In de afgelopen eeuw zijn er steeds meer interpretaties bij gekomen die quantumfysische fenomenen kunnen beschrijven en waarmee correcte voorspellingen gedaan kunnen worden. Theoretische of empirische studies kunnen talrijke interpretaties niet falsificeren en tussen wetenschappers is er geen consensus over 'de beste' interpretatie. Integendeel, de onenigheid tussen natuurkundigen erover of, en, zo ja, hoe de quantumtheorie geïnterpreteerd moet worden, staat bekend als een van de langstlopende wetenschappelijke controverses (Greca & Freire, 2014).

Door de centrale rol van twee strijdige modellen (golven en deeltjes) en de verschillende mogelijke interpretaties, is de quantumfysica een uitzondering in de schoolnatuurkunde. Vaak wordt natuurkunde in lessen, schoolboeken en toetsen gepresenteerd alsof er op elke vraag een eenduidig antwoord gegeven kan worden. Zo kunnen leerlingen bijvoorbeeld het idee krijgen dat modellen een weergave van de werkelijkheid zijn en dat wetenschappelijke kennis zo zeker is dat er nooit iets aan zal veranderen. Voor het leren van quantumfysica is een dergelijk beperkt beeld van de natuurkunde nadelig. Het kan bijvoorbeeld gebeuren dat leerlingen die ooit het (planetaire) atoommodel van Bohr geleerd hebben, denken dat dit 'waar' is en het nut van quantumfysische atoommodellen niet inzien.

Veel onderzoekers adviseren leraren daarom om bij de eerste kennismaking van leerlingen met quantumfysica in te gaan op de rol van modellen in het ontwikkelen van wetenschappelijke kennis (Henriksen et al., 2018; Hoehn & Finkelstein, 2018; Küblbeck & Müller, 2002; Levrini & Fantini, 2013; Müller & Wiesner, 2002). Bij een dergelijke benadering komen ook de veranderlijkheid van modellen, theorieën en interpretaties ter sprake. Sommige onderwijsbenaderingen benadrukken ook controverses in de quantumfysica en de grenzen van de wetenschap (Dunlop & Veneu, 2019; Garritz, 2013; Niaz & Rodríguez, 2002). Ook al wordt de term NOS in de vakliteratuur over quantumonderwijs zelden genoemd, pleiten veel vakdidactische onderzoekers ervoor NOS-aspecten met leerlingen te bespreken om de quantumfysica voor hen toegankelijker te maken.

NOS

Het begrip NOS is vooral in de Verenigde Staten al sinds de 1960er jaren een onderwerp in het vakdidactisch onderzoek van de natuurwetenschappen. Bij NOS in het onderwijs gaat het niet zozeer om de filosofische vraag wat de aard van de wetenschap precies is. Veel meer wordt NOS gezien als belangrijk leerdoel dat bijdraagt aan de 'wetenschappelijke geletterdheid' van leerlingen (Driver & Easley, 1978; Lederman, 2007; McComas et al., 2020). Deze wetenschappelijke geletterdheid moet ertoe bijdragen dat leerlingen deel kunnen nemen aan maatschappelijke discussies over vraagstukken met natuurwetenschappelijke achtergronden.

Er is geen vastomlijnde definitie van NOS, maar het gaat er bij NOS-onderwijs om bij leerlingen (en leraren) de blik op de inhoud, procedures en producten van wetenschap en wetenschappelijke werkwijzen te verruimen. Daarvoor zou het wenselijk zijn als in natuurkunde-, scheikunde- en biologielessen niet alleen de resultaten van wetenschappelijk onderzoek als 'feiten' gepresenteerd worden. Leerlingen zouden moeten leren hoe onderzoek wordt gedaan, hoe wetenschappelijke kennis ontstaat en hoe zeker wetenschappelijke kennis is. Ook de grenzen van wetenschap en hoe wetenschap en maatschappelijke omstandigheden of persoonlijke denkbeelden elkaar beïnvloeden zou een lesonderwerp op school moeten zijn. Tabel S-1 geeft een overzicht over aspecten van NOS, die in de quantumfysicalessen aangesproken zouden kunnen worden en die ik in één of meerdere studies in dit proefschrift onderzocht heb. De voorbeelden van gewenste en ongewenste NOS-opvattingen stammen uit de rijke literatuur over NOS in het onderwijs (Abd-El-Khalick, 2014; Lederman et al., 2002; McComas, 1998; McComas et al., 1998; Osborne et al., 2003).

Onderzoek heeft uitgewezen, dat niet verwacht kan worden dat leerlingen 'terloops', bijvoorbeeld door practica of door onderzoekend leren, adequate opvattingen over NOS ontwikkelen (Khishfe & Abd-El-Khalick, 2002). Er moet expliciet aandacht voor NOS in natuurwetenschappelijke lessen zijn. Daarbij is het belangrijk dat leerlingen de kans krijgen om op diverse NOS-aspecten te kunnen reflecteren (Khishfe, 2014; McComas et al., 2020).

Tabel S-1 Overzicht van opvattingen over NOS aspecten en mogelijkheden deze in quantumfysicalessen aan te spreken.

NOS aspect	**Voorbeeld van een ongewenste opvatting**	**Voorbeeld van de gewenste opvatting**	**Voorbeeld van NOS-aspecten die relevant zijn in de quantumfysica voor het voortgezet onderwijs**
Methodologie (de rol van waarnemingen, experimenten en wetenschappelijke theorieën)	Theorieën zijn vage vermoedens. Experimenten zijn noodzakelijk voor het verwerven van kennis. Waarnemingen en experimenten kunnen wetenschappelijke theorieën bewijzen of weerleggen.	Een theorie is een samenhangende structuur van gevalideerde en algemeen geaccepteerde verklaringen van natuurfenomenen. Wetenschappers gebruiken diverse methoden (o.a. experimenten) en onderlinge uitwisseling om wetenschappelijke kennis te ontwikkelen. Waarnemingen kunnen wetenschappelijke theorieën ondersteunen of verzwakken.	De methoden die in de klassieke natuurkunde worden gebruikt (zo als de relatie tussen waarnemingen en theorie) zijn ook van toepassing in de quantumfysica. Gedachte-experimenten zijn in de quantumfysica een essentieel middel om fundamentele concepten te bespreken. Vaak wordt geprobeerd het principe van gedachtenexperimenten in praktijk te brengen. Dit leidde onder andere tot de realisatie van verstrengelingsexperimenten.
De rol van wetenschappelijke modellen	Wetenschappelijke modellen zijn een zo volledig mogelijke weergave van de werkelijkheid.	Modellen zijn geen pogingen om de werkelijkheid zo volledig mogelijk weer te geven, maar om bepaalde aspecten van natuurverschijnselen te verklaren of te voorspellen.	Afhankelijk van de situatie kan het golfmodel of het deeltjesmodel gebruikt worden om het gedrag van elektronen te beschrijven. Sommige eigenschappen van atomen kunnen worden verklaard met het Bohr-model, maar om het bestaan van atomaire energieniveaus te verklaren, wordt het deeltjes-in een doos-model gebruikt.
Voorlopigheid van wetenschappelijke kennis	Wetenschappelijk onderzoek levert absolute bewijzen op. Wetenschappelijke kennis is zeker en onveranderlijk.	Wetenschappelijke kennis staat altijd open voor ontwikkeling, verandering en verbetering.	Het is niet mogelijk quantumverschijnselen te begrijpen met klassieke natuurkunde.
Creativiteit in de wetenschap	Wetenschappers volgen altijd een strikte onderzoeksmethode (de natuurwetenschappelijke methode).	Wetenschappers werken vaak niet met een vooraf vastgelegde methode, maar gebruiken hun creativiteit en verbeeldingskracht.	De ontwikkeling van de quantumtheorie was alleen mogelijk door out-of-the-box-denken en creatieve (gedachten-) experimenten.
Subjectiviteit in de wetenschap	Wetenschappers zijn objectief en daarom is er maar één juiste interpretatie van waarnemingen mogelijk	Wetenschappelijk onderzoek wordt beïnvloed door persoonlijke voorkeuren van onderzoekers en historische, culturele, sociale en economische omstandigheden.	In tegenstelling tot andere wetenschappers was Einstein ervan overtuigd dat de quantumtheorie nog niet volledige is, omdat hij de rol van toeval niet als fundamenteel kon aanvaarden.
Controverses in de wetenschap	Nieuwe wetenschappelijke kennis wordt door mede-onderzoekers direct erkend en aanvaard.	Discussies en meningsverschillen over wetenschappelijke ideeën zijn essentieel voor de wetenschappelijke ontwikkeling. Er kunnen verschillende interpretaties naast elkaar bestaan.	De discussies tussen Einstein en Bohr laten zien hoe persoonlijke filosofische visies tot verschillende interpretaties leiden. Er bestaat geen consensus over de interpretaties van de quantumfysica. Alleen een open debat zonder strikte ideologieën maakt nieuwe ontwikkelingen mogelijk.

Onderzoeksdoelen

Zoals boven besproken, is het leren van quantumfysica nauw verbonden met bepaalde NOS-gerelateerde vragen over modellen en interpretaties. Als deze vragen in de natuurkundelessen niet besproken worden, is de kans groot dat leerlingen quantumfysica als onlogisch en onbegrijpelijk ervaren en onjuiste ideeën ontwikkelen. Andersom lijkt de quantumfysica hierdoor een zeer geschikt onderwerp om samen met leerlingen op hun opvattingen over wetenschap te reflecteren.

Hoewel het verband tussen NOS en quantumfysica duidelijk lijkt, was er aan het begin van mijn onderzoek weinig kennis over praktische aspecten van de integratie van NOS in het onderwijs over quantumfysica. In Nederland was bijvoorbeeld niet bekend of andere landen curricula voor het secundair onderwijs hadden waarin verbanden tussen aspecten van NOS en quantumfysica expliciet genoemd worden. Ook internationaal was er weinig onderzoek gedaan naar de inhoud van quantumcurricula in verschillende landen of naar de veronderstelde voordelen van NOS in quantumfysicalessen. Het was bijvoorbeeld onbekend of leerlingen of leraren nadrukkelijke aandacht voor NOS in de quantumfysica als nuttig zouden ervaren.

Het doel van deze dissertatie was het om de integratie van NOS in het quantumfysica-onderwijs vanuit verschillende perspectieven te onderzoeken. Ik heb ervoor gekozen om te beginnen met het zoeken naar goede voorbeelden in buitenlandse natuurkundecurricula. Vervolgens zocht ik uit of er bij het onderwerp quantumfysica een verband bestaat tussen het conceptuele begrip van leerlingen en hun ideeën over NOS-aspecten. Tenslotte ging ik met behulp van speciaal ontwikkeld lesmateriaal het perspectief van docenten op het gebruik van NOS in quantumfysicalessen verkennen. Hieronder vat ik de doelstellingen en resultaten van mijn onderzoeken samen.

Internationale curriculumperspectieven (hoofdstuk 2)

Om de huidige stand van zaken van quantumfysica in het natuurkundeonderwijs op scholen in verschillende landen te analyseren, heb ik curricula (officiële landelijke leerplannen of syllabi) van vijftien, voornamelijk Europese, landen verzameld, vergeleken en geanalyseerd. De doelen van dit onderzoek waren: (a) het geven van een gestructureerd overzicht van quantumfysica-onderwerpen in de natuurkundecurricula van verschillende landen; (b) het vaststellen van overeenkomsten en verschillen tussen de inhoud van quantumfysica in de curricula; en (c) het onderzoeken of en hoe quantumfysica in verband wordt gebracht met NOS-aspecten in de curricula van verschillende landen.

In dit onderzoek werden 23 curriculumdocumenten uit 15 landen betrokken, die meestal alleen in de landstaal beschikbaar waren. De documenten kwamen uit Australië, België, Canada, Denemarken, Duitsland (documenten van zeven deelstaten), Finland, Frankrijk, Italië, Nederland, Noorwegen, Oostenrijk, Portugal, Spanje, Verenigd Koninkrijk (twee documenten) en Zweden. Zie voor een gedetailleerd overzicht van alle onderwerpen per land tabel 2-4.

De volgende zeven onderwerpen waren in natuurkundecurricula van minstens acht van de 15 onderzochte landen (of minstens 15 van de 23 onderzochte documenten) te vinden, en vormen daarmee het actuele kerncurriculum voor quantumfysica in het voortgezet onderwijs: discrete energieniveaus (lijnenspectra), interacties tussen licht en materie, golf-deeltje-dualiteit/complementariteit, materiegolven met kwantitatieve berekeningen (de Broglie-golflengte), technische toepassingen van quantumfysica, het onbepaaldheidsprincipe van Heisenberg, en het probabilistische of statistische karakter van voorspellingen voor quantumfysische experimenten.

In de zeven landen met uitgebreidere leerplannen voor quantumfysica konden drie verschillende thematische zwaartepunten worden vastgesteld: (1) golffunctie en wiskundige beschrijvingen, vergelijkbaar met de traditionele universitaire curricula; (2) atoomtheorie, waardoor een verbinding met het scheikundecurriculum mogelijk is; en (3) filosofische aspecten, zoals gedachte-experimenten en verschillende interpretaties van de quantumfysica.

Hoewel er voor de verplichte leerdoelen in de quantumfysica in de meeste landen duidelijke begrippenlijsten bestonden, werden NOS-aspecten over het algemeen als vrijblijvende desiderata geformuleerd. Expliciete verbanden tussen quantumfysica en NOS waren schaars. Alleen de Noorse en zes Duitse curriculumdocumenten vermeldden expliciet NOS-gerelateerde leerdoelen in de quantumfysica. Daarin wordt bijvoorbeeld in detail het niveau beschreven dat van leerlingen verwacht wordt bij het evalueren en communiceren van NOS-aspecten in de quantumfysica.

Samenvattend heeft dit onderzoek veel resultaten opgeleverd die relevant en nuttig zijn voor diverse onderzoekers en beleidsmakers: er werd aangetoond dat quantumfysica in veel landen (soms al decennia lang) een vast onderdeel van het verplichte natuurkundecurriculum voor 17- tot 19-jarigen is. De inhoud van deze curricula kan een inspiratie voor curriculumontwikkelaars in verschillende landen zijn. Ook kan de ontwikkelde structurering de basis vormen voor verder onderzoek. Voor mijn eigen onderzoek kon ik vaststellen dat het gebrek aan onderzoek over NOS in quantumfysica in het voortgezet onderwijs te verklaren is doordat veel landen (zoals het Verenigd Koninkrijk, Frankrijk of Italie) weliswaar ervaring hebben met quantumfysica, maar een verband met NOS niet zichtbaar is in officiële curriculumdocumenten. In de VS, waar veel aandacht is voor NOS-onderwijs, is daarentegen quantumfysica bijna nooit onderdeel van het highschoolcurriculum.

Perspectieven van leerlingen (hoofdstuk 3)

Hoewel veel onderzoekers argumenteren dat een beperkt begrip van NOS-aspecten hinderlijk is bij het leren van quantumfysica, is hierover geen onderzoek bekend. Met dit onderzoek wilde ik daarom verkennen of er een verband bestaat tussen NOS-opvattingen van leerlingen en hun begrip van quantumfysica. De hoofdhypothese voor deze fase van het onderzoek was dat goed ontwikkelde (gewenste) opvattingen over NOS en het begrijpen van quantumfysica elkaar versterken. Deze hypothese zou bevestigd worden als leerlingen met een goed ontwikkeld begrip van NOS hoger scoren op een quantumfysicabegrippentoets, en andersom leerlingen met een goed conceptueel begrip van quantumfysica aspecten van NOS beter begrijpen.

Aan dit onderzoek namen 240 leerlingen van zes scholen deel. Alle deelnemende leerlingen hadden reguliere natuurkundelessen (zonder speciale aandacht voor NOS) gevolgd, waardoor een variatie aan NOS-opvattingen verwacht kon worden. Er werden twee deelonderzoeken uitgevoerd: met een speciaal ontwikkelde meerkeuzetoets werd van alle deelnemers hun begrip van quantumfysicabegrippen bepaald. Vervolgens werden 24 leerlingen geselecteerd op verscheidenheid van resultaten in de quantumfysicabegrippentoets. Door middel van interviews werden hun NOS-opvattingen in de context van quantumfysica bepaald. De onderzochte NOS-aspecten in dit onderzoek waren: wetenschappelijke modellen, veranderlijkheid van wetenschappelijke kennis, creativiteit, subjectiviteit en controverses in de wetenschap.

Het verrassende resultaat van dit onderzoek was dat alle geïnterviewde leerlingen - onafhankelijk van hun score op de quantumtoets - zeer goed ontwikkelde en genuanceerde opvattingen over alle onderzochte NOS-aspecten in de quantumfysica hadden. Hoewel dus de onderzoekshypothese niet bevestigd kon worden, leverde deze studie een interessant inzicht op: In tegenstelling tot veel NOS-onderzoeken in andere contexten (Lederman et al., 2002; Moss et al., 2001), had geen enkele deelnemer 'naïeve' of ongewenste opvattingen (zie Tabel S-1) over NOS in de context van quantumfysica. Dit duidt er op dat quantumfysica inderdaad een uitstekende context is om leerlingen te laten reflecteren op hun ideeën over de aard van de natuurwetenschap.

Lesmateriaal (hoofdstuk 4)

Bij het onderzoek voor hoofdstuk 3 viel op dat alle deelnemende leerlingen weliswaar in de interviews goed ontwikkelde NOS-opvattingen konden formuleren, maar dat zij bijvoorbeeld nooit iets over verschillende interpretaties van de quantumfysica in hun lessen gehoord hadden. Om de aandacht voor NOS-aspecten in quantumfysicalessen te bevorderen, heb ik lesmateriaal ontwikkeld dat docenten hierin kan ondersteunen.

Om dit materiaal flexibel en aanpasbaar te maken, heb ik voor de vorm van een PowerPoint-presentatie gekozen. In deze presentatie (van ca. 150 slides) wordt de gehele inhoud van het onderwerp 'quantumwereld' uit de Nederlandse syllabus gedekt. De meeste slides bevatten uitleg over quantumfysische begrippen, experimenten, uitlegvideo's, rekenopgaven of computersimulaties. De inhoud van de presentatie is onder andere gebaseerd op verschillende onderzoeken naar leerproblemen van leerlingen en mogelijke efficiënte onderwijsstrategieën voor het leren van quantumfysica en NOS (Baily & Finkelstein, 2015; Bungum et al., 2018; Clough, 2020; Levrini & Fantini, 2013; Myhrehagen & Bungum, 2016; Smith et al., 2009). Daarbij heb ik ook gebruik gemaakt van vrij op het internet toegankelijke bronnen. Op verschillende slides wordt nadrukkelijk aandacht besteed aan NOS-aspecten in de quantumfysica, zoals wetenschappelijke modellen en interpretaties. Om een actieve, reflecterende rol van leerlingen te bevorderen, bevat het materiaal schrijfopdrachten, discussiestellingen en conceptvragen (Mazur, 1997) die argumentaties stimuleren.

Onderzoek heeft uitgewezen, dat leraren alleen veranderingen in hun lessen toepassen, als die verandering past in hun eigen manier van lesgeven, praktisch uitvoerbaar is, en niet te veel voorbereidingstijd en energie kost (Doyle, 1977). Een belangrijk doel van het lesmateriaal is daarom dat het docenten met verschillende voorkeuren en in verschillende onderwijsomgevingen makkelijk gemaakt wordt om expliciet aandacht te besteden aan NOS-aspecten bij de behandeling van de quantumfysica. Noch het aantal te gebruiken slides, noch de volgorde of manier van gebruiken werd de docenten voorgeschreven. Op deze manier is het voor docenten mogelijk het materiaal aan te passen aan hun eigen manier van lesgeven, hun lesdoelen, hun lesboek en hun leerlingen.

Perspectieven van docenten (hoofdstuk 5)

Om leerlingen te stimuleren op hun NOS-opvattingen te reflecteren, is het noodzakelijk dat NOS-aspecten in de natuurkundelessen besproken worden. Mijn hoofddoel in dit deel van het onderzoek was te verkennen of docenten er in hun dagelijkse lespraktijk iets voor voelden NOS aspecten in quantumfysica te bespreken. Dit is niet vanzelfsprekend omdat NOS-aspecten niet in het eindexamen getoetst worden, omdat docenten weinig kennis van NOS uit hun eigen opleiding meebrengen en omdat de meest gebruikte natuurkundemethodes in Nederland weinig ondersteuning voor NOS-aspecten in de quantumfysica bieden (Borin, 2021).

In dit onderzoek was het niet de bedoeling om ‘in principe’ de mening van docenten over NOS in de quantumfysica te testen, omdat zelfs een positieve houding van docenten niet betekent dat zij NOS inderdaad in hun lessen gebruiken. Evenmin wilde ik docenten ervan overtuigen of zelfs verplichten om NOS in hun quantumfysicalessen te gebruiken. Ook dat zou namelijk niet garanderen dat docenten er langdurig gebruik van zouden maken. Het in hoofdstuk 4 besproken lesmateriaal is. Want docenten gebruiken nieuw lesmateriaal in de praktijk alleen al zij dit achten vinden voor het behalen van hun - vaak onbewustte - doelen (Westbroek et al., 2017).

Om te onderzoeken of docenten in de praktijk NOS-aspecten in lessen over quantumfysica gebruiken, werd tien docenten van verschillende scholen gevraagd het in hoofdstuk 4 besproken lesmateriaal te gebruiken. Concreet waren de doelen van deze studie om te onderzoeken (a) welke aangeboden NOS-aspecten door docenten in hun quantumfysicalessen gebruikt werden en welke werkvormen zij daarbij kozen; (b) welke doelen de docenten wilden bereiken door deze NOS-aspecten in de lessen quantumfysica te behandelen. De vorm van het onderzoek kan een ‘ecologische benadering’ genoemd worden, omdat het niet alleen om de interactie van de docent met het materiaal gaat, maar ook nadrukkelijk rekening gehouden wordt met het ´ecosysteem´ waarin het leren plaatsvindt: de alledaagse complexe onderwijspraktijk van leraren.

De deelnemende docenten stond het vrij om delen van het lesmateriaal in hun reguliere 6-vwo-klassen al dan niet in combinatie met hun methode te gebruiken. Zij kregen vooraf een korte uitleg over conceptvragen, die door de leerlingen via een online-stemsysteem beantwoord konden worden. Tijdens de lessenserie over quantumfysica (gedurende drie tot vijf weken) observeerde ik bij elke docent minstens één les en verzamelde ik schriftelijke en online-antwoorden van leerlingen. Na afloop van de lessenserie heb ik de docenten over het gebruik van het materiaal uitgebreid geïnterviewd.

Uit de lesobservaties en de interviews bleek dat negen van de tien deelnemende docenten reflectieve NOS-lesactiviteiten in hun lessen gebruikt hadden. Acht van de tien docenten hadden expliciet de rol van modellen in de quantumfysica met de leerlingen besproken. Ze deden dit vooral om leerlingen te helpen concepten zoals de golf-deeltjedualiteit te begrijpen. Twee andere NOS-aspecten (de veranderlijkheid van wetenschappelijke kennis en controverses in de wetenschap) werden elk door vijf docenten in hun quantumfysicalessen besproken.

De doelen die docenten met de NOS-gerelateerde lesactiviteiten wilden bereiken, waren meestal niet primair het aanleren van adequate NOS-voorstellingen. Veeleer stelden acht docenten NOS-aspecten in dienst van het leren van begrippen uit de quantumfysica. Zes docenten wilden met conceptvragen over NOS-aspecten het nadenken en argumenteren van leerlingen stimuleren. Drie docenten beoogden nieuwsgierigheid en interesse bij leerlingen te wekken door de menselijke kant van de wetenschap te laten zien.

Hoewel de docenten dus verschillende doelen nastreefden, is de bemoedigende uitkomst van dit onderzoek dat de meeste deelnemers de waarde van NOS-aspecten bij het leren van quantumfysica erkenden. Dit is vooral opmerkelijk omdat er in de huidige natuurkundesyllabus geen NOS-aspecten van de quantumfysica genoemd worden en ook in de meeste Nederlandse lesboeken nauwelijks aan de orde komen. Uit dit onderzoek werd niet alleen duidelijk dat NOS-onderwijs in quantumfysica in de praktijk mogelijk is, maar ook dat het aangereikte materiaal om meerdere redenen aan een behoefte van de deelnemende docenten voldeed. Er is daarom reden om aan te nemen dat meer docenten aandacht aan NOS in hun quantumfysicalessen zouden besteden als zij geschikt lesmateriaal ervoor zouden hebben.

Conclusies

Dit proefschritft levert diverse bijdragen tot het onderwijs in de quantumfysica in het voortgezet onderwijs en de rol die NOS daarin kan spelen. Veel van de gevonden inzichten kunnen gebruikt worden voor zowel natuurkundedidactisch onderzoek als voor praktische toepassingen in de ontwikkeling van curricula, lesmateriaal en professionele ontwikkeling van docenten.

Zo is het categoriseren en analyseren van quantumfysicacurricula (hoofdstuk 2) belangrijk omdat het voor het eerst een vergelijking van officiële curriculumdocumenten in verschillende landen geeft. Dit kan als voorbeeld voor soortgelijke onderzoeken dienen, maar biedt ook beleidsmakers in verschillende landen de mogelijkheid hun curriculum met dat van andere landen te vergelijken en inspiratie voor veranderingen op te doen.

Dit proefschrift biedt ook vernieuwende methodologie: De ecologische benadering van het perspectief van de docenten (hoofdstuk 5) kan waardevol zijn voor vakdidaktisch onderzoek en onderwijsvernieuwingen. Door de manier van onderzoeken wordt rekening gehouden met diverse randvoorwaarden, zoals tijdsdruk en onrealistische verwachtingen over de mogelijkheden van docenten en leerlingen, die vaak het slagen van een onderwijsvernieuwing in de weg staan. Deze ecologische benadering zou een bijdrage kunnen leveren aan het doelgericht ontwikkelen van bruikbare onderwijsvernieuwingen.

Verder hebben de resultaten van dit proefschrift laten zien dat er veel potentie is in het verbinden van quantumfysica en NOS in het vwo:

- Enkele buitenlandse curricula laten zien hoe NOS-aspecten in de leerdoelen van quantumfysica geïntegreerd kunnen worden.
- Voor leerlingen biedt de context van quantumfysica een doelmatige ingang om op NOS-aspecten te reflecteren.
- Geschikt lesmateriaal stelt docenten in staat om NOS-aspecten van quantumfysica in hun lessen te behandelen.
- Docenten verwachten verschillende doelen te bereiken door NOS te gebruiken: in de eerste plaats het beter begrijpen van de quantumfysica.

Om meer leraren en leerlingen van de gevonden voordelen te laten profiteren, zouden zowel in de examensyllabus, maar ook in lesboeken en in de lerarenopleiding meer aandacht moeten komen voor NOS-aspecten in de quantumfysica. Voor Nederland betekent dit concreet, dat NOS-specten zichtbaar in het programma vastgelegd zouden moeten worden. Want als de examensyllabus van natuurkunde voor het vwo expliciet NOS-aspecten als leerdoelen van de quantumfysica zou noemen, is het waarschijnlijk dat auteurs van lesboeken er ook aandacht aan besteden. Dit zou leraren helpen om NOS vaker in hun lessen te bespreken. Idealiter zou er een ruime keuze aan lesmateriaal ontwikkeld moeten worden om het NOS-onderwijs voor leraren met verschillende voorkeuren en in verschillende omstandigheden te ondersteunen. Bij universiteiten en hogescholen zou al tijdens de opleiding van natuurkundedocenten meer aandacht voor NOS in de quantumfysica en voor het belang van NOS in het algemeen moeten komen. Bovendien zouden docenten de mogelijkheid moeten krijgen om ervaringen op te doen met werkwijzen die voor NOS onderwijs noodzakelijk zijn, maar in natuurkundelessen niet vaak gebruikt worden. Vooral het organiseren en leiden van discussies op verschillende manieren (peer discussion, of discussies in grotere groepen) lijkt hierbij belangrijk te zijn.

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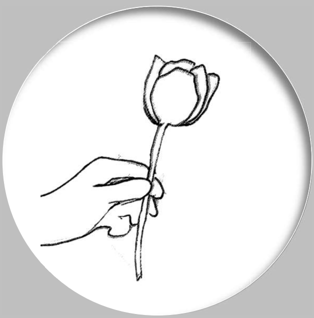
Dankwort



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Contributions

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PROFESSIONAL CONTRIBUTIONS

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Curriculum vitae[1]

Heike Kirsten Elisabeth Stadermann was born in Schwerte, Germany, on April 4, 1966. She completed her secondary education at Theodor-Heuss-Gymnasium in Hagen. From 1985 to 1993, she followed the undergraduate education in Physics and Mathematics at the University of Münster (WWU) and the University of Cologne. During her studies in Cologne (1988 - 1993), she received a scholarship from the Konrad-Adenauer-Stiftung for students of exceptional academic achievement and outstanding social commitment. From 1990 to 1993, she worked as a research assistant at the Max-Planck Institute for Radio Astronomy in Bonn.

In 1993, Kirsten moved to the Netherlands to attend the Physics graduate school at the University of Leiden. She wrote her master's thesis in Physics on infrared detection and mixing properties of MIM diodes while researching in the Quantum Optics Research Group in the Huygens Laboratory, Leiden, in 1994. Subsequently, she obtained a post-graduate teaching degree in Physics (University of Delft, 1995) and Mathematics (University of Leiden, 1996).

Kirsten worked as a physics and mathematics teacher at College Hageveld, Heemstede, from 1995 to 2002. After moving to the north of the Netherlands in 2002, she started teaching physics at Praedinius Gymnasium in Groningen. While there, she worked on curriculum projects to integrate modern physics into upper secondary education, supervised several STEM competitions, and developed projects for gifted students. She encouraged many students to participate in national and international science competitions and accompanied winning teams to the finals of the "International Young Physicists' Tournament" and the Beamline for Schools Competition". In 2009, the Netherlands' Physical Society (NNV) awarded her the price for the Dutch Physics teacher of the year. In 2015, she was selected for the Dutch delegation to the European conference 'Science on Stage' in London.

Since 2016, Kirsten has combined her work as a physics teacher with PhD research at the University of Groningen's Institute for Science Education and Communication (ISEC). She was awarded a Dodoc scholarship from the Dutch Ministry of Education, Culture and Science for her project on the connection between quantum physics and Nature of Science in upper secondary education. She is currently a lecturer for Physics Education at Europa-Universität Flensburg, Germany, and a lecturer and physics teacher trainer at the University of Twente, Netherlands.

Kirsten is married to Simon van der Sluijs. They have four children.

[1] The value of a person lies not in what they achieve, but in what they are (Theodor Calvary).