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Relativity, quantum physics and philosophy in the upper secondary curriculum: challenges, opportunities and proposed approaches

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Abstract
In this article, we discuss how quantum physics and relativity can be taught in upper secondary school, in ways that promote conceptual understanding and philosophical reflections. We present the ReleQuant project, in which web-based teaching modules have been developed. The modules address competence aims in the Norwegian national curriculum for physics (final year of upper secondary education), which is unique in that it includes general relativity, entangled photons and the epistemological consequences of modern physics. These topics, with their high demands on students' understanding of abstract and counter-intuitive concepts and principles, are challenging for teachers to teach and for students to learn. However, they also provide opportunities to present modern physics in innovative ways that students may find motivating and relevant both in terms of modern technological applications and in terms of contributions to students' intellectual development. Beginning with these challenges and opportunities, we briefly present previous research and theoretical perspectives with relevance to student learning and motivation in modern physics. Based on this, we outline the ReleQuant teaching approach, where students use written and oral language and a collaborative exploration of animations and simulations as part of their learning process. Finally, we present some of the first experiences from classroom tests of the quantum physics modules.

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1. Introduction: the relevance of modern physics

Physics is a fundamental science with philosophical implications that often fascinate young people. However, students' participation in post-compulsory physics education is a matter of concern, not only in Norway but also internationally (OECD 2008, Bøe and Henriksen 2013). Research indicates that in order to motivate and attract a larger, more diverse and gender-balanced group of students, physics education needs to focus on knowledge that is in context, collaborative forms of work and examples and applications with relevance to students' lives in the real world (Stokking 2000, Angell *et al* 2004, Murphy and Whitelegg 2006, Bøe and Henriksen 2013). Previous studies in Norway (Angell *et al* 2004, Renstrøm 2011) have shown that quantum physics and relativity are among the topics that engage physics students to a high degree, and students may find these to be more relevant than topics of everyday practical use, such as electricity or friction. Quantum physics plays an increasingly important role in modern technologies used in communication, medicine, etc. Links to modern technology such as GPS navigation, as well as to space exploration, cosmology and philosophy, exist for both special relativity theory and general relativity theory.

2. Quantum physics and relativity in the curriculum

In contrast to many other countries, the physics curriculum for upper secondary school (final year) in Norway allows students to explore these topics in some depth and through a qualitative approach, as students are expected to:

- give an account of the postulations that form the basis of 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 the photoelectric effect and give a qualitative account of how results from experiments with the photoelectric effect, Compton scattering and the wave nature of particles represents 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 consequences[5] (NDET 2006).

Comparing these competence aims with the curricula in countries with comparable educational systems, such as Sweden[6], Denmark[7], Finland[8], UK[9], France[10] and Australia[11], we find that none of these mention entangled photons. Neither Denmark nor Finland include special relativity in their curricula, and only Sweden includes general relativity. Wave-particle duality is common to all the curricula studied and the photoelectric effect is common to all except Denmark and France. Although the Swedish curriculum mentions Heisenberg's uncertainty relations, only the Norwegian one includes the epistemological consequences of the uncertainty relations and the phenomenon of entangled photons.

The Norwegian curriculum's unusual requirement for students' understanding provides opportunities as well as challenges for the innovative teaching of modern physics. The competence aims concerning quantum physics and relativity are demanding, but also have the potential for students to experience physics as personally relevant and engaging. In this field of physics, the curriculum does not require that students perform many calculations, but rather that they give qualitative descriptions and are able to discuss philosophical aspects of physics. In addition, modern physics presents limited opportunities for students to undertake lab work. Hence, these topics require teaching that engages students in other ways. These challenges

[5] 'Epistemological consequences' might be a better translation of the Norwegian term used in the original document.

[6] www.skolverket.se/polopoly_fs/1.194811!/Menu/article/attachment/Physics.pdf

[7] www.retsinformation.dk/Forms/R0710.aspx?id=152550#Bil13 and www.retsinformation.dk/Forms/R0710.aspx?id=152550#Bil23

[8] www.oph.fi/download/47678_core_curricula_upper_secondary_education.pdf

[9] http://filestore.aqa.org.uk/subjects/specifications/alevel/AQA-2450-W-SP-14.PDF

[10] http://eduscol.education.fr/physique-chimie/actualites/actualites/article/reperes-pour-la-formation-en-physique-chimie-au-cycle-terminal-scientifique.html

[11] www.australiancurriculum.edu.au/Download/SeniorSecondary

and opportunities are the starting point for the development and research undertaken in the ReleQuant project.

3. Students' understanding and challenges in quantum physics and relativity

Whereas a large body of research has documented students' conceptions and learning within a range of topics in classical physics (see Duit 2007), considerably less research has been conducted on students' understanding and learning in modern physics. In mechanics, for instance, research has focused on how the physical description of motion and forces appears counterintuitive when compared with students' everyday experiences (Driver *et al* 1994). The challenges in quantum physics and relativity are of a different nature, since these topics concern phenomena that cannot be visualized or experienced directly. Concerning quantum physics, Olsen (2002) found that wave-particle duality was poorly understood among upper secondary students and that some students clearly demonstrated misconceptions rooted in a classical physics worldview. Mannila *et al* (2002) found that student conceptions when studying light or electron beam interference patterns were dominated by classical pictures. These conceptions may arise because students are unaware that quantum physics breaks with some basic assumptions in classical physics, such as continuity, determinism and locality (Renstrøm 2011). Hence, students should be made aware of these important differences between classical and quantum physics (Hadzidaki 2008).

In the field of *relativity*, Dimitriadi and Halkia (2012) documented the learning challenges concerning the frames of reference concept and a tendency for secondary students to try and incorporate the theory of relativity into classical physics. Villani and Pacca (1987) found that students tended to believe that there was a 'privileged observer' position and that time dilation and length contraction happened only for the moving observer. Within general relativity, Bandyopadhyay and Kumar (2010) identified a large number of alternative conceptions within a limited sample of university students. However, the research literature on secondary school students' understanding of general relativity is scarce.

4. Theoretical perspectives on student learning in physics

ReleQuant is founded on a sociocultural view of learning physics, where conceptual development is seen as a result of social interaction and the use of language (see e.g. Vygotsky 1978). Hence, it is important that students learn physics concepts by using the language of physics, including all its forms of representation (Henriksen and Angell 2010).

A sociocultural view is also manifested in an emphasis on physics as a human product, as seen in current perspectives on the place of the Nature of Science (NoS) in the science curriculum (see e.g. Abd-El-Khalick 2013). Teaching science through the history of science is believed to be constructive both in building students' understanding of NoS and in benefitting their conceptual understanding of quantum physics (Renstrøm 2011) and relativity (Arriassecq and Greca 2012).

The language of physics is highly multimodal (Lemke 1998), involving verbal texts, images, diagrams, symbols and mathematical formulae. In order to master physics, students need to get acquainted with all of these modes of representation and learn how to translate between them (Airey and Linder 2009). Visualizations of theoretical concepts and principles are important in this regard. This is provided in ReleQuant through computer-aided animations and interactive simulations. According to Singh (2008), these may help students build links between the formal and conceptual aspects of quantum physics. Several studies have found that animations and simulations have positive effects on learning (e.g. Müller and Wiesner 2002, Lee *et al* 2010) and frameworks for how they should be designed to promote learning have been suggested (e.g. Ainsworth 2006, Plass *et al* 2009). However, as pointed out by Singh *et al* (2006), in order to address typical misconceptions in quantum mechanics, it is important that computer-based visualizations are combined with research-based teaching strategies. The integration of interactive, web-based resources into a teaching/learning sequence by teachers is an under-researched field (Hadjerrouit 2010), and ReleQuant provides a contribution in this regard.

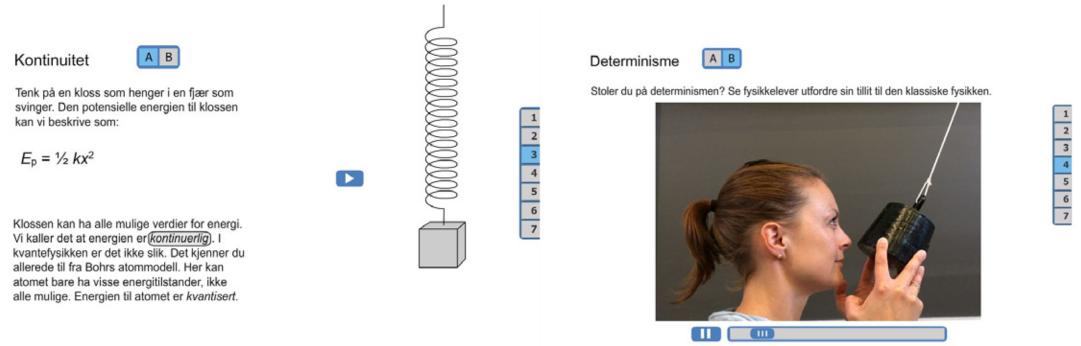

Figure 1. Screenshots of ReleQuant web pages. Left: a page discussing continuity, exemplified by an animation of a classical simple harmonic oscillator and comparing its continuously changing potential energy with the quantized energy states found in the Bohr atomic model. Right: a page addressing the concept of determinism, featuring a video of students and teachers releasing a heavy pendulum bob from nose height and awaiting its return.

5. ReleQuant: the outline of a teaching approach for quantum physics and relativity

Project ReleQuant—Learning and conceptual development in relativity and quantum physics[12] aims to develop evidence-based teaching practices and resources that promote motivation, conceptual learning and philosophical reflection in the field of modern physics in upper secondary school, with possibilities for adaptation to higher education. In this section we outline a teaching approach based on the perspectives presented above, and give examples of how a web-based learning environment is designed in order to support teaching and learning in quantum physics and relativity.

Our work in ReleQuant is inspired by Educational Design Research (see e.g. McKenney and Reeves 2012) where the aim is to develop teaching resources that are directly applicable in classrooms, in parallel with establishing evidence-based knowledge about students' learning processes and about favourable principles for the design of curricular materials. In the process of designing, testing and improving teaching resources through several iterations, ReleQuant involves teachers as team members together with physicists and science education researchers.

ReleQuant has developed eight to ten interactive web-based teaching modules in quantum physics and relativity. The modules will be accompanied by pedagogical strategies for using this material in the classroom. Based on the aims of the Norwegian curriculum, the project aims to design teaching resources that:

- draw on the sociocultural theories of learning;
- address documented conceptual challenges for students;
- facilitate students to use written and oral language in collaboration;
- allow students to explore digital animations and simulations of phenomena;
- illustrate how scientific knowledge is negotiated and developed as a human product and how it is applied in a range of real-world contexts;
- inspire epistemological reflections;
- support teachers' varied use of communicative approaches;
- support teachers to follow up and assess their students.

At the time of writing, only the quantum physics modules have been developed and have undergone the first classroom trials. Some examples from the first modules are presented below. Figure 1 shows screenshots from ReleQuant's web pages addressing some fundamental assumptions in classical physics and how quantum physics breaks with these. In each case, introductory texts and videos or animations are followed by problems and questions for students to solve or discuss.

[12] www.mn.uio.no/fysikk/english/research/projects/relequant/

ReleQuant's learning resources often challenge the students to discuss physics using their own words. This is done in three different ways.

1. Entering their responses in the learning platform[13] as exemplified in figure 2, where the teacher can view and comment on each student's response and uses them in formative assessment.
2. Discussing in pairs: this type of discussion is often used as an introduction to a topic. This is an informal approach and less intimidating than having to speak in front of the whole class. When discussing in pairs, less mature ideas can be tested and the first steps towards understanding are taken.
3. Classroom discussions: this method is useful to sum up key concepts, address misunderstandings and make sure that all students have a chance to grasp the essence of the topic addressed.

6. The first experiences from classroom tests of the quantum physics modules

Research was conducted in parallel with the development of ReleQuant modules, addressing the students' conceptions in quantum physics and relativity, their motivation, their epistemological reflections and their collaborative learning processes, while using written and oral language and digital visualizations. We made use of various data sources: audio recordings of student dialogues, written responses collected through the learning platform, and focus group interviews with students and teachers to investigate how the material answered the students' and teachers' needs. The first round of classroom data collection was conducted in March 2014.

Three quantum physics modules (approximately 90 min each) were tested in three classes distributed in two upper secondary schools. The aim of this paper is not to present a comprehensive analysis; nevertheless, we present here two examples of the preliminary results.

The first result concerns the thought experiment 'Schrödinger's cat' (see figure 2). This involves a cat sealed in a box, where the cat's life or death depends on the state of a subatomic particle.

[13] www.viten.no/art.html?stid=1194969&lang=eng

Figure 2. Screenshot of a ReleQuant web page asking: 'Discuss with a fellow student. What do you think about Schrödinger's cat? Does it influence your way of thinking about quantum physics? Enter your response below.'

According to Schrödinger, the Copenhagen interpretation implies that the cat remains both alive and dead (to everyone outside the box) until the box is opened. The students were challenged to reflect on the idea that a system could be in a superposition of states until one makes a measurement. From the writing task, we identified three broad categories of student responses:

1. trivial interpretations; we don't know if the cat is dead until we look into the box;
2. Schrödinger's cat can teach us something about quantum physics;
3. critical voices: quantum physics is absurd.

An example from category 2 is:

> *'It is a good way of explaining what superposition means. It is a little difficult to understand that observations and measurements determine the state of a particle, but when you think about it on a macroscopic level it is easier to understand.'*

And here is a critical voice, resembling Schrödinger's argument in proposing the thought experiment with the cat:

> *'I find quantum physics absurd and abstract. Things are what they are, right? Determinism is wrong?! I don't think so. Why should it make a difference whether you have a video recording or not? How can particles behave differently depending on whether or not a camera or a person is standing there and watching? These are the problems I have with quantum physics at the moment. Also, cats are too cute to experiment with.'*

This shows that after working with the ReleQuant material, the students are able to articulate some core philosophical dilemmas that physicists are challenged with in quantum physics.

The second sample result concerns ReleQuant's focus on the use of language in learning. Focus group interviews with students revealed that some students valued the opportunity to talk and discuss, in order to understand difficult concepts:

> *'Talking together worked very well, because then we discovered very easily if we had understood it or not. So if … when trying to explain it, you are unable to say anything, you realize that you have not understood it.'*

7. Conclusion

Through this work, we hope to stimulate discussions about teaching and learning modern physics and to establish a teaching approach based on the results and perspectives derived from science education research. Through multiple iterations of development and classroom testing, we aim to contribute to and extend the knowledge base on students' conceptual development in relativity and quantum physics. In particular, we hope to demonstrate through ReleQuant how students' motivation and learning may be supported through carefully designed learning activities involving discussions, written tasks, visualizations and simulations, that stimulate not only conceptual understanding, but also philosophical and epistemological reflections.

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