‘Why don’t you just tell us what light really is?’ Easy-to-implement teaching materials that link quantum physics to nature of science

To cite this article: Kirsten Stadermann and Martin Goedhart 2022 Phys. Educ. 57 025014

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‘Why don’t you just tell us what light really is?’
Easy-to-implement teaching materials that link quantum physics to 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

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activities, while being adaptable to teachers’ individual needs and affordances. We hope to inspire teachers to address NOS in their QP lessons.

Keywords: secondary school, teaching materials, quantum, nature of science, teacher, quantum poster

Supplementary material for this article is available online

1. Teaching quantum physics (QP) 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 do 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 [1], 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 4 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.

2. Theoretical background

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 [2, 3]. 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 [4]. Therefore, many national science curriculum documents mention NOS in their general intentions. However, explicit measurable NOS learning outcomes are rarely expressed in these documents [5], 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 [6, 7]. NOS teaching should include reflective elements, and ideally be provided in both highly contextualised and decontextualised activities [8–10]. Typical examples for decontextualised NOS instruction are black (or even pink) box activities [11–13], 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 [14].

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 [15].

Unfortunately, there are many reasons why NOS receives little attention in physics lessons: teachers lack the necessary teaching strategies [16, 17], physics textbooks generally pay little attention to NOS [18, 19], and teachers do not see it as their task to teach NOS because it is not tested in summative exams [20, 21].

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 [22]. 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 [23]. However, topics in the physics curriculum should also serve those students who will not study sciences beyond school [24, 25]. 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 [26].

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 1 (see appendix 1 available online at stacks.iop.org/PED/57/025014/mmedia). This poster gives an overview of NOS aspects relevant to teaching conceptual QP. It is a practical support for teachers because textbooks commonly do not emphasise these NOS aspects [27]; 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
### 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 [28], 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

<table>
<thead>
<tr>
<th>NOS aspect</th>
<th>Example of the NOS aspect in Quantum Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>The role of scientific Models</td>
<td>Depending on the situation, either the wave model or the particle model is useful to describe electrons or light.</td>
</tr>
<tr>
<td>Tentativeness of scientific knowledge</td>
<td>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.</td>
</tr>
<tr>
<td>Creativity in science</td>
<td>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.</td>
</tr>
<tr>
<td>Subjectivity in science</td>
<td>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)</td>
</tr>
<tr>
<td>Controversies in science</td>
<td>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.</td>
</tr>
</tbody>
</table>

Figure 1. Connection between NOS aspects and QP (classroom poster). [The image in the third row has been obtained by the author(s) from the Pixabay website https://pixabay.com/photos/cat-feline-animal-kitty-box-5453535/ where it was made available under the Pixabay License. It is included within this article on that basis. The image in the fourth row has been obtained by the author(s) from the Pixabay website https://pixabay.com/photos/dice-six-gambling-to-play-689618/ where it was made available under the Pixabay License. It is included within this article on that basis. The image in the fifth row has been obtained by the author(s) from the Wikimedia website https://commons.wikimedia.org/wiki/File:Albert_Einstein_ETH-Bib_Portr_05937.jpg, where it is stated to have been released into the public domain. It is included within this article on that basis.]
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particular class situation. Some parts of the materials are intended to provide teachers with content about unfamiliar topics (for e.g. 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. 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 2 [29]. 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.

5. Examples

The introductory slide (figure 2) gives teachers a sense of the type of material in the presentation. Teachers will probably not use this 1st slide in class.

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 3 [30]. 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 [31]. Similar to the designers of the Norwegian ReleQuant [32, 33], 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 [34] 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 [35]. 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 3 are also suitable to begin a class discussion on NOS aspects such as ‘the role of scientific models’ and ‘the tentative-ness of science knowledge’.

Another way to start a discussion is by introducing the history of QP. Education researchers point out that students who encounter QP for the
Figure 2. First slide of the teaching material.

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!

Figure 3. Example slide with a concept question without a clear answer.

What is an electron?

Choose one or more correct answers.

A. A very small negatively charged particle.
B. A particle in one of the shells of an atom, never in the nucleus.
C. If it comes from the nucleus of an atom: Beta radiation.
D. A standing wave.
E. A travelling wave.
F. None of the above is correct.
first time experience similar problems to those experienced by scientists at the beginning of the 20th century [36, 37]. Figure 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.

The material explicitly addresses some conceptual problems which are often neglected in QP teaching [38]. For example, the slide in figure 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 the different perspectives of scientists are necessary for scientific development [26]. 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 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?’.

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 [39]. 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 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
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.

Figure 5. Example of an explanatory slide. [This image of Niels Bohr has been obtained by the author(s) from the Wikimedia website https://commons.wikimedia.org/wiki/File:Niels_Bohr.jpg, where it is stated to have been released into the public domain. It is included within this article on that basis.]

Alternative interpretation 2

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/WHyT7DkUarQ
(Veritasium: Is This What Quantum Mechanics Looks Like? - YouTube)

Figure 6. Example slide with an explanatory video. [This image of water has been obtained by the author(s) from the Pixabay website https://pixabay.com/photos/drop-of-water-drop-impact-ripples-578897/ where it was made available under the Pixabay License. It is included within this article on that basis.]
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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 [39]. 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.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We want to thank all teachers who shared their ideas about the teaching resources with us. The research for this article is supported by DUDOC (PhD grant for teaching- and teacher-related studies), funded by the Dutch Ministry of Education, Culture, and Science (OCW).

Ethical statement

Research for this paper was carried out in accordance with the principles outlined in IOPP’s ethical policy. This paper does not contain any personal data, and the anecdotally quoted students and teachers cannot be identified. All students and teachers have given explicit consent to participate in a research project.

References


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Received 21 August 2021, in final form 16 October 2021
Accepted for publication 15 November 2021
https://doi.org/10.1088/1361-6552/ac39e7

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Phys. Educ. 57 (2022) 025014
Why don’t you just tell us what light really is?

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Kirsten Stadermann started her career as a research physicist in Germany and subsequently became a secondary school physics teacher in the Netherlands. In her research at the University of Groningen she has studied the possibilities to integrate Nature of Science in the teaching of quantum physics at upper secondary schools. Currently, she is working as a teacher trainer at the University of Flensburg (Germany) and at the University of Twente (The Netherlands).