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## Literature study

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# Contents

Introduction . . . . .	4
Method . . . . .	4
Results . . . . .	5
Conclusion . . . . .	10
<b>References</b>	<b>12</b>

## Introduction

The literature study is an important aspect of writing scientific literature, and therefore also relevant for designing educational resources. It contains a description and evaluation of the existing literature relevant to the topic of the study (Steehouder et al., 2006). For a successful literature study, the researcher has to formulate research questions. The answers to these questions can then be used for completing and deepening the analysis.

In the case of designing resources to teach the fundamental principles of quantum mechanics, it is important to look at the different studies which investigate the teaching of quantum mechanics. Hence, the main research question for this literature study is:

What is known about teaching quantum mechanics from earlier research?

From this main research question several different follow-up questions follow:

- What are relevant topics within quantum mechanics education?
- What are the motivations to teach quantum mechanics?
- What are the intrinsic difficulties of teaching quantum mechanics?
- What are the pre-existing conceptions that students have about microscopic phenomena?
- What are the teaching strategies recommended by the literature?
- How is quantum mechanics currently taught in secondary education?
- What are aspects important for implementing quantum mechanics teaching in schools?

Initially, the method used to gather and systematically analyse the articles will be described, which will be followed by a summary of the results from the literature study.

## Method

First, the search terms for the literature study had to be considered. To achieve this, an initial look on Google Scholar with the terms "quantum mechanics teaching" already yielded many relevant results. Then, the thesaurus from EBSCO Host was consulted to look for relevant similar terms. When looking for "quantum mechanics", the only relevant term which was found was "modern physics", which is the umbrella term used for both quantum mechanics and relativity theory. Another term similar to quantum mechanics is quantum physics, but because everything quantum related could be relevant, the term used was "quantum\*". This resulted in the first search term being "quantum\*" OR "modern physics". The term "teaching" could be elaborated by terms like "instruction", "learning" and "education", but this set of terms already became obsolete during the next step, which entails considering the databases.

The first consulted database was ERIC, the database for articles in the field of education. Because the articles within this database are already education related, it was decided to only consider the first set of terms ("quantum\*" OR "modern physics") resulting in 1,225 articles. Then, a couple of limiters were applied, limiting the results to only peer reviewed articles published in scientific journals and with the full text available, resulting in 636 articles. After that, a limiter was added to search for articles concerning secondary education only, yielding 63 articles. Finally, only articles published since 2003 were considered, because quantum mechanics — especially quantum mechanics teaching — is a changing field, and articles older than 12 years might not be relevant anymore. With all these limiters — peer reviewed, published in scientific journals, full text available, secondary education only and published since 2003 — 26 articles remained.

Psycinfo, Scopus and Web of Science were also consulted. The terms used were the same as the terms used with ERIC plus the teaching set and the terms "highschool" OR "secondary education". This resulted in the term ("quantum\*" OR "modern physics") AND ("teaching" OR "learning" OR "education" OR "instruction") AND ("highschool" OR "secondary education"). However, this only yielded a limited amount of results, of which the articles were either irrelevant or already found by using ERIC.

There was one other article found separate from ERIC, written by McKagan et al. (2008). Three articles cited by this article were also added to the collection of consulted articles.

After this, the articles themselves were considered. Four articles were dismissed by title only. These were articles about other topics than quantum mechanics, so they were irrelevant. The rest of the articles were read by abstract, introduction and conclusion. After this, 16 articles contained (partial) answers to the research questions, so the rest of the articles was dismissed as well. After this, a literature matrix was set up with the research questions in one axis and the different articles in the other, and then the cells were filled in by reading the articles thoroughly. The results of this filled in literature matrix will be discussed in the next section.

## Results

### Topics within quantum mechanics education

The first logical question which should be asked would be the question which topics exist within the domain of introductory quantum mechanics, because only then we can delve into the question how these topics could or should be thought to novice learners. This exploration would have to start with a topic the students are already familiar with. Such a topic is the Rutherford-Bohr Model of the Atom, also known as the Bohr Model, which presents a description of a hydrogen atom (see figure 1). Students in upper secondary education should at least be familiar with this model, especially those with a technical profile. This gives way to introduce the students to the concept of elementary particles, which are the particles which exhibit quantum behaviour. The Bohr-model is also often referred to in the studied literature (Dori, Dangur, Avargil, & Peskin, 2014; McKagan et al., 2008; Müller & Wiesner, 2002; Papaphotis & Tsaparlis, 2008a, 2008b).

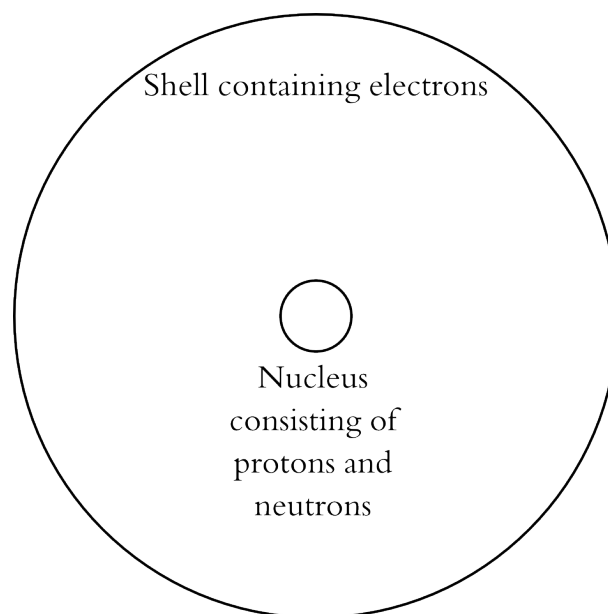


Figure 1: The Rutherford-Borh Model of the Atom

Some of the studies (Erduran, 2005; Hubber, 2006; Müller & Wiesner, 2002; Thacker, 2003) then describe properties of specific elementary particles, mostly of electrons or photons. Often used properties

are the photoelectric effect or the polarisation of light (Henriksen et al., 2014; McKagan et al., 2008; Müller & Wiesner, 2002). These properties could give more meaning to what the elementary particles are and do. Another benefit would be that these properties are used in the various experiments conducted within the field of quantum mechanics.

The double-slit experiment is the most famous of these experiments, and also the most studied tool for educational purposes (Asikainen & Hirvonen, 2014; Henriksen et al., 2014; Hobson, 2012; Levirini & Fantini, 2013; McKagan et al., 2008; Müller & Wiesner, 2002; Papaphotis & Tsaparlis, 2008a; Singh, Belloni, & Christian, 2006; Thacker, 2003). A reason why this experiment is famous is because it was the first experiment in history to demonstrate phenomena of quantum mechanics. The experiment entails shooting elementary particles through two narrow slits in a wall, projecting them on a large wall behind these two slits. When the two slits are separated very little, an interference pattern emerges. This is a result expected when the elementary particles would not be particles but waves. However, if the particles are observed and information is available through which slit each particle traversed, a diffraction pattern emerges, which would be the behaviour of particles. The most apparent phenomena demonstrated by this experiment is the wave-particle duality of elementary particles, which then could give way to mathematical descriptions of quantum mechanics like the Schrödinger equation. The Centraal Eindexamen of 2015 also already contained this experiment (Laan, 2013), so educational resources for teaching this experiment already exist.

For understanding the double-slit experiment, the concept of superposition is vital. Superposition means that when a particle is not observed, it is in all possible states at the same time. In the case of the double-slit experiment, superposition means that the particle goes through both slits at the same time. It then interferes with itself because of the probability function of where the particle ends up. However, when the particle is observed through which slit it travels, the information through which slit the particle travels is known and forces the probability function of the particle to collapse to either the left or the right slit. Because of this, it behaves like a particle and a diffraction pattern emerges. A video which demonstrates the double-slit experiment can be seen on <https://upload.wikimedia.org/wikipedia/commons/transcoded/e/e4/Wave-particle.duality.ogv/Wave-particle.duality.ogv.480p.webm>. The double-slit experiment can provide the learner with an explanation of the observer dependency of the elementary particles. However, only Müller and Wiesner (2002) mentions this concept in his study, and it also does not appear in the Centraal Eindexamen of 2016 (Groenen et al., 2014).

The concept of superposition also has different cases. There are other properties of elementary particles which can be in superposition, for example the polarity of photons. Upon measurement, the polarisation value of a photon particle collapses to a certain value, but before this collapse it has all the different polarities at the same time. This gives way to the concept of entanglement, mentioned in some studies (Henriksen et al., 2014; Hobson, 2012; Kuttner & Rosenblum, 2010). Entanglement is a phenomenon which occurs between elementary particles, and it has as effect that the collapse of the different particles are interdependent of each other. This entanglement has two forms: boson entanglement and fermion entanglement. When the two particles are bosons, they always collapse to the same state on observation, and when the two particles are fermions, they always collapse to each others opposite state.

Since the discovery of the phenomena occurring within quantum mechanics, scientists have debated fiercely about how to interpret these phenomena (Barnes, Garner, & Reid, 2004). Roughly speaking, the scientists could be divided into two camps: the camp of the realists and the camp of the ontologists. The realists thought that there has to be something underneath quantum mechanics which could explain the strange phenomena of superposition and entanglement, whereas the ontologists thought that the phenomena of quantum mechanics stand on its own. The phenomena of entanglement played a huge role in this debate. The realists first thought that they could use entanglement to prove that there is a reality underneath quantum mechanics, but it eventually led mostly to evidence towards the camp of ontologists. One example of this is Bell's inequalities (Kuttner & Rosenblum, 2010; Müller & Wiesner, 2002), which is beyond the scope of this literature study to explain.

Henriksen et al. (2014) writes that there are three main differences between classical mechanics and quantum mechanics. The first difference is the fact that classical mechanics are deterministic and that

quantum mechanics are probabilistic, also brought up by Levrini and Fantini (2013) and by Papaphotis and Tsaparlis (2008a). Classical mechanics rely heavily on deterministic causal effects, which can ultimately be explained. This is very apparent in systems of force, where everything moves according to certain laws, take for example the three Newtonian laws. Quantum mechanics however relies heavily on probabilistic models, where certain properties of certain elementary particles collapse to certain values according to probability functions.

A second difference between classical mechanics and quantum mechanics mentioned by Henriksen et al. (2014) is the locality of classical mechanics and the non-locality of quantum mechanics, also mentioned by Hobson (2012). On the scale of classical mechanics, it is possible to determine the exact position of an object, at least it is possible to do this on a significant scale. On a very small scale however, on the scale of quantum mechanics, the exact position of an object cannot be determined. There is an inherent uncertainty about the position of an object, which is very small and insignificant on the scale of classical mechanics, but quite significant on the scale of elementary particles. This is also true for the momentum of an elementary particle, which can be translated to the speed of an elementary particle. This uncertainty can be demonstrated by the uncertainty principle of Heisenberg (Henriksen et al., 2014; Müller & Wiesner, 2002; Velentzas, Halkia, & Skordoulis, 2007), which has as implications that neither the location nor the momentum of an elementary particle can be exactly known and that the more certain the location of an elementary particle is known, the less certain the momentum of an elementary particle can be known and vice versa.

Finally, Henriksen et al. (2014) mentions that classical mechanics are continuous and that quantum mechanics are discrete. This is because of the Planck length, which is the shortest measurable length. In classical mechanics, this length is very insignificant, and because of that the world looks continuous. A fully continuous world would mean that there is no tiniest unit, but that it is always possible to “go smaller”. For example, if one had a plank of wood, it could be divided in half infinitesimally. However, on a quantum scale, this is not possible, because it is not possible to have something smaller than the Planck length.

Because of the inherent difficulty with quantum mechanics, some scientists have posited thought experiments, which allows the learner to make a mental model about the different concepts of quantum mechanics. The most famous thought experiment is that of Schrödingers cat (Müller & Wiesner, 2002; Velentzas et al., 2007), where the life of a cat depends on the collapse of an elementary particle. When the cat is then observed, the state of the elementary is observed indirectly, which causes it to collapse and either kill the cat or let the cat live. This teaches the student about observer dependency, the way observations are linked to the random collapse of an elementary particle. Another thought experiment mentioned in the studied literature is the EPR paradox (Kuttner & Rosenblum, 2010; Müller & Wiesner, 2002; Velentzas et al., 2007), which can be used to teach the student about how entanglement is related to deep questions about the nature of quantum mechanics. This thought experiment however is related to the EPR experiment, which lies beyond the scope of this study to explain.

Finally, there are some studies which recommend certain mathematical approaches to quantum mechanics, namely the Schrödingers equation (Müller & Wiesner, 2002; Singh et al., 2006), the Hermitian operator (Singh et al., 2006), the aforementioned Bell’s inequalities (Kuttner & Rosenblum, 2010; Müller & Wiesner, 2002), the eigenvalue equation (Müller & Wiesner, 2002) and the DeBroglie energy levels (Dori et al., 2014; Gianino, 2008; McKagan et al., 2008). However, these mathematical approaches rely on a thorough conceptual understanding of quantum mechanics and are therefore not relevant to this study.

The topics relevant to teaching quantum mechanics can be summed up as the Rutherford-Bohr model of the Atom and elementary particles, the double-slit experiment, superposition, entanglement, the debate between realists and ontologists, the differences with classical mechanics, thought experiment and the mathematical side of quantum mechanics.

## Motivations to teach quantum mechanics

The needs assessment mentions that the need for teaching quantum mechanics exists because of the Centraal Eindexamen. This is an example of extrinsic motivation. However, is there also intrinsic motivation to teach quantum mechanics on high schools? First of all, there is no article which claimed that quantum mechanics should not be taught on high schools. On the other hand there are but a few authors who did have some arguments in favour of teaching. Müller and Wiesner (2002) and Henriksen et al. (2014) state that quantum mechanics shapes our world view and that educated citizens should therefore become acquainted with the topic. It is also regarded as fundamental and should therefore be taught (Henriksen et al., 2014; Hobson, 2012). Finally, Erduran (2005) states that the teaching of philosophical themes in science education has been advocated for several decades, and quantum mechanics is one of these themes.

## Intrinsic difficulties of teaching quantum mechanics

There exists a consensus within the studied articles that quantum mechanics is a difficult topic, and this is also a consensus among educators (Gianino, 2008; Papaphotis & Tsaparlis, 2008a, 2008b). There are a couple of reasons mentioned within the articles to explain this topical difficulty. A couple of sources state that quantum mechanics is a very counterintuitive topic (Henriksen et al., 2014; Levrini & Fantini, 2013; McKagan et al., 2008; Singh et al., 2006), because it contradicts many aspects of our daily experience, like locality or determinism. Quantum mechanics is also considered to be a very abstract topic (Barnes et al., 2004; Gianino, 2008; McKagan et al., 2008; Papaphotis & Tsaparlis, 2008a; Singh, 2006). Because quantum mechanics differs a lot from our everyday experiences and because of its abstractness, it is difficult for learners to visualise the concepts of quantum mechanics (Henriksen et al., 2014; McKagan et al., 2008). Another factor contributing to the difficulty of quantum mechanics is that it is mathematically challenging (Gianino, 2008; McKagan et al., 2008), it involves mathematical skills that most high school students — even vwo 6 students — do not possess.

## Pre-existing conceptions from students about microscopic phenomena

When developing an instruction, it is important to consider the already available conceptions on the topic. In quantum mechanics, these preconceived models often prove to be incorrect (Asikainen & Hirvonen, 2014; Papaphotis & Tsaparlis, 2008b; Thacker, 2003). This partly comes from the nature of quantum theory (Papaphotis & Tsaparlis, 2008b), but also partly from textbooks and instruction (Hubber, 2006; Papaphotis & Tsaparlis, 2008b). The problems often stem from depending on outdated deterministic or realist models (Hubber, 2006; Papaphotis & Tsaparlis, 2008a, 2008b), an often mentioned example of this is that students often mix up the deterministic planetary model with the indeterministic atom model (Dori et al., 2014; Henriksen et al., 2014; Hubber, 2006; Müller & Wiesner, 2002; Papaphotis & Tsaparlis, 2008a, 2008b). McKagan et al. (2008) also mentions that it is difficult for students to recognise the scale in which quantum mechanics take place.

Thacker (2003) describes how much knowledge of students consists out of memorised facts, for example that light is a wave and electrons are particles. When the student then is confronted with new or different information from what they know, they develop new memorised facts instead of creating the right model. This then results in models consistent with fragmented models of microscopic processes, which are often incorrect but self-consistent with a certain experiment (Hubber, 2006; Thacker, 2003). When the student cannot model the fragments anymore, this can result in deep skepticism towards quantum mechanics (Barnes et al., 2004; Henriksen et al., 2014; Levrini & Fantini, 2013). Müller and Wiesner (2002) has created a long list of exact conceptions students hold about microscopic phenomena, which are too detailed to enlist fully in this article.



## Teaching strategies

The literature provides a lot of strategies which can be used to teach quantum mechanics. These can be categorised in four categories. There are recommendations for which content to use. Others describe aspects of the medium used to teach quantum mechanics. Some of the strategies focus on meta-cognitive aspects. Finally, there are a few frameworks which can be used to teach modern physics.

Some of the content-related strategies emphasise the importance of embedding the instruction in real-world contexts, for they help with understanding (McKagan et al., 2008; Thacker, 2003; Dori et al., 2014) and help appreciate the relevance of quantum mechanics (Barnes et al., 2004; Henriksen et al., 2014; McKagan et al., 2008). Furthermore, Thacker (2003) suggests introducing microscopic processes as an integral part of a study of electricity and magnetism. This could help demystify the topic, which also would contribute towards a better understanding (Barnes et al., 2004; Müller & Wiesner, 2002). An example of how this can be done is by using the e/m experiment, where the electromagnetic effect is demonstrated by the properties of electrons. Furthermore, the language of physics is important (Henriksen et al., 2014), and should be used carefully (McKagan et al., 2008). The consulted articles all recommend a conceptual approach above a mathematical-oriented approach. Mathematical-oriented approaches might be more common, but most high school students lack proper background in mathematics at the required level (Dori et al., 2014). Barnes et al. (2004) and Henriksen et al. (2014) believe teaching through history of science is believed to be constructive.

The recommendations for different aspects of the medium used for the delivery of the instruction entail interactivity, visualisation, the combination of different modes of representation, and the use of computation. By making it able to interact with the medium, it is possible for students to experiment with the different concepts, which gives way to inquiry learning (Adegoke, 2012; Asikainen & Hirvonen, 2014; Dori et al., 2014; McKagan et al., 2008). Visualisation is a powerful tool, and can make the matter less abstract (Dori et al., 2014; Henriksen et al., 2014; McKagan et al., 2008). It also is easier to build mental models of quantum mechanics. Levrini and Fantini (2013) warns however against the use of oversimplified visualisations, because pictures are extremely partial and can be misleading. Therefore, it is important that the visualisation does not entail any unnecessary simplified representation of the matter. This combined with other different modes of representation, for example a textual description of the concept, makes it possible for the student to complete their mental model (Dori et al., 2014). Finally, the use of computation makes it possible to take away the mathematical complexity from quantum mechanics, making way for a purely conceptual approach (Barnes et al., 2004; McKagan et al., 2008; Velentzas et al., 2007). One could combine all these aspects by using simulations, which is also recommended by McKagan et al. (2008).

Papaphotis and Tsaparlis (2008a) states that critical thinking skills are crucial for understanding quantum mechanics, because students have to investigate the new material in a critical way to build the correct mental models. Active learning also contributes to investigation of the material. Because the students easily build misconception, right feedback is vital to prevent misconceptions and can stimulate students to build correct mental models. Finally, Papaphotis and Tsaparlis (2008a) suggests collaboration, which is also suggested by Adegoke (2012) and Barnes et al. (2004). Collaboration could lead to peers providing each other with critical questions and feedback. Especially in the case of female students this could benefit to learning quantum mechanics (Adegoke, 2012).

The frameworks mentioned by different authors are directly or very similar to thought experiments (Asikainen & Hirvonen, 2014; Erduran, 2005; Levrini & Fantini, 2013; Velentzas et al., 2007). Asikainen describes the most elaborated framework for a well-conducted thought experiment, which includes the steps question and general assumptions, description of the features of the system, performance of the thought experiment itself, extraction of the results and drawing conclusions. Erduran (2005) and Levrini and Fantini (2013) also describe a framework, but the steps they mention already overlap with those of Asikainen and Hirvonen (2014).

## Quantum mechanics in current secondary education

Quantum mechanics is already part of the standard curriculum in other countries than the Netherlands. Often, quantum mechanics is introduced with great emphasis on learning and practising algorithmic skills (Papaphotis & Tsaparlis, 2008a, 2008b). However, it is also found that high school students show higher interest in the conceptual aspects than the algorithmic aspects (Papaphotis & Tsaparlis, 2008a, 2008b; Levrini & Fantini, 2013). When focusing on the conceptual aspects, it engages students (Henriksen et al., 2014) and students start asking fundamental questions (McKagan et al., 2008). Because the usual focus on the algorithmic aspects, students often do not learn what instructors want them to learn (Asikainen & Hirvonen, 2014; McKagan et al., 2008), and improved student learning is possible by shifting the focus to conceptual understanding (McKagan et al., 2008).

## Aspects important for implementing quantum mechanics teaching

Quantum mechanics teaching is not only difficult for the students learning the topic, but it is also a difficult topic to implement and integrate within high schools. As mentioned in the previous section, the consulted articles state that quantum mechanics can be taught at best by using new innovations, like computer simulations. However, teachers often prefer traditional lectures, because that is easier to implement in their classroom (Adegoke, 2012). This difficulty has to be overcome if quantum mechanics is to be taught successfully. Another problem which has to be solved is the fact that teachers often show to possess misconceptions about quantum mechanics (Asikainen & Hirvonen, 2014), similar to undergraduate students. However, experienced teachers who are teaching modern physics are more capable of teaching quantum mechanics (Asikainen & Hirvonen, 2014).

## Conclusion

There is a wide variety of topics available for quantum mechanics education. It is advisable to start any instruction with the Rutherford-Bohr model of the Atom and its relation to elementary particles, for this is the scale on which quantum mechanics take place. A next step could be introducing the different phenomena which happen on a quantum scale, such as superposition, observer dependency and entanglement. One way to introduce superposition and observer dependency is by using the double-slit experiment. This also teaches about the wave-particle duality of elementary particles. Furthermore, the students could be taught the differences between classical mechanics and quantum mechanics, which are determinism and probabilism, locality and non-locality, and continuous and discrete distances. One way to highlight the strangeness of quantum mechanics is by using the debate between realism and ontology, this emphasises that quantum mechanics are different than a student might think at first. There are also famous thought experiments, for example Schrödinger's cat, which could be used to create different mental models with the students. Finally, there are some mathematical approaches to quantum mechanics, however there is a consensus within educators that a conceptual approach is more effective.

Not a lot of studies write why quantum mechanics should be taught on secondary education. There is however no study which claimed it should not be taught. Reasons why it should be taught are that educated citizens should be acquainted with quantum mechanics and that it is regarded fundamental.

Quantum mechanics is regarded to be a difficult topic, because it is counter intuitive, it contradicts daily experienced locality and determinism, it is regarded to be abstract, it is difficult to visualise and it is mathematically challenging.

Misconceptions about quantum mechanics can arise out of the nature of quantum theory, but also from textbooks and previous instruction. It is important that the information handed to the students are not simplified, because this can lead to misconceptions. Problems also often originate from outdated deterministic or realist models. The students therefore have to be confronted with the fact that their own models cannot be applied in the context of quantum mechanics. Students also find it difficult to recognise the scale in which quantum mechanics take place. Hence, the students should be informed that quantum mechanics take place on the scale of elementary particles. Knowledge of students often consists out

of memorised facts, and when confronted with new or different information, new facts are memorised instead of creating right models. This results in fragmented incorrect but self-consistent models. Because of this, the instruction should provide the student with a coherent description of quantum mechanics.

The literature prescribes different strategies for teaching quantum mechanics, namely recommendations for content, aspects of the medium to use, meta-cognitive aspects and a framework. Content related strategies entail embedding the instruction in real-world contexts, letting the student appreciate the relevance of quantum mechanics, introducing microscopic processes as an integral part of electricity and magnetism, using the language of physics, and using a conceptual approach instead of a mathematical approach. The medium used should be interactive, it should visualise the concepts, it should make use of different modes of representation, and it should make use of computation. It should be noted however that one should be careful with visualisation, for this can easily lead to misconceptions. The use of simulations are suggested. Furthermore, critical thinking skills, active learning, feedback and collaborative learning could contribute to students building the correct mental models of how quantum mechanics work. Finally, thought experiments are regarded to be very effective for learning quantum mechanics, this entails questions and general assumptions, a description of the features of the system, performance of the thought experiment itself, extraction of the results and drawing conclusions.

In secondary education, instructions often emphasise learning and practising algorithmic skills. This however clashes with the recommendations from the literature, which advocates an emphasis on conceptual understanding. It is also found that students show higher interest in conceptual aspects than the algorithmic aspects. Conceptual approaches engage students and probes the student to ask fundamental questions. Because of the focus on algorithmic aspects, student currently often do not learn what is intended by the developer of the instruction, improved student learning might be possible by shifting the focus to conceptual understanding.

Finally, quantum mechanics teaching is a difficult topic to implement and integrate within high schools for two reasons. The literature prescribes the use of new innovations for teaching quantum mechanics, whereas teachers prefer the use of traditional lectures. Because of this, the implementation and use of the software should be made as easy for teachers as possible. Furthermore, a lot of teachers have misconceptions about quantum mechanics themselves. Because of this, it is vital that teachers get instruction about quantum mechanics and its difficulties before they teach it themselves. Experienced teachers who teach modern physics are more capable of teaching quantum mechanics, so they might be used for teaching quantum mechanics to less experienced teachers.

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