”From the cat’s point of view”: Upper secondary physics students’ reflections on Schrödinger’s thought experiment

Henning Vinjusveen Myhrehagen, Asker Upper Secondary School, Norway
Henning.Vinjusveen.Myhrehagen@asker.vgs.no

Berit Bungum, Programme for Teacher Education, the Norwegian University of Science and Technology
berit.bungum@ntnu.no

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Abstract

The thought experiment “Schrödinger’s cat” exposes fundamental dilemmas in how we interpret quantum physics, and has a potential for deepening students’ understanding of this part of modern physics, including its philosophical consequences. In this paper we report results from the project ReleQuant on how Norwegian physics students in upper secondary schools interpret the thought experiment. The analysis resulted in nine categories, and we discuss how these relate to interpretations made by physicists, in particular the concept of superposition. Even if students’ responses in many cases can be related to interpretations that make sense in physics, we conclude that lack of knowledge about the purpose and the historical context of the thought experiment limits students understanding of the physics content. Exploring the thought experiment from a historical perspective might deepen student understanding of key concepts in quantum physics as well as of how physics develops.

1. Introduction

Quantum physics challenges our view of the world in fundamental ways. Erwin Schrödinger's famous thought experiment about a cat placed in a closed box with a radioactive source exposes what superposition means when transferred to a macroscopic context. This formed part of a historical discussion on interpretations of quantum physics. Historical thought experiments such as Schrödinger's cat, originally set up to demonstrate the absurdity of quantum mechanics, are today possible to perform experimentally (see e.g. Haroche, 2013). The interpretations of quantum mechanics are, however, still being discussed.

In this paper, we present results from the Norwegian project ReleQuant (see Henriksen et al., 2014) on how upper secondary physics students interpret the thought experiment: In what ways do they understand the meaning of the claim that the cat in the box can be both dead and alive? How do their reflections relate to the interpretations made by physicists in quantum physics? Based on the results, we discuss opportunities for including interpretations of quantum physics and philosophical implications in the curriculum for pre-university students in physics.

2. Schrödinger's thought experiment

Figure 1. Erwin Schrödinger (1887-1961).
This image has been obtained by the author(s) from the Wikimedia website https://commons.wikimedia.org/wiki/File:Erwin_Schr%C3%B6dinger_%281933%29.jpg, where it is stated to have been released into the public domain. It is included within this article on that basis.

The Austrian physicist Erwin Schrödinger presented the thought experiment referred to as ”Schrödinger’s cat” in 1935, as part of the debate on interpretations of quantum physics. Niels Bohr and his colleagues suggested that outcomes of measurements on quantum phenomena were statistical in nature, and that a system could exist in a superposition of several states until an observation or a measurement was made. This combination of states can be described as a wave function Ψ, which will collapse into one of the possible states as a result of a measurement or other interaction. This way of understanding what quantum mechanics means, later referred to as the *Copenhagen interpretation*, developed in the 1930s and remains the prevailing interpretation. An alternative interpretation is that the theory for quantum phenomena is incomplete, and that a quantum system must have a definite state determined by *hidden variables* that remain to be explored in physics. Bell’s inequalities, that would hold for a hidden variables interpretation, but not for predictions of quantum mechanics, made it possible to distinguish between predictions of quantum mechanics and a local hidden variables theory. The results of the experiment by Aspect, Dalibard & Roger (1982), where they used a set of orientations leading to the greatest predicted conflict between quantum mechanics and Bell's inequalities, showed excellent agreement with the quantum mechanical predictions. This led to the greatest violation of generalized Bell's inequalities ever achieved.

A rather spooky interpretation is that of *many worlds* (see e.g. Osnaghi, Freitas, & Freire Jr, 2009), which states that we live in one of many parallel worlds corresponding to different outcomes of what state the wave function collapses into.

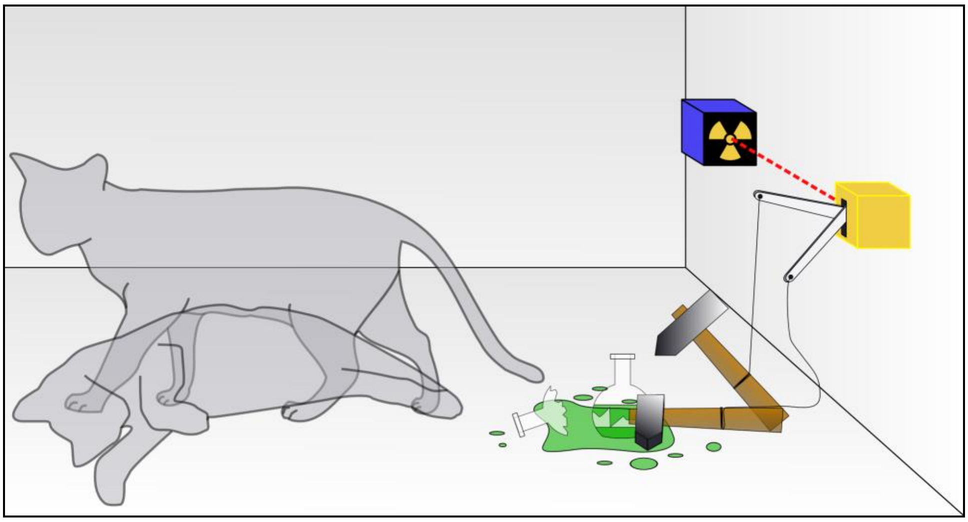

Figure 2. Schrödinger’s thought experiment: Can the cat be considered in a state of both dead and alive?
This image has been obtained by the author(s) from the Wikimedia website https://commons.wikimedia.org/wiki/File:Schrodingers_cat.svg, where it is stated to have been released into the public domain. It is included within this article on that basis.

Schrödinger constructed the thought experiment as an attempt to show that the Copenhagen interpretation has absurd consequences and hence must be false. He described a cat placed in a closed box together with a radioactive source and a flask of poison. When the radioactive source decays, the particle will release the poison, which in turn kills the cat. A radioactive source can be treated as a quantum system while the cat is obviously a macroscopic system. However, since the state of the cat can be considered as entangled with the state of the radioactive source (Haroche, 2013), the cat will be in a combined state of "dead cat" and "alive cat" if the source is in a superposition of decayed and not decayed. Schrödinger used his thought experiment to show that a description of quantum systems as a superposition of states can not be a description of the world as it actually is, and to warn against the naive acceptance of a "blurred model" as representing reality (Kragh, 1999). The question is whether the combined states represented by superposition of quantum states is a description of the world as it actually is - or whether it is due to how our limited knowledge of the world forces us to predict the outcomes only as statistics. Schrödinger described this difference in interpretations by comparing it to the difference between "a shaky or out-of-focus photograph and a snapshot of clouds and fog banks" (see Kragh, 1999, p. 217). Is the fogginess intrinsic to the motive or a result of failure in capturing it?

3. *Quantum physics: challenges and opportunities in the physics curriculum*

Quantum physics is a topic that often fascinates young physics students (Angell, Guttersrud, Henriksen, & Isnes, 2004). Its philosophical consequences are far-reaching, and it breaks with classical physics and our worldview in fundamental ways.

Research on university physics students has, however, indicated that their understanding of quantum physics often is fragmented and dominated by isolated facts and mathematical schemes not fitted into an internally consistent conceptual framework (Hadzidaki, 2008; Johnston, Crawford, & Fletcher, 1998). This may be due to how quantum physics on university level is dominated by mathematics and abstract formalism. Pospiech (2000) has pointed out that even if quantum physics cannot be fully understood without mathematics, the mathematical formalism often hides the philosophical issues important for understanding the full depth of modern physics. Studies from various countries also show that most university physics students are not aware of what constitutes the fundamental basis for quantum physics and how it breaks with classical physics. (Ayene, Kriek, & Damtie, 2011; Fischler & Lichtfeldt, 1992; Hadzidaki, 2008). Hence, students often maintain their classical or semi-classical conceptions while at the same time advancing their technical skills in quantum mechanics.

The philosophical foundation for quantum physics is seldom represented in curricula for pre-university physics (see Henriksen et al., 2014 for a brief overview) and hence seldom taught in any systematic way. The Norwegian curriculum for physics in upper secondary school does, however, make an attempt to familiarize students with how quantum physics breaks with classical physics. The curriculum states that students should be able to

- 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 represents a break with classical physics

and

- give an account of Heisenberg's uncertainty relations, describe the phenomena "entangled photons" and give an account of their cognitive consequences

Further, how physics progresses as a human enterprise is covered by stating that students should be able to

- elaborate on and discuss how various theories of physics can exist side by side, even though they are contradictory

and

- give an example of a scientific conflict that has been resolved and how, and an example of a scientific conflict that remains unresolved and why

These parts of the physics curriculum represent a challenge to teachers, as they deviate from the physics that can be taught by means of traditional teaching approaches such as calculation problems and laboratory work (see Bungum, Henriksen, Angell, Tellefsen, & Bøe, 2015).

4. The ReleQuant project and research approach

The project ReleQuant - *Learning and conceptual development in relativity and quantum physics* engages in Educational Design Research in order to meet the challenges of teaching quantum physics and relativity in qualitative ways on pre-university level. In the project, physics educators, physicists and experienced teachers collaborate in developing web-based teaching resources that foster students' qualitative understanding and philosophical reflection in upper secondary school physics in Norway (see also Henriksen, et al., 2014).

The ReleQuant resources are developed and researched through classroom testing and revisions in several cycles in line with Educational Design Research as a methodological frame (see McKenney & Reeves, 2012). Through the first cycle of development, we formulated seven principles for the development of teaching resources, based on a literature review and pilot studies on students' understanding and teachers' experienced needs (see Bungum, et al., 2015). These principles include clarifying how quantum physics breaks with classical physics and providing opportunities for students to use their own written and oral language to formulate their conceptions.

The curriculum does not explicitly mention Schrödinger's thought experiment, but it was nevertheless included as a short sequence in the teaching material as it was believed to interest students and to be suited to fulfil the overall aim of the curriculum. Hence, the teaching material developed in ReleQuant gives an opportunity to study how students perceive the physical meaning of Schrödinger's cat, how these perceptions relate to physicists' interpretations of quantum physics and the potential the thought experiment has in supporting students' development of a qualitative understanding of quantum physics.

5. Research methods, data material and analysis

Data material presented used for analysis presented in this paper stem from three successive cycles of testing in classrooms, involving 6 classes from 4 schools and a total of ca 170 students.

In the digital teaching material, students get a very brief description of the thought experiment formulated by Schrödinger. Ahead of this, they have been introduced to the concept of superposition.

Research data were students' written responses on the digital platform collected during physics lessons. Responses were mainly individual but in some classes made by pairs of students. The questions were answered as an integral part of the physics lesson, but students were informed and given their consent for their responses to be used in research. Students were not asked concrete questions with clear-cut answers, but rather to formulate their reflections on the thought experiment about Schrödinger's cat. We received 81 written responses.

Analysis of the student responses is done inductively from the data material by developing and refining codes through thematic coding (Braun & Clarke, 2006). The codes provide distinct types of student answers to what Schrödinger's cat means in term of physics. Quantitative measures are made by counting data units categorised in each code. We used open coding (Cohen, Manion, & Morrison, 2011), where the unit of analysis was any meaningful utterance in the student responses. This means that several codes can be assigned to each student response and hence to each student. The quantitative measures therefore do not represent number of students, but nevertheless they provide a picture of how frequent the ways students perceive the thought experiment about Schrödinger's cat are.

Figure 3. Norwegian physics students working on "Schrödinger's cat" with ReleQuant resources.

6. Results: Students' reflections on Schrödinger's cat

In an earlier paper from the project, Henriksen et al. (2014) reported after preliminary analysis three broad categories of student responses regarding 'Schrödinger's cat': i) trivial interpretations; we don't know if the cat is dead until we look into the box, ii) Schrödinger's cat can teach us something about quantum physics and iii) critical voices: quantum physics is absurd. These categories were extracted from the ReleQuant's first cycle of testing in classrooms.

The results presented in this paper is an analysis of written student responses from the same cycle of testing in addition to the two consecutive cycles. Our analysis identified 9 categories of student responses, summarized in Table 1. Some of the responses referred to as 'critical voices' (iii) makes one cornerstone of our ninth category, while categories 1-4 and 5-8 roughly elaborate i) and ii), respectively.

Table 1. Appearances of views in student responses.

View of Schrödinger's cat	Number of student responses exposing the view
1. We don't know whether the cat is dead or alive unless we open the box	**21**
2. The act of measurement determines the cat's state	**26**
3. The cat is either dead or alive	**14**
4.The cat is both dead and alive prior to measurement	**28**
5. Superposition is due to lack of human knowledge	**11**
6. Literal interpretation of superposition as a concept	**4**
7. Superposition implies probabilities of events	**11**
8. Quantum Physics describes the world at particle level	**12**
9. Quantum Physics is difficult and incomprehensible	**28**

In order to elaborate on the nine categories and exemplify how student's views can be linked to interpretations of quantum physics, let us embark on a journey through some student responses. The bracketed number in these responses correspond to the numeration of the categories in Table 1.

The first example point to our lack of knowledge of the cat's situation:
'The cat can be either dead or alive. You cannot know whether it is dead or alive before you open the box [1]'
Regardless of the apparently trivial nature of the response, this view is in accordance with the Copenhagen interpretation, in the sense that reality cannot be described beyond what can be measured.

Some students introduce the role of the measurement, for example
'If we try checking whether the cat is dead or alive, the result will change [2], and we will not be able to know it's state before the measurement [1]'
According to this student response, the act of measuring (opening the box) changes the cat's state from being in a superposition to be in the measured state. This category can be linked directly to the definition of quantum measurement, as mentioned above.

Our next response leads us to the third category, which reflect responses that acknowledges that being both dead and alive at the same time is a physical impossibility, so the cat must be either dead or alive:
'Schrödinger's cat tells us that there may be a probability for both states until we check on it. All right, but the cat is in «reality» either dead or alive, not both dead and alive. [3]'

Generalized, quantum systems are really in one state at a time only, even though this cannot be determined by measurements. Responses from this third category can thus be related to the hidden variables interpretation; since if the hidden variables in this system were to be found, one would know the cat's state at all times. The previous response points out that upon measurement, each outcome is equally probable. Connections to the role of probability in quantum physics like this is contained in our seventh category.

The fourth category, on the other hand, is derived from student responses referring to the fact that the cat can be thought of being dead and alive at the same time, and that this is the meaning of superposition:
'You cannot at any instant know whether the cat is dead or alive without opening the box [1], and that is why the cat is said to be in a superposition between dead and alive [5]. The cat is both dead and alive [4].'

As stated, the cat's superposition is due to lack of knowledge (fifth category), and the cat being in a superposition means that it is both dead and alive. Most of the student responses do not view this as a problem, though the wording in the previous response indicate that the cat being in a superposition means that it hovers between life and death. Another point of view is to consider the cat as an observer:
'Our logical way of thinking is that the cat is either alive or dead [3], but Schrödinger explained how, just like quanta, the cat can be dead and alive at the same time [4]. This relates to how all systems of reference are equally valid, because from our perspective the cat is both dead and alive, but from the cat's point of view it is either dead or alive'

This brings up questions like 'What does the cat see?' and 'Can the cat be regarded as an observer and thus cause the collapse of the wave function of the radioactive source?' Answering these question is beyond the scope of this article, but it is nevertheless interesting to point out that students may consider such questions when encountering Schrödinger's Cat. As mentioned above, our fifth category contains the view that superposition is due to lack of human knowledge. The two following responses problematize this to some extent:
'It is a paradox considering that the cat must be in one state at a time, but it is our lack of knowledge that creates this experiment. Quantum physics is then perhaps a type of physics due to our lack of knowledge and should perhaps not be applied as relevant physics.'

This response shows how this misconception of superposition can yield an erroneous description of quantum physics as a physical theory. Another misconception of superposition is likely to be a literal interpretation of the word 'super-position':
'We think that it [the thought experiment] shows what superposition in quantum physics means, where the particles [8] can be in several positions [6] because we cannot observe it [5]'

This response follows the same reasoning as the previous, that lack of knowledge yield the superposition, and reveals another misconception of superposition. As stated, a particle in superposition can be localized at different positions at the same time, it is hence in a superposition of states. Though the students are discussing the Schrödinger's cat, some students, like in the response above, connects quantum physics to particles. Such statements show an understanding that quantum physics indeed describe the world at particle level (eighth category).

The response that ends our journey is rich in detail, and exemplifies several of the categories above in addition to the ninth and last category, where quantum physics is seen as difficult and incomprehensible:
'Schrödinger's cat is an example of how quantum physics works. The cat is in superposition, and is either dead or alive [3]. We cannot know [1], and we cannot measure it's state. This

shows how difficult and different quantum physics from all "old physics", where everything can be calculated [9]'

Reasoning with this student, due to difficulties and how it differs from classical physics, nothing can be calculated in quantum physics! This kind of responses may be a result of how quantum physics is treated qualitatively without calculations at this level.

7. Conclusion: What place is there for "Schrödinger's cat" in pre-university physics?

Our results show that students interpret the thought experiment in a range of ways, whereof some are consistent with views held by physicists today as well as during the development of quantum physics. "Schrödinger's cat" is an example of how modern physics with stringent formalism is open to different interpretations and the kind of argumentation used by physicists.

However, many student responses miss out on key points. In order for students to understand the full depth of the thought experiment and the philosophical aspects of quantum physics it puts forward, they would need to be familiarized with the historical context where it was formulated. This should include how Erwin Schrödinger used the thought experiment in order to demonstrate how the principle of superposition of quantum states in the Copenhagen interpretation is flawed. The point that the cat as a macroscopic system is dependent on the quantum system in the radioactive source is here important, as it shows how quantum systems not only exist in a magic world of its own, but also have consequences for what we can know about macroscopic systems. Physics teaching could make students aware of the fact that real experiments that distinguish between interpretations have been conducted during the past decades (see Aspect, 1982; Haroche, 2013), which means that interpretations as well as hypothesis can be rejected. This might reduce the number of students that find quantum physics incomprehensible (Category 9) or that see it as only relevant in a microscopic world (Category 8).

Many have pointed to the value of using the history of physics in order for students to learn physics content as well as aspects of the nature of science (e. g. Arriassecq & Greca, 2012; Kolstø, 2008; Renstrøm, 2011). Renstrøm (2011) has shown in a comprehensive study that pre-university students indeed may learn physics content through historical approaches to the teaching of quantum physics. Several obstacles, such as the culture of teaching physics, do, however often hinder a successful implementation of these approaches (Höttecke & Silva, 2011).

Quantum physics related to Schrödinger's cat is an example of a field that probably will benefit from inclusion of the history of physics in the curriculum for pre-university physics students. It captures the core of interpretations of quantum physics, and hence historical approaches may support students in learni ng the physics content as well as developing their understanding of the nature of science, how scientists may disagree on interpretations and how argumentation plays an important role in the advancement of science.

The Norwegian curriculum for upper secondary physics has taken one step towards an approach where students can reflect on interpretations and philosophical consequences of quantum physics and develop a qualitative understanding as a foundation for studying the formalities of quantum mechanics at university level. Extending this part of the physics curriculum with the inclusion of history would give students opportunities to elaborate further on interpretations of quantum physics in more informed ways, and contribute to deepening of their understanding of the principles upon which quantum physics is built.

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