Investigating teachers' and students' experiences of quantum physics lessons: opportunities and challenges

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Investigating teachers’ and students’ experiences of quantum physics lessons: opportunities and challenges

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ABSTRACT

Background: Quantum physics has found its way into upper secondary school physics curricula worldwide. This trend coincides with increased attention for conceptual understanding in physics education in general and quantum physics education in particular. Students’ conceptual difficulties of learning quantum physics are regularly reported. Little systematic attention has been paid to the opportunities and challenges teachers and students experience for teaching and learning quantum physics.

Purpose: The opportunities and challenges secondary school teachers and their students experience were examined to gain insights into their perspectives teaching and learning quantum physics. These insights inform improvements in teaching and learning quantum physics at the secondary school level.

Sample: Three teachers and five of each teacher’s students participated in this study.

Design & Methods: A context analysis was conducted to explore the experiences of the teachers and students. Teachers were individually interviewed; students were interviewed in a focus group session. The semi-structured interviews were analysed resulting in three case reports. These case reports were used to conduct a cross-case analysis to find common opportunities and challenges among teachers’ and students’ experiences.

Results: Teachers and students felt that teachers had an important role in supporting students’ understanding of quantum physics. Teachers were challenged to enthuse their students for quantum physics as they struggled to convey the relevance of the subject to their students. Freely available digital materials were considered as an opportunity to support students’ conceptual understanding as they have the potential to engage students and benefit their conceptual development.

Conclusion: Several implications are discussed to improve teaching and learning of quantum physics, such as opportunities for teacher professional development as well as ways to effectively use freely available digital materials.

KEYWORDS
Context analysis; interview study; physics education; secondary education; teachers’ and students’ experiences

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Introduction

Quantum physics (QP) has recently found its way into many upper secondary school curricula in countries such as the UK, Germany, and France (Stadermann, Van Den Berg, and Goedhart 2019). These curriculum changes aimed at providing secondary school students with the chance to learn about modern physics (e.g. Bøe, Henriksen, and Angell 2018). It was assumed that incorporating QP into the physics curriculum would overcome the growing tension between physics as taught in secondary schools and physics as taught in universities and communicated through the media (cf. Lyons 2006). Conceptual understanding of QP and visualisations are more emphasised at the secondary school level, compared to the curricula at universities (Bøe, Henriksen, and Angell 2018; Krijtenburg-Lewerissa et al. 2017).

Secondary school students have difficulties when developing their conceptual understanding which has been reported across a variety of settings and approaches. Topics in QP that students struggle to understand are for example light (Henriksen et al. 2018), atomic spectra (Savall-Alemany et al. 2019), potential wells, and tunneling (Krijtenburg-Lewerissa et al. 2020). Students have conceptual difficulties because they are required to a) map abstract mathematical models to experiences in the physical world, b) come to terms with counterintuitive phenomena and concepts, c) transition from a deterministic worldview to a probabilistic one, and d) understand the language to express QP phenomena and concepts (Bouchée et al., under review. These requirements hinder students’ meaning-making process leading them to hold on to classical or common sense notions while learning QP (e.g. Krijtenburg-Lewerissa et al. 2020). Insights into students’ conceptual difficulties have led to the development of different teaching strategies, such as the use of digital materials or discussing the history and philosophy of QP (Krijtenburg-Lewerissa et al. 2017).

There is a large body of literature available on students’ conceptual difficulties learning QP, however, there is relatively little known about the challenges teachers and students experience for teaching and learning QP. These experiences can provide a valuable addition to research on conceptual difficulties as they provide insights into the demands teachers and students face while teaching and learning QP. One example of this kind of research concerned Norwegian secondary school teachers (Bungum et al. 2015). They reported to experience the lack of mathematical skills of their students as a challenge to support students’ conceptual understanding of QP. Their students experienced difficulties adopting new learning strategies and engaging in self-regulatory activities in an environment where conceptual understanding of QP is emphasized and mathematical skills receive less attention (Bøe, Henriksen, and Angell 2018). Exploring these types of challenges combined with the opportunities teachers and students indicate to meet their challenges, can provide new and different insights into ways to support QP teaching practice and benefit student learning.

This study aimed to provide an in-depth exploration of the opportunities and challenges secondary school teachers and students experience for teaching and learning QP. A context analysis through interviews (Nieveen and Folmer 2013) was conducted to explore the experienced opportunities and challenges of teachers and their students for teaching and learning QP. This context analysis was conducted in the Netherlands where
QP was introduced in 2013 as part of the revised Dutch physics curriculum set by the government for upper secondary school level for the pre-university track.

To guide our context analysis the subsequent research question was formulated: *What are the opportunities and challenges teachers and students experience for teaching and learning quantum physics?*

**Teachers’ and students’ experiences of quantum physics**

The available literature on teachers’ and students’ experiences with QP education mainly focuses on the university level. It is claimed that university teachers’ attitudes and approaches towards QP are shaped by the belief that a major goal of QP courses is to ensure that students learn the mathematical formalism associated with QP to prepare students for research in the field of physics (Siddiqui and Singh 2017). This belief is implicitly or explicitly reflected in teaching practices which emphasize the mathematical formalism and can be disconnected from everyday experiences (e.g. Dreyfus et al. 2019; Johansson et al. 2018). University teachers experience QP as difficult to teach due to its abstract and counterintuitive nature (Akarsu 2010) and disagree on various pedagogical issues, such as a) which philosophical stances about the physical interpretation of QP to take on, b) whether to avoid reference to classical physics, and c) if conceptual aspects of QP should be considered (e.g. Akarsu 2010; Baily and Finkelstein 2015; Siddiqui and Singh 2017).

Secondary school teachers felt more insecure and less confident in teaching QP than other parts of the physics curriculum (Bungum et al. 2015). Teachers reported that it was difficult to support secondary school students’ conceptual understanding, as teachers were not able to discuss the details of the mathematical formalism of QP since students lacked mathematical skills. Teachers said that they depended more on textbooks for teaching QP than when teaching other parts of the physics curriculum and that they sometimes struggled to engage students with the QP content (Bungum et al. 2015).

Some secondary school students experienced QP to be more motivating than other topics in physics due to the philosophical implications (e.g. Bungum et al. 2015), while others felt that QP is abstract and even absurd, and they had problems accepting the probabilistic worldview that QP inherently imposes (e.g. Henriksen et al. 2014). Students can experience disappointment and lose interest in QP when problem-solving activities are overemphasized (Johansson 2018). In these environments, there was little room for students’ conceptual questions which did not match their initial expectations about QP as an exciting and thought-provoking topic (Johansson 2018). A lack of problem-solving exercises could also lead students to experience difficulties (e.g. Petri and Niedderer 1998). In environments where a conceptual understanding of QP was emphasized, students struggled to develop self-efficacy since they needed to change their previously acquired (problem-solving-centred) learning strategies to develop their understanding (Bøe, Henriksen, and Angell 2018).
The Dutch Quantum Physics Curriculum

In the Dutch educational system, the learning goals are set by the government in the national curriculum. Teachers have a certain amount of freedom to work towards these goals. Generally, teachers can design the content scheduling of their lessons, the learning activities that students undertake, and the materials that they use to meet the goals set by the curriculum. These materials can be textbooks created by printing houses that align with the curricular goals set out by the government or freely available online materials, created and trialed by other teachers, or themselves.

QP is a mandatory subject for students within the physics curriculum and is assessed in the national examinations in the final year of upper secondary education. The QP content should be taught with a focus on conceptual understanding (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo 2010). This focus means that questions in the national examinations focus on conceptual understanding and reasoning, where explicit quantitative calculations would be evenly matched with qualitative (i.e. reasoning) questions (Paus 2012).

The rationale to add QP to the physics curriculum was that current and relevant physics contexts and topics could enthuse students, subject matter in the new curriculum needs to relate to modern research (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo 2010), and scientific literacy should be promoted (Krijtenburg-Lewerissa et al., 2018). QP content should allow teachers and students to discuss current scientific insights and technological developments (i.e. addressing scientific literacy) through the addition of numerous applications, such as digital cameras, lasers, and electron microscopes (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo 2010).

Method

The experiences of three Dutch teachers and their students (fifteen in total) with the QP part of the physics curriculum were explored in this study. A context analysis through interviews was chosen because it allowed the development of a deeper understanding of teachers’ and students’ opportunities and challenges for teaching and learning QP (Nieveen and Folmer 2013). Each teacher together with his/her five students was considered as an individual case; hence there were three cases. The analysis of these three cases allowed for an in-depth investigation and comparison of both the experiences of teachers and their students, within each case and across the cases.

Participants

Several upper-secondary school teachers that participated in an in-service teacher education activity on QP content were approached to participate in this study. Teachers with two different approaches to teaching were purposely selected to participate in this study. The first teaching approach was a student-centred approach where students were encouraged to learn actively and collaboratively, and through self-exploration. This student-centred approach was chosen since research has shown that these active learning environments can promote students’ engagement and can contribute to students’ understanding of QP (e.g. Krijtenburg-Lewerissa et al. 2017), and therefore might result in
Table 1. Information of participants.

<table>
<thead>
<tr>
<th>#</th>
<th>Pseudonym</th>
<th>Age</th>
<th>Experience</th>
<th>Education</th>
<th>School</th>
<th>Teaching approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rick</td>
<td>30</td>
<td>Five years</td>
<td>Master of science in applied physics Master of science in physics education</td>
<td>I</td>
<td>Student-centred approach frequently using digital materials to encourage students to learn actively, collaboratively, and through self-exploration.</td>
</tr>
<tr>
<td>2</td>
<td>Sarah</td>
<td>37</td>
<td>Over 10 years</td>
<td>Master of science in applied physics Master of science in physics education</td>
<td>II</td>
<td>Teacher-centred approach using lectures and classroom discussion to teach QP. Digital materials were seldomly incorporated into the classroom.</td>
</tr>
<tr>
<td>3</td>
<td>George</td>
<td>52</td>
<td>Over 10 years</td>
<td>Master of science in physics Master of science in physics education</td>
<td>II</td>
<td>Teacher-centred approach using lectures and classroom discussion to teach QP. Digital materials were occasionally used in the classroom.</td>
</tr>
</tbody>
</table>

different students’ learning experiences. The second approach was a more teacher-driven teaching approach (i.e. lecturing) which is common for Dutch physics teachers (Ottevanger, Folmer, and Heijnen 2018). Three teachers from two schools responded positively to our request. Table 1 presents an overview of these three teachers.

Rick (pseudonym), working in school I, frequently used digital materials to support his student-centred teaching practices. He supplemented the textbook with digital materials, such as YouTube videos and simulations. The digital materials were presented on a school-related website hosted by Rick. In the lessons, students commonly worked in pairs or groups on the assignments presented on the website or in the textbook. Rick assisted students when they had questions about the assignments or the QP content.

Sarah and George (pseudonyms) were colleagues at school II. They were asked (and volunteered) to participate in this study because they worked with the same textbook as Rick and used a more teacher-driven approach to teaching QP as compared to Rick. This teacher-driven approach meant that they mainly used lectures and classroom discussion to teach QP, with hardly any (Sarah) or occasional (George) digital materials.

Students were selected by their teachers, based on their perceived (potential) experience of learning QP (a mix of positive, neutral, and negative). Teachers were also asked to obtain a relatively equal distribution between girls and boys. All students (five per teacher) were in the last year of upper secondary school in the pre-university track. Eight girls and seven boys, aged 17 or 18, participated.

Data collection strategies

Semi-structured interviews were conducted after a series of (on average) sixteen lessons of 50 minutes on QP. The students were interviewed (in groups of five) in a semi-structured focus group interview (45–50 minutes). The teachers participated individually in an hour-long semi-structured interview. Teachers were interviewed after their students,
to be able to inquire on issues that arose from the students' interviews. This sequence also provided teachers with the chance to discuss students’ recommendations for improvement (i.e. opportunities).

The interview questions were inspired by the curricular spider web (Van den Akker 2003), which is a general model that systematically captures ten important topics related to teaching and learning (Figure 1). The interview questions related to the ten spider web components made it possible to discuss a variety of topics, all linked to teachers’ and students’ experiences.

The interview questions that accompanied each curriculum component were slightly different for teachers than for students, to fit the aim and context of our investigation. Examples of questions to teachers were: ‘what was the aim of teaching QP?’ and ‘what materials did you use while teaching QP?’ Examples of student questions were: ‘what was the aim of the lessons on QP?’ and ‘what materials did you use to learn QP?’. Additionally, the researcher asked the teachers how they prepared for the lessons on QP and what they felt about the QP questions in the national examinations.

The researcher moderated the interviews by keeping participants on topic and by summarising participants’ remarks for validation. Specific opportunities or challenges that came up during the interviews were explored more thoroughly when deemed appropriate by the interviewer. The interviews were audio-recorded and transcribed for data analysis.

Figure 1. Curricular spider web (Van den Akker 2003) as presented by Van den Akker (2013, 59).
Data analysis

The transcribed interviews were segmented using ATLAS.TI software in the first round of data analysis. The ten components of the curricular spider web were used to identify interview segments and descriptively code these segments (Miles, Huberman, and Saldana 2014). Segments could consist of a sentence, sentences, or a whole paragraph when a statement related to a particular component persisted through more sentences. Multiple codes were given to a segment when this segment would include statements on different components.

After this round of descriptive coding, two other researchers (the second and third authors) coded the identified segments in Sarah’s interview independently. The coding of the segments and the meaning of the codes were discussed among the three researchers until full consensus was reached. In practice, the discussion centred on segments coded as ‘rationale’ or ‘goal’. It was decided to code segments that expressed a reason for learning QP (or lack thereof) as ‘rationale’. Segments that said something about the feasibility of learning QP were coded as ‘goal’. The final codes were described in a final version of the codebook. With this extended codebook, the first author coded the remaining transcripts.

To continue the data analysis, first, the previously coded segments were synthesized into themes that came up per spider web component (like a parent node). Second, these themes were either coded as an opportunity or a challenge, based on whether the theme was described as an enabler or a constraint for teaching and learning QP (like child nodes). Third, three preliminary case reports were written (Miles, Huberman, and Saldana 2014) that provided an overview of the opportunities and challenges that were discussed within each case per spider web component.

The audit procedure (Akkerman et al. 2008) was used to assess the quality of this second analysis. Two auditors (second and third authors) separately read the preliminary case descriptions and subsequently identified the main issues within each case. Next, the three researchers discussed the analysis of each case until consensus was reached about the specific opportunities and challenges that defined each case. An overview of these opportunities and challenges within each case is provided in Table 2. It should be noted that an empty cell indicates that there were no particular opportunities or challenges related to that particular spider web component that arose during the interviews, or these issues were found to be tangential for that case.

Based on the outcomes of the audit procedure, three final case reports were written to describe the essence of each case as discussed in the research team; they are summarized in the following results section. The final case reports were presented to the individual teachers as part of a member check (Miles, Huberman, and Saldana 2014), to ensure that their experiences were appropriately interpreted. The teachers indicated that their perspectives were well interpreted.

Finally, a cross-case analysis was conducted to explore the opportunities and challenges across the cases based on the similarities and differences of teachers’ and students’ experiences. For instance, the use of digital materials was experienced as an opportunity for learning in all cases. These opportunities and challenges across the cases were related to literature on teaching and learning QP with the constant comparative method (Timonen, Foley, and Conlon 2018). Comparing and contrasting our results with the
Table 2. Opportunities and challenges as found in each case.

<table>
<thead>
<tr>
<th>Spider web component</th>
<th>Dutch curriculum</th>
<th>Rick</th>
<th>Sarah</th>
<th>George</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rationale</strong></td>
<td>QP helps students understand current scientific insights and technological applications. QP helps to relate several STEM subjects. QP should help overcome growing distance between university physics and school physics. QP should help enthuse students for physics.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>QP helps students understand current scientific insights and technological applications.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Why should students learn?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>QP helps to relate several STEM subjects. QP should help overcome growing distance between university physics and school physics. QP should help enthuse students for physics.</td>
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</tr>
<tr>
<td></td>
<td>O: Rick said that QP made it possible to talk about modern physics in classroom. C: Rick felt that QP did not help prepare students for university physics. O: Rick's students felt that QP made it possible to talk about modern physics.</td>
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<tr>
<td></td>
<td>C: Sarah was dissatisfied with the addition of QP to the physics curriculum.</td>
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<tr>
<td></td>
<td>C: Sarah said that her students experienced QP to be irrelevant.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: Sarah said that students disliked QP, especially girls that are interested in health related studies.</td>
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<tr>
<td></td>
<td>C: Sarah's students questioned the relevance of QP.</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>O: George felt that students needed to understand QP to be aware of current scientific insights.</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>C/O: George's students mentioned that addressing more technological applications could help students experience more relevance.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O: George's students experienced that understanding QP is feasible.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Aims and objectives</strong></td>
<td>Students should realize that QP is necessary to describe the behavior of light and matter at the smallest scale. Students should understand how QP differs from classical physics. Students should be able to apply wave-particle duality, Heisenberg uncertainty relationship, QP tunneling and the concept of energy quantization in several contexts.</td>
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</tr>
<tr>
<td></td>
<td>Towards which goals are students learning?</td>
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</tr>
<tr>
<td></td>
<td>O: Rick felt that the learning goals are feasible.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: Rick mentioned that the learning goals for QP are too vague as expressed in the Dutch QP curriculum.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: Rick's students said that it was difficult to reach learning objectives with the current teaching approach.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: Sarah found the aims and objectives of QP unfeasible.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: Sarah's students had problems understanding why or when QP is necessary to explain or reason about certain QP phenomena.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O: George felt that the QP curriculum is feasible and that students can handle the content.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: George experienced that students lacked conceptual understanding of QP.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O: George's students experienced that understanding QP is feasible.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
Table 2. (Continued).

<table>
<thead>
<tr>
<th>Spider web component</th>
<th>Dutch curriculum</th>
<th>Rick</th>
<th>Sarah</th>
<th>George</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Content</strong></td>
<td>Conceptual understanding of QP phenomena and properties. Numerous practical applications of abstract QP properties, such as the Scanning Tunneling Microscope or the Transmission Electron Microscope. Topics, such as the wave-particle duality, PE-effect, energy quantization, Heisenberg uncertainty relation and QP tunneling.</td>
<td>C: Rick said that conceptual understanding is emphasized as compared with other topics in the curriculum. C: Rick said that his students found QP to be difficult and abstract. C: Rick felt that QP is not a good preparation for physics at university. C: Rick's students noticed a focus on conceptual understanding. C: Rick's students experienced little coherence between QP topics.</td>
<td>C: Sarah felt that QP lacked practical applications and context. C: Sarah expressed that QP is too difficult for her students. C: Sarah's students experienced QP to be different from other topics because conceptual understanding is emphasized. C: Sarah's students experienced that QP had no practical applications. C: Sarah’s students found QP to be difficult because it is weird and refutes everything that was learned earlier.</td>
<td>C: George stated that the emphasis is on conceptual understanding when teaching QP. C: George felt that QP lacked clear context and applications to help explain QP. C: George expressed that QP is difficult and abstract for students. C: George felt that he lacked knowledge of QP applications and context to improve his teaching. C: George's students realized that conceptual understanding is emphasized. C: George's students said that more applications should be addressed.</td>
</tr>
<tr>
<td>Learning activities</td>
<td>Demonstration experiments and simulations should help students understand.</td>
<td>O: Rick appreciated the diversity and coherence between the learning activities. C: Rick felt that there were too many learning activities. C: Rick's students said that there were too many learning activities and that they took too much time.</td>
<td>O: Sarah valued lecturing and collective classroom discussion when teaching QP. C: Sarah's students felt that Sarah's lectures were insufficient to grasp QP topics. C: Sarah's students said they focused more on understanding theory by reading and summarizing rather than doing problem solving exercises, because conceptual understanding was emphasized. C/O: Sarah's students watched videos and read internet sites to help them understand QP topics.</td>
<td>O: George felt that lecturing and collective classroom discussion were essential when teaching QP. O: George said that watching videos together with his students helped students understanding. O: George's students felt that his lectures were beneficial for their understanding of QP. O: George's students expressed that watching videos helped them visualize abstract QP topics.</td>
</tr>
</tbody>
</table>
### Table 2. (Continued).

<table>
<thead>
<tr>
<th>Spider web component</th>
<th>Dutch curriculum</th>
<th>Rick</th>
<th>Sarah</th>
<th>George</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Teacher role</strong></td>
<td></td>
<td>O: Rick felt that future students would need more substantive support when learning QP.</td>
<td>O: Sarah felt that she should be the content expert when teaching QP.</td>
<td>O: George felt that he should be the content expert when teaching QP.</td>
</tr>
<tr>
<td>How is the teacher facilitating students’ learning?</td>
<td></td>
<td>O: Rick’s students wanted him to take on the role of the content expert.</td>
<td>O: Sarah’s students said that she was not able to convey QP appropriately.</td>
<td>O: George’s students helped students understand the essence of videos that were watched collectively during his lessons.</td>
</tr>
<tr>
<td><strong>Materials &amp; resources</strong></td>
<td></td>
<td>O: Rick expressed that digital materials supported students’ understanding.</td>
<td>O: Sarah felt that digital materials are beneficial because they can visualize QP phenomena.</td>
<td>O: George’s students valued his enthusiasm for the subject.</td>
</tr>
<tr>
<td>With what are students learning?</td>
<td></td>
<td>O: Rick said that digital materials allowed students to learn QP in different ways.</td>
<td>C: Sarah seldom used digital materials in her classroom and referenced them in homework assignments.</td>
<td>O: George’s students valued his enthusiasm for the subject.</td>
</tr>
<tr>
<td><strong>Grouping</strong></td>
<td></td>
<td>O: Rick’s students said that digital materials helped their understanding.</td>
<td>C: Sarah’s students did not use digital materials made available by Sarah. They instead used videos, internet sites they found online to learn about topics they found difficult.</td>
<td>O: George’s students said that digital materials helped visualize QP phenomena.</td>
</tr>
<tr>
<td>With whom are students learning?</td>
<td></td>
<td>C: Rick’s students found it difficult to collaborate on assignments because every student worked on their own pace.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td></td>
<td>C: Rick’s students found it difficult to be on task in the classroom because the table setting and the overall layout of the classroom allowed for social talk.</td>
<td>C: Sarah said that students were expected to work at home with several simulations on QP because she lacked the time and computers were not easily available during her lessons.</td>
<td>O: George watched the videos in class, so he could guide students’ interpretation of the content.</td>
</tr>
<tr>
<td>Where are students learning?</td>
<td></td>
<td>C: Sarah’s students reported that they did not use any simulation at home or at school.</td>
<td>C: Sarah’s students reported that they did not use any simulation at home or at school.</td>
<td>O: George’s students watched the videos in class and at home to rehearse the content that was addressed.</td>
</tr>
<tr>
<td>Spider web component</td>
<td>Dutch curriculum</td>
<td>Rick</td>
<td>Sarah</td>
<td>George</td>
</tr>
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<td>----------------------</td>
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</tr>
<tr>
<td><strong>Time</strong></td>
<td>N/A</td>
<td>C: Rick’s students said that there were too many learning activities and that they took too much time.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><em>When are students learning and how much time does it take them?</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Assessment</strong></td>
<td>Assessment focused on conceptual understanding. Additionally, new types of questions and more recent context will be included</td>
<td>C: Rick stated that the focus on conceptual understanding in assessment is too much.</td>
<td>C: Sarah felt that QP should not be a part of the national examination. C/O: Sarah’s students used various digital materials, such as videos and internet sites to prepare for their examinations.</td>
<td>C: George felt that students have problems assessing their own understanding. O: George wanted to add more diagnostic questions so students could assess their own learning better. O: George’s students wanted more diagnostic questions to assess their own understanding.</td>
</tr>
<tr>
<td><em>How is their learning assessed?</em></td>
<td></td>
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</tbody>
</table>

O: Opportunity & C: Challenge
literature helped to position our findings into a broader context and to identify possible implications to improve QP teaching and learning.

**Results**

The results first present the within-case analyses of Rick, Sarah, and George, and their respective students. The results from the cross-case analysis are discussed subsequently.

**Rick’s case**

Rick and his students felt that the aims and objectives of the QP curriculum were feasible. Rick commented: ‘Yes, what we do now is feasible and within the capabilities of the students (Rick)’. They all recognized that QP made it possible to discuss recent scientific issues in the classroom, which is in line with the rationale of the Dutch QP curriculum.

Rick experienced two challenges when teaching QP. First, Rick wondered why QP was taught at the upper secondary school level. He said that although teaching QP introduced his students to modern physics, he felt that other topics might better suit this purpose. He added: ‘I noticed that it [learning QP] is difficult because quantum physics is pretty mathematical and abstract and that it does not coincide with students’ prior knowledge and skillset (Rick).’ Students found QP difficult as well, one reason being: ‘They are all quite different topics that you had to learn, as I experienced it, and I found that to be difficult (Student 2-Rick)’. Rick felt that the way the content of QP was covered at secondary school did not prepare students for university. He said: ‘I do not think this is a foundation that is useful at university, where other subjects that were traditionally taught would have added more (Rick)’.

Second, Rick found the learning goals of the QP curriculum to be vague and student assessments were focused too much on conceptual understanding: ‘In any case, it is a trend that there are much less quantitative problems and much more qualitative problems. Well, that is good on the one hand, although I feel that it is a bit too much in quantum physics (Rick)’. His students also noticed that conceptual understanding was emphasised and commented that it differed from other physics subjects where conceptual understanding received less attention. For instance, one student said: ‘It took much more effort [to learn QP] because it was different from what we have learned before (Student 5-Rick)’.

Rick and his students acknowledged digital materials, such as videos and computer simulations, as an opportunity for learning because they support students’ conceptual understanding. Rick felt that his learning activities with digital materials helped them understand QP better. One student confirmed: ‘… those simulations (…) it helped you understand the content very well because every time you had to take that next thinking step. First this, so this and that, and then this happens and why does that happen, so yes … in hindsight it was worthwhile, for me (Student 1-Rick)’. Rick added when he was asked how students learned with digital materials: ‘I feel that students were very involved with the content. I hope that students noticed that they understood the content better. Additionally, there were all kinds of different ways that they could learn this topic (Rick)’.

However, both Rick and his students felt that the number of learning activities with digital materials was too large. This meant an overload of work for the students: ‘… after a while I was like, okay, this is just too much. (…) I thought after completing the first couple of questions, that I understood it, and then I would have to do the same all over (Student
Students said that they could not collaborate while working with digital materials because they all worked at their own pace. Therefore, students could not engage in the collaborative process of exploration and sense-making as was intended by Rick. Additionally, Rick and his students mentioned that substantive support on the content was lacking to help students overcome their insecurities about their understanding. One student, for instance, commented: ‘However, I would have liked if there had been a little more classroom instruction, like, yes guys, normally (in classical physics) you have learned it like this, but now (in QP) it’s like that (Student 5-Rick).’

Overall, Rick and his students reported that QP learning goals were feasible. Nonetheless, Rick and his students experienced QP to be a difficult topic because it is mathematical and abstract, and because topics felt unrelated and differed from what they had learned before. Rick and his students expressed that the addition of QP made it possible to discuss recent developments in science and technology. Digital materials, such as videos and computer simulations, were perceived to be an opportunity for the development of conceptual understanding. Several issues related to the implementation of the digital materials into the classroom (e.g. the number of learning activities, teacher role, grouping, timing) remained, which resulted in students experiencing a need for more classroom instruction.

Sarah’s case

Sarah found it challenging to understand why QP was added to the physics curriculum. She said: ‘I actually think quantum physics shouldn’t be a topic in the national examination.’ She felt that QP was irrelevant for her students because it is abstract and lacked clear applications and context. She said: ‘The importance, why do I have to learn that, that is what students asked me and why do I have to be able to do this? Why, what is the relevance, … if the national [QP] curriculum could clarify this, then students would find it [QP] more interesting (Sarah)’. Sarah found QP to be too abstract for some of her students and she indicated that it was not feasible for these students to reach the objectives of the national QP curriculum.

Sarah’s attitude towards teaching QP reflected, to some extent, in the attitudes of her students, as her students also struggled to describe clear applications and to find the relevance of QP: ‘It [QP] is difficult, you cannot see quantum physics, it is difficult to illustrate. For example, when you have to learn momentum, you can use the standard example of two colliding billiard balls to visualize it for students. However, quantum physics, that is weird, it is possible to understand but much harder (Student 1-Sarah)’. Another student added: ‘Whether it [QP] is relevant, for me … its learning about electricity or forces and all, that seems relevant to me. However, I cannot see why learning quantum physics is relevant to me (Student 4-Sarah)’. Students reported that QP was challenging and different from other physic topics because it emphasised conceptual understanding: ‘I think it is also a different way of thinking. Because there is a clear set of rules at other topics … rules, formulas and when you can use them, quantum physics, for me, was a totally different way of thinking (Student 4 – Sarah)’. Another student said: ‘I found it [QP] to be weird, especially at the start, because you never heard anything about it and … [laughs]. You learn things in physics for six years and then suddenly everything is incorrect, and you have to learn something entirely different. That is a bit strange (Student 5-Sarah)’.
Sarah provided classroom instruction about the QP content and engaged in a classroom discussion about the meaning of certain QP concepts. Most students agreed that Sarah’s classroom instructions were difficult to understand. When students were asked to provide suggestions for next year’s lessons, one student said: ‘after a classroom instruction … doing a problem together, [that helps you understand] how to tackle such a problem (Student 4-Sarah)’. Sarah’s teaching practice was not aligned with the challenges her students experienced, and students resorted to different types of learning activities at home (e.g. reading the textbook, writing summaries, and using digital materials found online, like YouTube videos and websites). One student commented: ‘Especially browsing online for [information about] phenomena that I did not understand and whether another teacher can explain this digitally (Student 3-Sarah)’.

Sarah acknowledged the use of digital materials, such as computer simulations, as an opportunity to engage her students. She said: ‘I have looked at several computer simulations and I think they are interesting, fun, and different than my uninteresting explanation (Sarah)’. However, Sarah felt that she lacked time to prepare and use digital materials in her classroom. She decided to give homework assignments that involved the use of such simulations. When Sarah’s students were asked whether they used computer simulations when learning QP, they all said that they did not use any simulations at home.

Overall, Sarah and her students experienced a variety of challenges with the implementation of the QP curriculum. Sarah felt that QP was too difficult and irrelevant for her students to learn and she was dissatisfied with the addition of QP to the physics curriculum. Sarah’s attitude towards QP might have influenced her students who were mainly sceptical about the addition of QP, the relevance of the content, and the quality of the learning activities. After reading the case report, Sarah said that her instruction with a new group of students was simplified and the importance of QP for science and technology was emphasized. She felt these changes to her teaching approach had helped her students’ understanding.

**George’s case**

Both George and his students experienced the benefits of the addition of QP to the physics curriculum and felt that the learning objectives were (eventually) feasible. George said: ‘I think that something [the theory of QP] that is 100 years old should simply be part of the curriculum . . . recent insights are included in other subject matters, so it is weird not to include it [in the physics curriculum]. Of course, it is difficult and abstract, but that is just the way it is. So, it is weird if you [student] would leave here [secondary school] with the image that an electron is a ball that revolves around the nucleus (George)’. George and his students experienced QP to be difficult, but they all suggested that the lectures and classroom discussion were essential to support the learning of QP. One student said: ‘. . . because he explained the theory and accompanied this with an assignment. He directly applied the theory [in the assignments], and that is nice (Student 5-George)’.

There were two challenges that George and his students experienced. George and his students felt that QP lacked clear applications. This lack of applications led some students to perceive a lack of relevance. One student recommended: ‘I have heard many people ask, why am I doing this [QP], why do I have to learn this? However, there are applications and future applications that can be discussed in the classroom so students will understand
something more about the aim of [learning] quantum physics. Therefore, if you can talk about technologies and devices in which it [QP] is used, then it would be less abstract (Student 2-George). Nonetheless, George and his students expressed that QP allowed the development of particular modern technology and to discuss recent scientific insights.

The second challenge was the lack of materials (e.g. exam questions) to assess students’ level of understanding. George experienced that his students had problems assessing their conceptual understanding and stated that understanding was often superficial: ‘They [students] sometimes think they fully comprehend everything. While, in fact, they can only apply the formula … (George).’ George and his students recommended adding more diagnostic questions to help future students better prepare for upcoming assessments.

George incorporated digital materials in his teaching by asking his students to search for videos on QP that were available online. Students had to provide George with links to the videos that they found, and George assessed the quality of these materials. He checked whether the videos fitted his didactical intentions, and, if so, used these videos in his classroom to discuss particular QP topics. During these plenary discussions, George encouraged students to make sense of the topic at hand by posing questions and elaborating on students’ difficulties. This approach exposed students to QP topics in a variety of ways through multiple digitally available materials. In turn, this approach helped students appreciate the affordances of digital materials to visualise abstract QP phenomena and concepts: ‘I think the image that a video depicts stays with students, so when we talk about the experiment the image automatically reappears (Student 3-George).’ Furthermore, George explained that he supported the development of students’ conceptual understanding by clarifying the content of the digital materials and evoking classroom discussions. George said: ‘… they [the videos] are very fast, and in English and afterwards, it is like, what is the essence of this, what have we learned? You try to discuss this in a classroom discussion, everyone watches the video, collectively, and we discuss this. What was the most important issue … (George).’ In this process, George seemed able to transform the online available materials into effective instructional materials by aligning the aims and content of the video, together with the role of the teacher to facilitate student learning.

Overall, although QP was experienced as a difficult topic by George and his students, the use of classroom lectures, discussion, and digital materials were experienced to be opportunities for learning as these helped students overcome their initial insecurities. The two challenges identified were that George and his students lacked clear applications of QP and proper materials to assess student learning.

**Cross-case analysis**

In this section, common opportunities and challenges found across the cases are discussed. These opportunities and challenges are compared and contrasted with available literature to put our results into context.

A first opportunity that came up in all three cases was that both teachers and students acknowledged the role of the teacher as a content expert for supporting students’
understanding of QP. However, the QP-content expert role is new and challenging to Dutch teachers, who now face teaching and learning difficulties.

Our teachers and students experienced that QP is difficult for students because a) QP could not be directly experienced (cf. McKagan et al. 2008), b) topics felt unrelated, c) QP contradicted what students learned in classical physics (cf. Taber 2005), and d) learning QP felt unrelated to earlier learning experiences in classical physics since a conceptual understanding of QP was emphasized (cf. Boe, Henriksen, and Angell 2018). As one student said: ‘Perhaps another way of thinking is required [when learning QP]. I mean, if you have a formula, and you know the rules of algebra, then you can just fill in [the formula] and solve it [the problem] and with quantum physics that just does not work at all [Student 2-George]’. This discontinuity was noticed by students in all cases and could be related to the limited amount of calculations and concrete answers, as conceptual understanding in QP classroom practice was emphasized (Boe, Henriksen, and Angell 2018). George noticed that his students often overrated their conceptual understanding, as his students resorted to mathematical problem-solving to express their conceptual understanding (cf. Dreyfus et al. 2019). Sarah and George both expressed that lectures and classroom discussions were opportunities to help students develop conceptual understanding. Their students added that working on problem-solving activities supported by the teacher could benefit their understanding since this prepared them for their homework exercises.

The three teachers each considered the rationale differently, and their attitudes towards teaching and learning QP were reflected in their students’ attitudes. Sarah was very critical towards the addition of QP to the physics curriculum and did not understand why one would need to teach it at the upper secondary level. This attitude affected her students who also questioned the relevance. Rick and his students were somewhat ambivalent towards the addition of QP. Although Rick and his students said that QP allowed for more modern physics in the classroom, Rick suggested that other topics might be better suited to prepare students for university. Students added that learning QP was challenging and took more effort than other topics. George felt that QP should be taught at secondary school, and his students were more positive about learning it than for instance Sarah’s students. At the same time, all three teachers had problems to enthuse their students for QP and struggled to convey the relevance of QP.

George, Sarah, and their students all perceived a lack of practical and technological examples and applications of QP, implying a need for such examples and applications. This perceived lack of applications did not align with the intentions of policymakers and curriculum developers, since the intended Dutch curriculum explicitly mentioned various modern physics applications and examples to promote students’ interest (Commissie Vernieuwing Natuurkundeonderwijs havo/vwo 2010). Although in each case some students were enthusiastic about the addition of QP to the physics curriculum, most students across the three cases felt that QP made physics less enjoyable to them. These opposing learning experiences confirm the dichotomy, as described in the literature, that QP can make physics more interesting for some students while others struggle with the learning experience (e.g. Bungum et al. 2015; Henriksen et al. 2014).

An opportunity to improve QP teaching and learning that came up in all three cases was the use of freely available digital materials, such as YouTube videos and computer simulations. Teachers and students indicated that digital materials had the potential to
engage students with QP and to support their conceptual understanding through exploration and visualization of the phenomena (cf. Bøe, Henriksen, and Angell 2018).

Two challenges came up incorporating these digital materials. The first challenge was found in Rick’s case. His students were required to assume a more active, self-directed role when engaging in small-group discussions while learning QP as lectures or plenary discussions were not included in Rick’s lessons. Research by Bungum, Bøe, and Henriksen (2018) has shown that digital materials that elicit small-group discussion can help students to a) articulate conceptual difficulties, b) deepen their understanding through the exchange of ideas, and c) pose new questions. Nevertheless, in Rick’s case, incorporating digital materials led to a tension between students’ self-exploration of QP phenomena and the provision of enough structure and substantive support for students’ conceptual development (cf. Gong et al. 2015).

A second challenge concerning digital materials emerged in Sarah’s case. Sarah only occasionally used digital materials in her classroom or in homework assignments to enhance classroom lectures and discussions. Sarah’s students tended to resort to digital materials that they found on the internet at home in preparation for their classes or exams but ignored extra-curricular materials made available by Sarah or the textbook. In the students’ home environment, it was difficult for students to check the reliability of the content of these digital materials. Such unguided use of digital materials might hinder conceptual understanding of QP (Girwidz et al. 2019).

Discussion

This study aimed to explore the opportunities and challenges upper secondary school teachers and students experienced. The opportunities and challenges found in this study were compared and contrasted with literature to provide suggestions for teaching and learning QP. In this section, the implications of our findings will be discussed.

Results from this study illustrate several challenges teachers experienced to provide support of students’ learning process, regardless of the chosen pedagogical approach (i.e. student- or teacher-centred). The results suggest that providing feedback and addressing the rationale of QP are ways teachers can support student learning.

Three findings from this study illustrate the need for effective feedback and provide suggestions on what this feedback might look like. First, QP is difficult due to its abstract and counterintuitive nature (Krijtenburg-Lewerissa et al. 2017). Students in this study experienced difficulties to visualize or illustrate QP phenomena as well as difficulties to accept the strange and weird consequences these phenomena inherently impose. Second, students struggled to reduce the insecurities about their understanding. Students felt that QP contradicted what they had learned earlier in classical physics and they had to adopt different learning strategies as conceptual understanding of QP was emphasized. This emphasis on conceptual understanding made it difficult for students to resort to mathematical problem-solving to express their understanding (cf. Bøe, Henriksen, and Angell 2018; Dreyfus et al. 2019). Third, some students seemed to overrate their understanding of QP as they falsely held on to mathematical problem-solving to express their conceptual understanding.
Combining these three findings, it seemed that students needed the teacher to provide feedback on their developing understanding as the teacher sanctions their meaning-making process as content expert, even more than in classical physics, due to students’ lack of personal experience with these abstract and counterintuitive phenomena (Taber 2005). Moreover, providing students with feedback should allow them to become aware of the fallacies in their presumptions and make them sensitive for more suitable strategies to come to understand QP. Effective feedback on students’ meaning-making process in QP should therefore be at the task and process level (cf. Hattie and Timperley 2007). At the task level, feedback needs to be provided on students’ conceptual understanding and address their conceptual difficulties. At the process level, feedback should provide students insights into their current understanding, as well as make them aware that different learning strategies are required to develop their conceptual understanding.

Teacher support for learning can also be improved by addressing the rationale for QP. The current study found that students’ attitudes towards QP can be positively impacted if the teacher better understands or conveys the rationale for QP education, as, for instance, George did. Teachers and students lacked available rationales for QP as they only mentioned addressing modern physics and university readiness as reasons. Rationales could be addressing the various aspects of the nature and history of science in QP (Stadermann, Van Den Berg, and Goedhart 2019) or the different elements of scientific literacy that QP allows to discuss (Krijtenburg-Lewerissa et al., 2018). Providing teachers with multiple rationales might help them better understand the added value of QP in education and shape their role as content expert with a spectrum of reasons.

Addressing more (or different) applications and examples than the ones recommended by the curriculum or textbook might help teachers provide rationale and enthuse their students for QP. Teachers and students in this study lacked clear applications which they felt hindered them to explain or understand the rationale of QP education. Applications and examples of QP should relate to students’ life-world to motivate students to overcome their initial difficulties (e.g. Bungum et al. 2015; Rodriguez et al. 2020). These contexts could include more current technological applications (e.g. quantum computers), as recommended by one of the interviewed students. Discussing current technological applications based on QP principles was shown to develop students’ scientific literacy and their conceptual understanding, which could, in turn, promote relevance and student interest (e.g. Baily and Finkelstein 2015; Bungum et al. 2015; Krijtenburg-Lewerissa et al., 2018). Other contexts could also be considered to promote relevance and student interest, such as design, art, fiction (e.g. Bobroff and Bouquet 2016), and the historical and philosophical foundations of QP (e.g. Bøe, Henriksen et al. 2018; Bungum et al. 2015). Future research could explore such new contexts to understand what and how contexts can promote relevance and student interest.

Furthermore, this study has shown the opportunities of the use of digital materials to improve the teaching and learning of QP. This is in line with earlier research that found that the use of digital materials is generally experienced by students as a beneficial tool for their understanding of QP (e.g. Bøe, Henriksen, and Angell 2018; Gong et al. 2015; Kohnle et al. 2015). Nevertheless, several challenges were experienced while implementing these materials (e.g. the provision of structure or substantive support). Two
suggestions can be made based on our findings to further capitalize on the opportunity to use freely available digital materials for teaching and learning QP.

The first opportunity to improve the use of digital materials is that whole-class discussions on QP topics could be included when digital materials are used by students to explore QP phenomena or concepts (cf. Rodriguez et al. 2020). The cross-case analysis showed that teachers and students assigned an important role to the teacher to support students interpreting QP. In all cases, teacher mediation of the digital materials was perceived to be essential because a lack of support hindered the effective use of these materials. These findings support earlier findings that students can perceive difficulties while working with digital materials when teacher mediation is limited (Bungum, Bøe, and Henriksen 2018; Gong et al. 2015). As Bungum, Bøe, and Henriksen (2018) suggested, Rick’s students might have benefited from a combination of dialogic and authoritative approaches that George used when he incorporated digital materials in his classroom.

The second opportunity to improve the use of digital materials is to include interactive assessment methods, such as quizzes and puzzles, that allow for ongoing formative assessment and the development of students’ conceptual understanding. Teachers can use such assessment methods to quickly evaluate students’ understanding, elicit students’ conceptual difficulties, provide feedback on students’ understanding, and adapt their teaching approach accordingly. The use of interactive assessment methods has been shown to increase students’ engagement and improve their conceptual understanding of QP (Deslauriers and Wieman 2011).

The methodology used in this context analysis allowed for three extensive case reports to convey our results in-depth and to make them understandable and applicable to others. Multiple discussions within the research team during the data analysis and member checks were conducted to portray these three cases as honestly and unbiased as possible (Yin 2017). The case reports were used to explore the opportunities and challenges across these cases based on the similarities and differences of teachers’ and students’ experiences. The cross-case findings were related to the literature on teaching and learning QP. Comparing and contrasting our results with the literature helped to illustrate that our findings are not particular for the Dutch context and helped to formulate suggestions to tackle the challenges and capitalize on the opportunities identified in this study.

One limitation of this study concerns the small number of participants. Three teachers and five of their students participated in our study. More participants could provide more and different examples of the QP teaching and learning experiences of Dutch teachers and students. In turn, this could lead to more and different opportunities and challenges.

The interview data were self-reported. Follow-up research will include an evaluation of whether the opportunities identified in this study indeed enhance students’ learning experiences when put into practice. In our future research a study is performed into a) how the role of the teacher could be shaped to let students experience more suitable teacher support and b) the implementation of digital materials that allow students to develop their conceptual understanding, as well as to experience more relevance and interest in QP.
Conclusion

First, both teachers and students expressed the need for teachers to support students’ understanding as content expert. This content expert role could be further improved if teachers provide feedback on students’ conceptual difficulties, sanction students’ conceptual understanding, and make students aware of different learning strategies more suitable for learning QP. Providing teachers with more, or different, rationales for QP could also benefit their role as content expert. Second, a common challenge experienced by teachers in this study was to enthuse their students for QP, as they lacked clear applications and struggled to explain the relevance of QP to their students. It is suggested that more (or other) contexts can be explored and included to promote relevance and interest. Third, further evidence was provided that the implementation of digital materials can be an opportunity to overcome students’ difficulties (e.g. Bøe, Henriksen, and Angell 2018; Kohnle et al. 2015). Freely available digital materials, such as YouTube videos and computer simulations, were experienced or suggested to engage students with QP and to support their conceptual understanding. However, the lack of structure and substantive support provided by the teacher at school (in Rick’s case) or at home (in Sarah’s case) while working with digital materials can limit their potential. The use of digital materials can be improved through whole-class discussions and ongoing formative assessments. Taken together, the opportunities provided in this study should allow more students than before to understand QP at a conceptual level and be(come) enthusiastic about QP.

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