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ReleQuant

– Improving teaching and learning in quantum physics through educational design research

Abstract

Quantum physics and relativity are demanding for teachers and students, but have the potential for students to experience physics as fascinating and meaningful. Project ReleQuant engaged in educational design research to improve teaching and learning in these topics in Norwegian upper secondary schools. The paper focuses on the first cycle of development of a teaching module on quantum physics and how design principles were developed. We construct the design principles by reviewing relevant research literature and conducting three pilot studies. The process resulted in the following principles for designing the quantum physics teaching module: 1) clarify how quantum physics breaks with classical physics; 2) use simulations of phenomena that cannot be experienced directly; 3) provide students to use written and oral language; 4) address and discuss wave-particle duality and the uncertainty

principle; 5) use examples of the conceptual development from the history of physics, 6) show examples of how contemporary physicists may disagree on interpretations of quantum physics and 7) present technical applications. Finally, we describe how these principles are implemented in the first prototype ReleQuant teaching module on quantum physics.

INTRODUCTION

Quantum physics and relativity challenge our understanding of the physical world in fundamental ways. The topics hence cause challenges for teachers to teach and students to learn. Project *ReleQuant, Learning and conceptual development in relativity and quantum physics*, aims at advancing knowledge of how quantum physics and relativity can be taught in ways that are experienced as meaningful and motivating for students and that foster deep conceptual understanding.

In order to develop and test web-based teaching material and associated teaching strategies adapted to the curriculum for physics in upper secondary schools in Norway, we engaged in educational design research (EDR, also referred to as design-based research or design experiments). This methodology is appropriate in ReleQuant, as it addresses educational problems in real-world settings and has two primary goals: to develop knowledge and to develop solutions (Reeves & McKenney, 2012).

Research in line with EDR starts out by identifying perspectives on learning that are relevant for the purpose. Teaching material is then developed, tested and refined according to these perspectives and empirical results in several cycles. Research results in this process may be “design principles” that guide the further development of resources (Edelson, 2002). In this paper, we report results from three pilot studies leading to design principles for teaching modules in quantum physics in ReleQuant.

The pilot studies investigated students’ motivation for and conceptual understanding of quantum physics and teachers’ challenges in teaching the topic and their experienced needs for teaching resources. We also include results on students’ pre-knowledge from the first trial of a teaching module as they complement results from the pilot studies and give directions for further development. Based on a literature review and the results of this first cycle of development, we formulate and discuss principles for designing teaching modules for quantum physics in ReleQuant. Further, we describe the prototype of the ReleQuant web environment as one possible implementation of the design principles extracted during this first cycle of the educational design research project. The development of teaching modules is done in collaboration with physics researchers and physics teachers in selected schools, in order to ensure scientific quality as well as appropriateness for teachers and students. This includes taking time constraints and flexibility for teachers into account, in order to ensure relevance and sustainability of the teaching material in schools.

MODERN PHYSICS IN THE NORWEGIAN CURRICULUM

Modern physics does not have a well-established place in school physics internationally. In some countries it is hardly part of the curriculum at all, and where it is included there is a wide variety of content and approaches (for examples, see Henriksen et al., 2014). In Norway, qualitative approaches and philosophical aspects of modern physics are emphasised. The Norwegian upper secondary physics curriculum (NDET, 2006) states that students of physics in the highest level of physics (Physics 2) in year 13 should be able to

- give an account of the postulations that form the basis for the special theory of relativity, discuss qualitatively some of the consequences of this theory for time, momentum and energy, and give a qualitative description of the general theory of relativity.
- give an account of Einstein’s explanation of photoelectric effect, and give a qualitative account of how results from experiments with photoelectric effect, Compton scattering and the wave nature of particles represent a break with classical physics.

- give an account of Heisenberg’s uncertainty relations, describe the phenomena “entangled photons” and give an account of their cognitive consequences¹.

These competence aims call for ways of teaching that differ from how physics is traditionally taught. Rather than performing calculations and experiments, the curriculum requires that students give qualitative descriptions and discuss the philosophical and epistemological aspects of physics. This opens up for going deeper into the nature of science and may stimulate students’ motivation and conceptual understanding of physics. Previous studies using survey data (Angell, Guttersrud, Henriksen & Isnes, 2004), interview data (Renstrøm, 2011) and a combination of quantitative and qualitative data (Rødseth & Bungum, 2010), have shown that quantum physics and relativity are among the topics that engage and motivate Norwegian physics students. It has been shown that Norwegian physics students wish for more qualitative discussions in physics classes (Angell et al., 2004). This provides for new and engaging teaching approaches that motivate students for conceptual understanding in physics.

AIMS AND RESEARCH QUESTIONS

This paper reports the first phases of the educational design research project ReleQuant. The project’s overall aims are to:

1. develop and test teaching modules in relativity and quantum physics that promote conceptual understanding and are experienced by students as relevant and motivating.
2. develop insight into students’ understanding of relativity and quantum physics and investigate teaching strategies designed to promote qualitative understanding and appreciation of the epistemological implications of physics.

The development of the teaching resources departs from a sociocultural view of learning, which entails that language is important in the learning process and that students through interaction with others make physics concepts their own (Mortimer & Scott, 2003; Vygotsky, 1978). The web-based resources we develop will hence provide for students to use their own language orally and in writing, discuss with peers and become familiar with how physicists themselves “talk physics”. However, as the curriculum contains many other topics, the time available for teaching quantum physics is limited. Time requirements for using the modules need to be adjusted accordingly. Further, modules should be flexible in order for teachers to adapt them to their own teaching style, and to the needs and preferences of their students.

The first teaching modules concern quantum physics, while relativity will be addressed in later modules. Hence, the first cycle of development described here focuses on the quantum physics part of modern physics.

Included in this report from the first cycle of development is 1) an overview of relevant theoretical perspectives and empirical research; 2) results from three pilot studies, and 3) results from the first classroom trials of the prototype of the ReleQuant teaching module. The pilot studies concerned students’ motivation and learning challenges related to quantum physics and teachers’ challenges in teaching the topics and their need for supporting resources.

Specific research questions for the empirical part of the first cycle of development were:

1. What characterises students’ understanding of central concepts in quantum physics?
2. What characterises students’ motivation to learn quantum physics?
3. What are teachers’ experienced challenges and needs for support in teaching quantum physics?

¹ “Epistemological consequences” might be a better translation of the term (“erkjennelsesmessige konsekvenser”) used in the Norwegian version of the document.

Results from this first cycle form an important basis for the development of material in ReleQuant. Based on the literature overview and results via testing of the prototype of the teaching module we are able to give prescriptive design principles to meet challenges of teaching and learning in quantum physics.

PREVIOUS RESEARCH ON TEACHING AND LEARNING QUANTUM PHYSICS

Whereas a large body of research has documented students' conceptions in classical physics (see Duit, 2007), considerably less research has investigated students' understanding and learning in modern physics. Some results and scientifically founded recommendations have, however, been presented about the teaching of quantum physics in order to foster students' understanding.

Johnston et al.'s (1998) survey study demonstrated that university students' understanding of conceptions of quantum physics is often fragmented and dominated by isolated facts not fitted into an internally consistent conceptual framework. Another survey by Olsen (2002) reported on challenges in Norwegian students' understanding of concepts such as wave-particle duality of photons. He found that the wave-particle duality was poorly understood among upper secondary students in Norway, and some students clearly demonstrated misconceptions rooted in a classical physics worldview. To avoid this confusion, Ireson (2000) suggested that concepts such as wave-particle duality and matter waves should be avoided. Instead, based on a questionnaire study among GCE Advanced level physics students, he recommended that photons as well as electrons should be described as *quantum objects* rather than as particles or waves.

Misconceptions where students maintain aspects of classical physics in their interpretation of theories in modern physics are also identified in other areas. Based on students' written responses to qualitative questions, Mannila et al. (2002) found that students' conceptions of interference patterns for either low intensity light or an electron beam were dominated by classical pictures and trajectory based reasoning. In an article proposing frameworks for quantum physics instruction, Cheong and Song (2013) claimed that teaching quantum physics is particularly challenging due to the lack of consensus about quantum theory interpretations among physicists. They argue that the various interpretations (e.g. the Copenhagen interpretation or Bohmian mechanics) lead to differences in how, for example, wave-particle duality can be understood. In contrast to Ireson (2000), Cheong and Song (2013) recommended using duality in quantum physics teaching, in particular as a starting point for discussing interpretations of quantum theory. However, they emphasized that different levels of meaning of duality should be taught on appropriate stages in physics education. For example, introductory courses should focus on "light has both a particle property and a wave property", without relating duality to core formal concepts such as wave function or superposition.

In accordance with the empirical results from Mannila et al. referred above, Hadzidaki (2008) has argued that students need to explicitly be made aware of how quantum physics breaks with the principles of classical physics. This includes the classical conception of subatomic entities and mechanistic-deterministic perception of the physical world. Also Fischler and Lichtfeldt (1992) have warned against the use of the Bohr model of the atom in physics teaching, as it over-emphasizes conceptions in classical physics.

The Copenhagen interpretation of quantum theory tends to be assumed in textbooks, without reference to the related previous and ongoing debates, and this can make it hard to coordinate theory and important experiments, causing fragmented learning (Cheong and Song, 2013). For example, Cheong and Song (2013) claim that Bohr's complementarity stance on the nature of light – that light behaves like particles or waves depending on the experiment, and that we cannot measure particle and wave properties at the same time – makes it difficult to link wave-particle duality to quantum theory concepts such as wave function and probabilistic behavior. Rather, in accordance with Ireson (2000),

they propose that light should be introduced to students as neither classical particles nor waves, but as quantum objects including both a particle-like and a wave-like nature.

Renstrøm (2011) did an empirical study that demonstrated how Norwegian upper secondary physics students, after a teaching unit emphasizing the conceptual content, the historical development and the break between classical and quantum physics, were able to express their understanding in an accurate, and yet personal, language. Historical approaches may hence be a fruitful approach to quantum physics in the curriculum.

Historical approaches are also advocated by Asikainen and Hirvonen (2014), who suggest using historical thought experiments and processes in physics teaching, claiming they could be useful for learning quantum physics and for understanding the nature of science. Their argument is supported by Reiner and Burko (2003), who analyzed historical thought experiments, and gave three reasons for their use in physics instruction: Familiarizing students with physics culture and processes; forcing students to combine intuitions, knowledge and logical derivation strategies into one thought process; and promoting conceptual refinement through group discussions of the thought experiments.

With regards to Heisenberg's uncertainty principle, Velentzas and Halkia (2011) have described a teaching sequence based on a thought experiment, and their qualitative study demonstrated positive learning outcomes in understanding the essence of the principle and how it differs from how we look upon uncertainty in classical physics.

Based on case studies of quantum interactive learning tutorials, Singh (2008) has pointed to the importance of visualizations for students in order to build links between formal and conceptual aspects of quantum physics. Since quantum physics is difficult to study and visualize in everyday settings or in a laboratory, several authors have pointed to the potential of modern technology and ICT in teaching these topics (e.g. Müller & Wiesner, 2002; Singh, 2008).

Summarized, these results point towards teaching approaches that provide good visualizations of abstract matter, elaborate on challenging concepts and familiarize students with the historical context of how quantum physics has evolved and with scientific debates over its interpretations.

RESEARCH METHODOLOGY

The research approach chosen for the ReleQuant project as a whole is Educational Design Research (EDR), also referred to as Design-Based Research (see Juuti & Lavonen, 2006) or design experiments (Brown, 1992). The research proceeds through several cycles of theoretically and empirically informed development and classroom testing of teaching resources.

Close collaboration with practitioners is essential in an EDR-project (Juuti & Lavonen, 2013). In ReleQuant, this collaboration is undertaken in a team consisting of researchers of physics education, physicists, and five experienced teachers. The teachers participate in regular meetings during development of the material. In the meetings, they give feedback on ideas and preliminary versions of the material, and discuss further development with the researchers. In particular, the teachers' feedback has been very important in ensuring that the resources are suited for the target group in terms of time consumption, and realistic in terms of conceptual demands. Three pilot studies were conducted prior and parallel to the first cycle of development of the web-based resources.

The pilot studies investigated students' conceptions and motivation in quantum physics and teachers' needs for teaching resources in the context of the Norwegian curriculum. For student conceptions, we also include results from the first trial of a teaching module, as these also reflect students' pre-

conceptions before working with the modules. The pilot studies applied mixed methods approaches, and data gathering will be described below respectively with the pilot studies.

Data from questionnaires, focus group interviews, and written and oral student responses have been analysed qualitatively in order to map teachers' main challenges, students' understanding of key principles in quantum physics and their motivation for learning the topic. The analysis is done by use of thematic coding (Braun & Clarke, 2006) with challenges in learning modern physics documented in research literature as important starting points.

For student responses, descriptive quantitative measures are included for results on multiple choice questions but, due to the size and nature of the sample, results can not be generalised to a larger population by statistical inference.

PILOT STUDIES

Students' understanding of quantum physics

Methods in Pilot study 1 and first trial of teaching module

Pilot study 1 was an electronic questionnaire addressing students' understanding of central concepts as well as their motivation by means of a combination of open-ended and multiple-choice questions. None of the students had worked with ReleQuant material, hence they represent a more general population of physics students. The questionnaire was constructed on basis of misconceptions described in the literature in combination with what is required in the Norwegian physics curriculum, in order to discern specific challenges for the students in our target group.

Two versions of the questionnaire were made. One version was for students in the course Physics 1 (grade 12) where students have not been taught much quantum physics, but for example Bohr's atom model. Another version was made for students in the course Physics 2 (grade 13) where quantum physics forms part of the curriculum. The questionnaires were administered to the students of the teachers participating in ReleQuant, and the grade 13 version also to first year university physics students who attended an introductory course in quantum physics on university level. A total of 108 responses were received, whereof 52 from Physics 1 students and 56 from Physics 2 / university physics students. The questionnaire was distributed and all responses collected anonymously through a digital learning platform. The sample of upper secondary students were from two of the schools collaborating in the ReleQuant project, but students had not yet worked with the ReleQuant material. It should be mentioned that one of the Physics 2 classes came from a high performing school. The sample of university students was from an introductory course on quantum physics at a Norwegian university.

Results from the trial of the first ReleQuant module in classrooms are used to complement the results from the questionnaire. The module focuses on how quantum physics breaks with classical physics, and is designed for a 90 minute teaching sequence. It has been tested in the physics classes of three of the teachers involved in ReleQuant. The teaching was undertaken by the teachers themselves while the researchers have been observers and performing video recording. The data used are students' written responses to a question in the very beginning of the module. The question asked students to describe in their own words what they think light is. Responses are collected through the digital platform. Since student responses at this point are not influenced by the content of the teaching module, they are included in our analysis in order to complement the results on students' understanding of the wave-particle duality for light from the questionnaire in pilot study 1.

Results of pilot study 1 and first trial of teaching module

Results from the student questionnaire in pilot study 1 indicated that students have a reasonable grasp of several quantum physical concepts such as the position of the electron in the hydrogen atom,

and the concept of quantization. Also for the nature of light and the concept of wave-particle duality, many students responded adequately. Several used the concept “energy package” in their description of a photon. Results from a multiple choice question on how light can best be described are shown in Table 1. The table shows that 79 of 108 students (73 %) responded that light is both particles and waves, which is consistent with a wave-particle duality model for light. This is also the case with the 10 students who chose to tick “Other”; they gave their own descriptions about how experiments can show wave or particle properties, that is, the wave-particle duality.

Table 1. Student responses to the question: “Which of the following statements do you think is the best description of light, based on what you have learnt in your physics education so far?”

Description	Number of students
Light is both waves and particles	79
Light is particles	2
Light is either waves or particles	5
Light is waves	2
Light is neither waves nor particles	5
Other – explain or comment	10
No response	5
TOTAL	108

The students were also asked directly about the wave/particle duality in an open question. Many did not elaborate on this but rather repeated the question. Some did, however, give good descriptions emphasizing properties of light resulting from experiments, for example:

It means that [light] in some experiments shows wave properties (like interference etc), while it in other experiments behaves like particles (f. ex. photoelectric effect).

The first ReleQuant teaching module had a similar question as an introduction to the topic. Some students participating here emphasized the quantum properties of light:

Light is electromagnetic radiation with both wave- and particle properties. We imagine that light behaves like photons, or light quanta, where a quant is the smallest possible measurable entity of something.

Light is a stream of many small quantized energy packages called photons.

Another response showed an understanding of the dilemma of duality:

... Light has properties that can fit into two different models... The two theories explain different properties of light. They cannot be used at the same time; light is either waves or particles, never both.

One student even addressed the need for a new model, since neither the particle model nor the wave model can give a satisfactory description:

In some cases, light behaves as particles, whereas other times as waves. Since none of the models are satisfactory alone, it isn't unlikely that an entirely new model should be used.

This student touches on the suggestions by Ireson (2000) and Cheong and Song (2013), that photons and electrons should be considered as “quantum objects”, rather than particles and/or waves.

Even if the quantitative results and the quotes indicate that students understand the wave-particle duality well, results from the first trial of ReleQuant modules revealed that even if students are able to reproduce correct descriptions, they may still hold inadequate conceptions of what the wave-particle duality for light means. When asked to describe in their own words what light is, some student responses described light as particles following a wave-shaped trajectory, resembling findings from Olsen (2002). Two examples from student responses in ReleQuant are:

Light is waves of particles called photons.

Light can be looked upon as waves and particles. As I have understood it, light is particles with wave properties. Hence particles move in a wave pattern.

The difficulties in comprehending the parallel descriptions of light as particles and waves is also evident when one student describes light as photons, and that different colors of light correspond to the photons’ “different length”. It seems that students tend to mix up the two models for light, alternatively combine them consciously in an attempt to create a consistent conception. These problems could be signs of the kind of fragmented learning Cheong and Song (2013) suggested might occur if one interpretation of quantum theory was favored too early, here in describing light as both waves and particles, in line with Bohr’s complementarity stance.

Another challenge concerns Heisenberg’s uncertainty relation. The “uncertainty” described by Heisenberg is a fundamental property of nature that means that there is a limit to how accurately the value of f. ex. momentum and position can be found simultaneously. Table 2 shows students’ responses to a multiple choice question (pilot study 1) on what Heisenberg’s uncertainty relation means. These results are only from highest level physics students in upper secondary school and university students, since the younger students have not yet been taught about Heisenberg’s uncertainty principle. The results show that almost half of the respondents saw the uncertainty as introduced by an actual measurement, rather than as an inherent property of nature, a misconception described by Velentzas and Halkia (2011). It is interesting to note that this misconception seems to be prevailing also in Norwegian physics classrooms, despite the fact that the Norwegian name of the Heisenberg’s uncertainty principle uses ‘*uskarphet*’ (blur) rather than ‘*usikkerhet*’ (uncertainty). Our results, however, indicate that using the more appropriate term does not seem to diminish students’ misinterpretations to any considerable degree, and students still tend to understand the uncertainty in quantum physics as being caused by inaccurate measurements. These challenges should be explicitly addressed in teaching material in quantum physics, in order to build a deeper understanding of the ways in which light is described in quantum physics, what the wave-particle duality entails and the meaning of Heisenberg’s uncertainty relations.

When it comes to motivation, a majority of respondents (75 %) reported that they found quantum physics more motivating than other areas of physics. Some related this to the philosophical aspects of modern physics. For example, one student wrote:

... There are so many things we still don’t understand, and quantum physics has some ideas that require us to think of the world in a different way.

Table 2. Student responses to the question “Which of the following statements do you think best describes Heisenberg’s uncertainty relation?” Responses from students on the highest level physics in upper secondary school (Physics 2) and university students.

Description	Number of students
Everything in nature is uncertain	4
For some pairs of physical entities it is impossible to talk about absolute accuracy; blur is an inherent property of nature	24
For some pairs of physical entities there is a lower limit to how accurately we can measure both entities simultaneously, because every measurement in itself will introduce a blur	23
When we do scientific experiments, the apparatus and instruments we use will always introduce some uncertainty in the results	2
Other – explain or comment	1
No response	2
TOTAL	56

Another student characterised quantum physics – alongside astrophysics – as attractive, due to the extreme conditions these fields of physics describe:

It appears impossible to understand, and it attracts me, it is like a different world. Quantum physics and astrophysics are the most interesting things we have come across in upper secondary, the conditions are so extreme.

This illustrates that students may see quantum physics as challenging, and that the intellectual challenges this field of physics entails may have a motivating effect on them.

The results suggest that teaching material should provide for students to go deeper into the meaning of challenging concepts such as the wave/particle duality for light and the uncertainty expressed in Heisenberg’s relation.

Teachers’ challenges and needs for teaching resources in quantum physics

Methods of the pilot studies 2 and 3

Pilot study 2 was a focus group with the five teachers participating in ReleQuant, in an initial phase of the project. Teachers discussed challenges, opportunities, and needs for teaching resources in quantum physics. One of the researchers acted as moderator in the focus group interview, which lasted ca 30 minutes.

In order to validate results from the focus group among a larger sample of teachers, a questionnaire was constructed in pilot study 3. This was administered to two groups of physics teachers participating in an in-service training course and a teacher conference respectively. The questionnaire had three open questions: 1) What do you think makes quantum physics interesting for students? 2) What do you see as the main challenges for students in modern physics? and 3) What are the main challenges for you as a teacher to teach quantum physics? A total of 26 responses were received. These teachers had no familiarity with ReleQuant and its aims and plans beforehand, but responded to challenges they experienced in teaching quantum physics and what they would wish for material to support their teaching.

Results of the pilot studies 2 and 3

Results from the teacher questionnaire (pilot study 3) showed that teachers see a need for easily accessible resources on appropriate level to complement the textbook, as they tend to be more reliant on textbooks than when teaching other topics where they have better knowledge, other sources and a repertoire of experiments for creating variation in the teaching. More than half of the teachers felt considerably less confident in teaching modern physics than other parts of the curriculum.

Some teachers reported in the questionnaire that they feel insecure in teaching modern physics, as they are unable to answer all the demanding questions from students adequately. But it may also be beneficial for students to experience that the teacher does not always have the correct answer. In the focus group interview (Pilot study 2), one teacher described it this way:

Well, the subject matter is definitely a challenge [...] it is quite fun, pedagogically, to admit to the students that you don't understand it, and that that's the way it is, actually. [...] Showing your limits is somewhat valuable too.

The other teachers in the focus group agreed, and asserted that nobody really understands quantum physics:

Yes, I agree. [...] That humility, I think, is important.

I take comfort in, I don't remember who or which quote it is, but somebody said that no one in the world really understands this².

My students don't understand it. That's because I don't understand it. Nobody does!

In the teachers' view, it may be of value for students to realize that researchers do not always agree and cannot always give consistent descriptions of phenomena in modern physics. This deviates from the typical situation in physics classrooms, and may be motivating for the students. One of the teachers expressed it this way:

The questions that we can't quite answer ... the students think they are quite interesting. Up until quantum physics, it is mostly about putting two lines underneath the final answer and we know everything [...]. The teacher knows everything and physics can answer almost everything, and then quantum physics comes along and breaks everything up quite nicely.

One teacher confessed that when you are not proficient as a teacher in quantum physics, you may actually "lean on" the philosophical aspects of it:

The philosophical part of it is also quite interesting. Maybe, when you don't know that much about quantum physics, you lean on the philosophy. I'm joking a bit, but it [the philosophical aspect] is important too!

Also in the questionnaire, teachers expressed that students find quantum physics and relativity interesting and motivating. To an open question of *why* the topics are interesting to students, most teachers mentioned philosophical aspects, unsolved questions and how theories and their consequences are counterintuitive and in contradiction to everyday experience. Paradoxically, these characteristics of modern physics were also mentioned as the main challenges for students by many teachers.

² The teacher refers to a famous quote from Richard Feynman: "I think I can safely say that nobody understands quantum mechanics".

One teacher expressed that students experience modern physics as difficult simply because it is difficult:

Difficult because it is difficult, deep and mathematical and at the same time it is supposed to be treated qualitatively.

This quote also illustrates the dilemma of qualitative treatment of theories that are in essence mathematical. Several other teachers described it as demanding to bring students to a deep understanding and avoid trivial descriptions. However, some teachers also expressed that they appreciate that modern physics gives more room for unsolved questions and discussions, and that this appeals to some students who struggle with the mathematics for example in mechanics. On the other hand, some teachers expressed that they find it hard to engage students actively in the topic, and they called for activities that will promote student activity. Some reported that the qualitative approaches required by the curriculum are challenging, but just as many responded that this in itself does not represent a problem for their teaching.

Other challenges teachers mentioned in their questionnaire responses, and that can be specifically addressed by ReleQuant, are the need for visualizations, illustrations and activities where students can deepen their understanding. Specific topics teachers describe as challenging are the wave-particle duality of photons, Heisenberg's uncertainty principle, how quantum physics breaks with classical physics, epistemological consequences and entangled photons. The inclusion of entangled photons in the physics curriculum in upper secondary schools has been highly controversial. One teacher commented on it this way when giving recommendations for how ReleQuant material should be designed:

Entangled photons is a ridiculous topic in upper secondary – don't make it more terrible than necessary!

The topic of entangled photons is perhaps the topic that is regarded as the most mysterious in the physics curriculum, and the teacher quoted here saw it as a ridiculous topic to have in the curriculum. However, several teachers mentioned that students' association of quantum physics with mysticism and science fiction actually have a motivating effect, and that many students have read about such issues in popular science magazines and so on. One teacher stated that the controversial aspects of modern physics are those best known by students:

To a certain degree it is the most controversial and modern phenomena that are popularized and hence are known to the students. [This] influences students' expectations of the subject.

The popular science, even if it is controversial, may hence represent a possible path for students into philosophical aspects of quantum physics. However, teachers also underlined that the mystical aspects of modern physics and the association with science fiction do not appeal to *all* students. To reach the student group as a whole, some mentioned that also technological applications of modern physics should be emphasized in the teaching of modern physics. In the focus group interview, one teacher expressed it this way:

It's when we start talking about how it can be used, the impact it has [...]. Technology development and development of science [...]. That's what makes the eyes shine in both me and the students.

As examples of applications, another teacher mentioned the transistor, electron microscopes, uses of quantum physics in medical technology and in computer technology such as cryptography.

In questionnaire responses, a majority of teachers agreed that historical approaches may be constructive in fostering conceptual understanding of modern physics. In the focus group interview, one teacher described that modern physics is a more appropriate topic for illustrating the historical development and dynamic nature of physics than for example the achievement made by Isaac Newton:

The students often experience it [the history of quantum physics] as very recent. It has not been more than a hundred years since the development really started, and you have discoveries, the Nobel prize this year, for example, is the discovery of the Higgs boson. These are people that we know much more about too. Here [in quantum physics] there are real photos of people, there are film recordings, I mean, they are people, they are not just names in text books.

According to this teacher, students may better understand the human aspects and societal dynamics of physics in more recent history, where they can more easily envisage the scientists as real people. This might mean that even if quantum physics is difficult to understand, the topic might make it easier to understand what the nature of science entails.

Summarized, the results from pilot studies 2 and 3 call for teaching material that emphasize both philosophical aspects and technical applications of quantum physics, and that provide tools for teachers to support students' development of qualitative understanding as well as appreciation of unanswered questions and different interpretations in quantum physics.

DISCUSSION AND CONCLUSION

The present study has added to the Nordic and international research in the field of quantum physics education by investigating the conceptions and motivation of a contemporary student group in Norway, and teachers' challenges in teaching quantum physics in qualitative way. The findings leads to proposed teaching approaches and teaching material with focus on use of language, animations and simulations, qualitative understanding, epistemological implications as well as historical and technological perspectives.

Concerning students' conceptual understanding, our results show that many students have a grasp of central concepts. For instance, many can express "textbook accounts" of the wave and particle nature of light; however, student responses to open-ended questions also demonstrate inadequate understanding and misconceptions. An example of the latter is the notions that "particles move in wave-like trajectories", previously described by Olsen (2002) and possibly related to the observation made by Mannila et al. (2002) that students attempt to fit quantum phenomena into a classical physics understanding. Cheong and Song (2013) suggest that such problems could be caused by lack of attention paid to the different interpretations of quantum theory. The results from pilot study 1 indicate that; simple questionnaire questions do not fully capture students' conceptions; inappropriate understanding may be held by more students than those who make this explicit in their responses, and students may be able to reproduce textbook formulations without a deeper understanding. In line with a sociocultural view of learning, teaching resources should provide for students to go deeper into what the wave-particle duality entails and to use their own language in expressing their conceptions. Quantum physics' challenge to our conceptions of the world from classical physics and everyday experiences is also illustrated by our observation that the Heisenberg uncertainty relation was interpreted by around 40 % of our respondents as caused by the measurement rather than as an inherent property of nature. Students' discussions of the consequences of modern physics with peers, with support from adequate resources (e.g. thought experiments and visualizations), may be a key to meet this challenge (Velentzas & Halkia, 2011).

In line with previous research from Norway (Renstrøm, 2011; Rødseth & Bungum, 2010), our respondents found quantum physics motivating. For some, this was related to the philosophical aspects; others expressed how the intellectual demands of modern physics are challenging but also motivating. This resembles findings from Angell et al. (2004), who describe physics students' view of the subject as “frightful but fun”. Bøe and Henriksen (2013) argued that some students were drawn to physics because of its reputation as difficult and challenging.

The teachers in our pilot studies expressed less confidence in teaching modern physics than other parts of the curriculum and accordingly wished for supplementary teaching resources in these topics. Some teachers turned their inadequate grasp of the subject matter to an advantage, using it to demonstrate to their students the many open and challenging questions in physics, thereby counteracting the “prototypical” physics instruction with focus on objectivity, rigor, individual problem-solving, correct answers, and sparsity of historical, philosophical, and science and society approaches (Bøe & Henriksen, 2013; Carlone, 2003). Teachers mentioned visualisations, historical context, references to popular science and to modern technology as potential ways of making quantum physics accessible to students. Particularly, historical approaches have a potential to support students' understanding of the conceptual content as well as the nature of physics and how it develops. This could be supplemented by showing students that current physicists do not necessarily agree on how models of the nature of light should be interpreted, and that disagreement and argumentation has also been important for the development of physics.

Results from the first cycle of development including the literature review and empirical results presented in this paper have led to the formulation of seven main principles for designing the first prototype of the quantum physics teaching module in ReleQuant. The modules should:

1. clarify how quantum physics breaks with classical physics; the breaks should be formulated explicitly and may also make students more aware of the philosophical foundation on which classical physics is built;
2. use visualizations and simulations of phenomena that cannot be experienced directly; these should be interactive in order to engage students;
3. provide for students to use written and oral language in their conceptual development; resources should assist the teacher by providing good questions and substantial content for the discussions;
4. address and discuss in depth challenging concepts such as wave-particle duality and the uncertainty principle; the teaching material should explicitly address typical misconceptions students have;
5. use examples from the history of physics in supporting conceptual development;
6. show examples of how contemporary physicists may disagree on interpretations of quantum physics;
7. present examples and applications that are relevant to students' life-world; this should include technological applications as well as philosophical aspects of quantum physics.

Prototypes of ReleQuant modules on quantum physics based on these principles are developed, and available from www.viten.no/relevant4. Its content facilitates students' use of language, discussion and reflection by explicitly stating questions to be answered in writing or orally in discussions with peers.

<p>Brudd med klassisk fysikk</p> <p>De fleste fysikere sålde med å klassifisere kvantefysikken i starten. Det fant nemlig sammenheng med sentrale prinsippene i den klassiske fysikken.</p> <p>Vi skal ta for oss tre sentrale prinsippene:</p> <ul style="list-style-type: none"> - kontinuitet - determinisme - lokal virkelighet 	<p>Determinisme A B</p> <p>Støter du på determinismen? Se fysikkvideoer utfordrer sin 1888 til den klassiske fysikken.</p> 	<p>Lokal virkelighet A B</p> <p>Ibrotteknikkene tenner i en verden med lokal virkelighet. Det vil si at de er påvirket av kvantefysikk slik at de utviser bremsekarakterer, og at vi kan slå til uten å være alene på det punktet der andre i det minste.</p> <p>I kvantefysikk har vi ikke nødvendigvis lokal virkelighet. Spill av antiprosopier med ulike lokal virkelighetsaktivert. Se hva som kan skje i kvantefysikken.</p> 
<p>a) Making breaks with classical physics explicit for students. Quantization versus continuity is illustrated by the steps versus the continuous slope of the mountain.</p>	<p>b) Illustrating the meaning of determinism in classical physics by means of a pendulum.</p>	<p>c) Using a simulation of ice hockey pucks to illustrate how the principle of local reality breaks with classical physics.</p>
<p>Kvantetilstander</p> <p>Hvor mange kubler ser du på bildet?</p>  <p>Hjernen din kan tolke bildet på to forskjellige måter. Enten ser du 9 kubler med hvite bunn eller så ser du seks kubler med hvite topp.</p> <p>Dette er en analogi til såkalte kvantetilstander. Bliker kan vise både 9 kubler og seks kubler på én gang. På samme måte som et kvantefysisk system i flere forskjellige kvantetilstander på én gang. Systemet er da i en superposisjon av tilstander.</p> <p>De på bildet er en gang til i net stykket du velger hvit topp eller bunn. "Nær" du bildet og kan telle enkelt kubler. Superposisjon i kvantefysikk oppfører seg liknende. Når vi måler på kvantefysikal system vil det "utlappes" til kun én av sine kvantetilstander.</p>	<p>Oppgave om kvantefysikk og filosofi</p> <p>Oppgave 3</p> <p>Dokument med en annen elev. Hva synes du om bildet/teksten? Gjør det noe med hva du tenker om kvantefysikk? skriv ned.</p> <p>Du må være innlogget som elev for å skrive en svar.</p> 	<p>Både bølge og partikkel?</p>  <p>En bølge er en bevegelige som forsvinner seg. En bølge har alltid størrelse, den blir ikke mindre bare så et øyeblikk.</p> <p>En partikkel er et bølge som er angrepet i et område i rommet.</p> <p>OPPGAVE</p> <p>Diskuter med en annen elev: Går det an å tenke seg ut lys er både bølge og partikkel?</p>
<p>d) Using an interactive visualization of cubes to discuss superposition and to address some of the philosophical aspects of quantum physics.</p>	<p>e) Using written language and discussion with peers in relation to a philosophical question on Schrödinger's cat.</p>	<p>f) Addressing explicitly the challenges involved in wave-particle duality.</p>
<p>Inspirasjon fra historien</p> <p>Under spør en forsker så da at dagens fysikere ikke er helt enige om hva de tenker om. Forskerne som tenker på kvantefysikken er heller ikke enige. Dette bildet er fra den såkalte Solov'ev-konferansen i 1927, da alle de beste fysikere var samlet for å diskutere kvantefysikk. Det de innrømte analyserte fremre du når det har noen av dem her.</p> 	<p>Spør en forsker: «Hva er lys og fotoner?»</p>  <p>Ans: Rikard er professor ved Universitetet i Oslo. Han forsker på mørk materie, og undersøker bl.a. om kvantefysikk og supersymmetri. Ans er foreleser - han jobber med teorier til kvantefysiske problemstillinger.</p> <p>Ans: Inge Valnes er forsker ved Universitetet i Oslo. Han har et kvantefysikklaboratorium der han undersøker egenskapene til lys. Han arbeider også med spørsmål knyttet til elektronoptikk, optikk og helv. Ans er inge av eksperimentalfysiker.</p> <p>Hva svarer forskerne hvis vi spør dem hva lys er?</p> <p>Hva svarer forskerne hvis vi spør dem hva fotoner er?</p>	<p>Tilbakespredning</p> <p>Compton-scattering kan gjøre vanlige oppgaver utvalgt, men effektivt kan brukes til å se gjennom vegger og mer! Compton-scattering er noen få meter sent tilbake med oppgaver. Dette kalles tilbake-spredning (back-scattering). De eksperimentelle data kan brukes til å lage bilder. Tilsvarende og ikke-instruksjon på fjellværet stråler eller spær stråler.</p> <p>Tekstene for analysert med tilbake-spredning:</p> <ul style="list-style-type: none"> • Reduksjon av Compton-scattering • Millimeterbølge-scanner (bryter elektromagnetisk stråling med millimeterbølger) 
<p>g) Using historical events for inspiration and to support conceptual development.</p>	<p>h) Video interviews showing how contemporary physicists disagree on the interpretation of "what are photons?"</p>	<p>i) Compton scattering as an example of technological applications of quantum physics. (Also showing millimeter wave scanner to avoid misconceptions).</p>

Figure 1. Examples of implementation of the design principles in the ReleQuant web environment. Screen shots are from the first prototype, with the exception of figure f), which is from a later version based on results from the first trial.

Figure 1 shows examples of how the design principles described above are employed in the implementation of the ReleQuant web environment. How quantum physics breaks with classical physics is made explicit (principle 1) in screen shot a), in terms of quantization rather than continuity, lack of determinism and local reality versus nonlocality. The image illustrates continuity versus quantization by means of the steps versus the continuous mountain slope. In screen shot b), physics educators discuss determinism and do experiments with predicting the height a pendulum will reach when it returns after being released. This way of prediction can not always be done in quantum physics as it does not obey determinism. Screen shot c) illustrates what nonlocality involves by means of a simulation of two ice hockey pucks initially connected by a spring. If you hit one puck, what happens to the other? When choosing the option nonlocality, both pucks change direction when one of them is hit, illustrating quantum phenomena such as entangled photons. Screen shot d) shows a visualization of what quantum states means, in line with design principle 2. The figure is ambiguous with respect to how many boxes you can count (flip the figure and the result may change). You may be able to see two different interpretations, but you can only see one at a time, just as a quantum system can have several states but only one can be measured at a time. Screen shot e) shows an example of how students are encouraged to use written and oral language, as prescribed by design principle 3. In this case, students are asked to discuss with a peer how they interpret the thought experiment about Schrödinger's cat, and then to write down what they think the thought experiment can tell us about quantum physics. This example also matches design principle 7 in terms of philosophical aspects of quantum physics. Screen shot f) addresses design principle 4, and is based on the empirical results that show that the wave-particle duality is challenging for students and a potential source for misconceptions. The dilemma of combining the two models for light is here addressed explicitly. Screen shots g) and h) are examples of how the module illustrates that the history of science as well as contemporary science involve disagreement between physics researchers (design principles 5 and 6). In screen shot h), students can watch video clips where two physicists express different interpretations of what light and photons are. Screen shot i) is an example of how the modules include applications of quantum physics in modern medical technology (design principle 7), in this case back scattering due to Compton effect in X-ray images.

The upcoming cycles of educational design research in ReleQuant will give deeper insight into students' conceptions of quantum physics and investigate further how teaching material following the above principles can support students' learning in quantum physics. In particular, it will further develop our understanding of the value of developing students' understanding in quantum physics by use of language and discussion of philosophical aspects of quantum physics and how it breaks with classical physics.

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