IJPCE
International Journal of Physics and Chemistry Education, 11(1), 1-5

www.ijpce.org
ISSN: 2589-8876

Pre-Service Teacher's Views on the use of Metaphors for Describing the Concepts of Uncertainty and Entanglement in Teaching Quantum Physics

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Abstract

Quantum physics is a fundamental theory of physics heavily relying on its description by mathematical structures. However, its successful handling ensures in no way its conceptual understanding. So teaching quantum physics in high school faces the problem of adequate strategies. Often visualisations are used in order to provide anchors for students. These have to be chosen carefully to avoid misconceptions. At the same time an adequate verbal explanation of quantum phenomena or of their visualization is sought as physics language is shaped by classical physics. As an additional method for teaching we propose the use of metaphors for making the quantum physical mechanisms more insightful without interference from classical physics.

Keywords

Quantum physics, Metaphors, Pre-service teacher education.

◆Received 30 November 2016 ◆ Revised 15 December 2017 ◆ Accepted 15 April 2019

Introduction

This contribution analyses how pre-service teachers view the use of metaphors for describing the concepts of uncertainty and entanglement in teaching quantum physics. The goal was to provide suitable metaphors providing understandable explanations for high school students. There have been investigations concerning the use of metaphors by physicists or how experienced teachers are using metaphors in constructivist teaching. These show students' difficulties connected to metaphors rooted in classical physics. Here we want to explore in more depth the possibilities of unusual metaphors avoiding the reference to classical physics.

Views on Quantum Physics and its Teaching

As a fundamental theory of physics, quantum physics should be part of the physics education at school. Every student leaving high school should have had at least a glimpse of quantum physics and a basic understanding of the differences to classical physics. The teaching with this goal has special challenges in mathematical and conceptual aspects.

Conceptual problems in teaching quantum physics

The content analysis shows that quantum physics is characterized by uncertainty and entanglement with the notion of superposition as basic idea. These concepts can be taught appropriately in the context of quantum information with two state systems using only very basic linear algebra. This approach very quickly leads to the mathematical as well as conceptual core of quantum physics.

As the mathematical knowledge of high school students is quite restricted the use of mathematical tools has to be considered very carefully. In general mathematical operations have a concrete underlying meaning, informing their use in physics (see e.g. Sherin 2001). In no physics area the interplay of physical meaning and mathematical operations is trivial. However, because of the deviation of quantum physics from classical physics here the interplay is equally especially difficult and important. The appropriate understanding of physical concepts such as superposition or uncertainty or the physical meaning of mathematical objects such as projection or (non)-commuting operators on an elementary basis has to be supported by other means, e.g. by an adequate verbal explanation or visual representation. The analysis of textbooks, however, reveals that many visual aids may be misleading as they refer to classical concepts such as particles, waves or trajectories. This leads to the effect that classical views will often not be reflected and thus remain unchanged. One famous example is the Bohr atomic model. Its usual depiction supports the implicit use of trajectories and inadequate concepts of quantum objects (Fischler & Lichtfeld, 1992).

Also verbal explanations can lead to misconceptions. A widely spread but misleading concept is the use of "Wave-particle dualism". The meaning is not well-defined and can cover a whole range from nearly classical to nearly quantum understanding. Also the descriptions of uncertainty often suggest the conception of an imprecise measurement or not exactly knowing the supposedly pre-existing fixed properties of quantum objects. Similar misunderstandings are related to the difference between classical (stochastic) indeterminism and quantum theoretical indeterminism.

All these difficulties mostly have their roots in an approach starting from classical examples. Therefore Michelini (2000) and Pospiech (1999) suggested to start from the fundamental concepts and stress the differences between classical and quantum physics.

Central notions besides the indeterminism are the followings:

- *Superposition Principle*, implying that a linear combination of state vectors is again a possible state vector,

https://doi.org/10.12973/ijpce/16113

- *Uncertainty* meaning the non-existence of fixed values for different physical properties at the same time. This notion has been greatly clarified and ensured by experiments starting from 1982 (Aspect, 1982)
- *Entanglement*, the physical description of a system with (at least) two parts differing from the description of the addition of the two parts as it is done in classical physics. Zeilinger has called this the decisive property of quantum physics.

The mathematical as well as physical involvement of these notions makes it nearly impossible to treat the differences between quantum and classics by verbal explanations using the technical language of (classical) physics. On the search for understandable as well as correct explanations for high school students we found that metaphors are often used to describe the quantum physical concepts. In this contribution we will discuss how metaphors could help in building a bridge between the mathematical operations and their physical meaning.

Metaphors and quantum physics

A metaphor is a figure of speech that identifies something as being the same as some unrelated thing. It brings together two concepts from different conceptual domains. It may provide insight by identifying or creating hidden similarities between two concepts.

Johnson (1995) stresses the overall presence of often unconsciously used metaphors in daily language. He transfers this use of metaphors shaping the human understanding to the scientific discourse where metaphors taken from one area to another area of physics influence scientific thought. However, he refers to physicists who know the realm of physics and hence move freely in a joint framework during communication. That this is not the case with learners, students at high school as well as at college, is pointed out by Brookes&Etkina (2007). In addition, Niebert, Marsh and Treagust (2012) stress the differences between students and teachers in employing, understanding and developing metaphors in scientific communication. Herewith they distinguish embodied and imaginative metaphors (not making a difference between analogy and metaphor). They also hint to the difficulties students have in correctly adopting the meaning of a metaphor presented by the teacher. Their conclusion is that the metaphors have to be embodied and reflected upon.

As metaphors relate two objects of different domains with each other, at least two of the three parts of the relation - source domain, target domain and the mapping between those domains - have to be known to the students. The metaphors in describing quantum physics may use different source domains, but mostly these reflect certain aspects of classical physics or everyday life objects or processes avoiding or at least hiding mathematical structures. This choice of metaphors strongly related to realistic objects leads to the effect that any discussion on quantum physics starting from here is restricted to general aspects. However, as quantum physics lives on its mathematical structures the use and fruitful interpretation of metaphors has to allow for a translation to the mathematics and experimental outcomes.

Metaphors in communication on quantum physics

The opportunities metaphors might provide in visualizing quantum physics or in illustrating the interplay of quantum physics with its mathematics have early been recognized. The master of metaphors in quantum physics was Schrödinger inventing some of the most famous metaphors. He created e.g. the "catalogue of possibilities" in describing the superposition principle and even more metaphors, mostly described in his famous article from 1935 (Schrödinger 1935). The "catalogue of possibilities" could be extended to describe the measuring process: The catalogue contains the whole information of the state of the quantum object. In the measuring process one single result will be obtained. This can be described by the metaphor of tearing one page out of the catalogue, getting the information of that page and loosing every other information. Schrödinger's metaphors focus on the correct mapping between the physical concepts and the elements of the metaphor as e.g. in the Schrödinger cat or other less well-known metaphors. One example has been analyzed in detail by Ceroni (2014). She tries to determine the quality of a metaphor (or analogy) and sees an important aspect in the perceived oddness of the metaphor. The oddness might have a negative impact on learning if the productive aspects in completing the metaphor by physical description are not being put forward. So metaphors cannot stand for themselves but have to be explained explicitly. This ensures that two parts of the threefold relation between source, target and mapping are known.

Metaphors in teaching quantum physics

As referred to above the use of metaphors might enhance understanding but also brings with it specific learning difficulties. Physicists use many different metaphors, mostly taken from classical physics as kind of analogy. The wording often belongs to the physics jargon. Even if the physicists can reason productively about quantum physics with help of the metaphors their application for reasoning is not per se familiar to the students. One example might be the sentence "the electron is a smeared paste," requiring knowledge of the quantum object and the metaphorical object and the mapping between them (Brookes & Etkina 2007). Only if the students know the source domain and the mapping then there is a chance that they also understand the target domain. If not, they might come up with an ad hoc mapping that is inappropriate to a given situation. In addition, metaphors with strong images might lead to the effect that students are being distracted by the metaphor, reducing their focus on quantum physics, even to the extent that students understand the physical ideas, but are confused about the language used to express the physical ideas, (Brookes & Etkina 2007). Because of the missing experience of students with the threefold relation described before students might be led to an overly literal interpretation of the metaphorical language they encounter in lessons on quantum physics. The related attempts to make sense of metaphorical terms such as "wave function" or "state" might lead to misconceptions (see also Singh 2006). It is observed that most explanatory metaphors for quantum mechanics are only used in very specific circumstances hence cannot serve as a reasoning tool (Brookes & Etkina, 2007).

Research Questions

The goal of the paper is to analyze the use of metaphors and analogies and its connections to the mathematical structure restricted to the case of two-state systems (2d-matrices and state vectors). Herewith we focus on unusual metaphors in the above sense.

- In which way are unusual metaphors suited for learning the main concepts of quantum physics: uncertainty and entanglement?
- What are the pre-service teachers' views about unusual metaphors on these two topics?
- Do pre-service teachers view metaphors as a possible help in building a bridge between the mathematical operations and their physical meaning, at the example of metaphors on uncertainty and entanglement?

Analysis of Metaphors in Popular Science Resources and Textbooks

In popular science books, no knowledge about the mathematics of quantum physics can be supposed. Therefore, the explicit explanation is more difficult and the authors have to resort to vivid images. Because of the general audience, the authors are forced to use intuitive metaphors for describing the laws of quantum physics. We want to know which possibilities the authors use and how accurate the created metaphors are.

In a first step, we perform a content analysis in textbooks and popular science books with focus on metaphors of uncertainty and entanglement, in order to analyze if and to what extent they could be used in teaching. We concentrated on metaphors, which do not refer to classical physics such as e.g. "the electron is (like)/behaves as a particle", "the electron is flying" or "the electron knows", but use objects from "normal" life. An example of such an "unusual" metaphor would be: "I do not know where your bone is, but I can tell you exactly how fast it is moving." (Orzel, 2009). Herewith we choose eight popular science books, 5 high school books and 5 textbooks for university, all with publication date starting from year 2000. The first result was that the chosen high school and university textbooks do not have any "unusual" metaphor.

Metaphors of uncertainly and entanglement

We identified some metaphors of uncertainty and entanglement and will discuss their suitability to provide an adequate picture of quantum physics, also with respect to their compatibility to the mathematical structure and the physical meaning. The found "unusual" metaphors show that any metaphor can only be an approximation of the physical meaning and has to balance the correctness with the understandability by the intended audience.

Perhaps the most famous "unusual" metaphor is Schrödinger's Cat. It could be seen as a metaphor of the superposition principle, but can be extended to a metaphor of entanglement by entangling the radioactive material and the two possible states "dead" or "alive" of the cat. Concerning entanglement there are some more examples in his paper of 1935 but those are more complicated to describe.

In the popular science books it turned out that, the metaphors are quite rich and taken from all areas of life, but only weakly mimicking the mathematical-physical background. As a rule, the mapping between the metaphor and physics is often not obvious but needs explicit translation.

> "Just an atom was chained in a microphysical dungeon but in the next moment it has freed itself from the bonds and on the quiet stole away into the night." (Chown, 2008)

Mostly the metaphors are embedded into a storyline. The problem of such a metaphor is that it needs long and involved texts. An example is a story taken from the book "Einsteins's veil" by Zeilinger (2003): "The tyrann and the oracle" which needs several pages to evolve. On the other hand, shortness often implies descriptions which are too much simplified or even wrong. One well-known example are "Bertlmanns socks". It can be told quickly and seems obvious but it is misleading in that it does not meet the core of the concepts uncertainty or entanglement, especially if only one variable is used. So, it seems that the length or the complexity of a metaphor is coupled with its correctness. The possible mathematical description, the well-known uncertainty relation, is introduced a bit deeper in the following description of uncertainty: "If he closed his fist even tighter he sensed how the thing fidgeted even more violently. The counter pressure developing in his hands became so strong that he soon did no longer have the force to keep hold on it." However, here the principle of two different incompatible (i.e. not commuting) quantities is only vaguely addressed. Therefore, the questions arises if this can lead to an adequate picture of uncertainty.

One example concerning entanglement reads: "If it is said that somebody had his hands entangled then this implies that the fingers of both hands are slid in such a way that they can no longer be turned independent of each other." (as cited in Hüfner & Löhken, 2010) (translated by the author)). This metaphor focusses on the fixed interrelation between the objects (hands). There is no mapping of the tensor product, the basis of the quantum effects of entanglement. Hence, it is not clear if this metaphor could induce more than some preliminary and vague everyday understanding of quantum physics.

So in order to have suitable material for teaching one has to invent own metaphors, adapted to the needs of prospective teachers. Such metaphors we applied in a seminar for teacher students on didactics of quantum physics.

The seminar

The seminar was intended to enhance the knowledge of teacher students and providing them with concrete material for teaching quantum physics at high school. It was expected from the participating students – and all the students met this requirement – that they had passed the normal course of quantum theory for teacher students. This course gives a standard introduction on the basis of a 90 minutes lecture and a 90 minutes tutorial per week, 15 weeks on the whole.

The goal of the additional seminar was to build a bridge such that the students would feel more confident to really teach quantum physics at school. Hence, the seminar focused on basic concepts such as superposition, uncertainty and entanglement. It treated the double-slit experiment with variations such as which-way information. The mathematics restricted itself to the elementary description of two-state-systems with help of 2*2 matrices, thus giving insight how the mathematical structure of uncertainty and entanglement could be handled on school level (see Pospiech 1999). Besides these subject-related topics, the students learned to know different teaching approaches, materials, animations, simulations and so on. Among these were different metaphors, described in the following section. In the end the students had to develop an own teaching unit on quantum physics in-group work.

Construction of own metaphors

One method to construct own metaphors relates persons or objects according to the mathematical structures and rules of quantum physics as described in Pospiech (1999). This process is best illustrated by an example, a metaphor "horses and cows" of uncertainty:

"A farmer owns a herd with cows and horses, which are either white and black. These he wants to count. In order to do so he uses a double gate: At the left gate only the cows can go through, at the right gate only the horses. After separation of the cows and horses, in a second step, he removes the horses and brings them to a far away field. Then he sorts the cows according to their color in order to get a herd with only white cows. Now he wants to be sure that his sorting was done correctly. He tests by sending only the white cows again through the double gate. Suddenly horses are found in the herd."

This example mimics the well-known Stern-Gerlach apparatus with two crossed magnetic fields and there is a one to one-mapping between the metaphor and the mathematics of a two-state system. This mapping was discussed in detail with the students.

A simpler metaphor of entanglement might be more intuitive, but without reference to mathematics: One could say that texts show "entanglement": Words of a text are "entangled" by their cohesion, the meaning of their words in the whole context. The change of single words in a text affects the whole text immediately without losing any time. This was the second metaphor. In addition, the famous Schrodinger cat metaphor was discussed in the seminar.

If we constructed metaphors with objects from classical physics, the entanglement would lead to contradictions with everyday experience. Overall, we can state that the use of metaphors has to balance simplicity and transferability. These two aspects seem to be fighting with each other.

Pre-service Teachers' Views on Metaphors

In this section, we analyze the views of the participating pre-service teachers on the relation of the developed metaphors from the previous section to the corresponding physical concepts: uncertainty ("horses and cows") and entanglement ("text", "Schrödinger's cat") and its mathematical background as treated in the seminar.

Method of study and Analysis

The participants of the study were 18 students, near the end of their study (specialized for teaching physics at high school) participating in the described seminar on didactics of quantum theory. The students' views were collected with a questionnaire consisting of two parts. The first part focused on the actual knowledge and understanding of students. It had three questions, each concerning one of the metaphors described in the preceding section and their relation to uncertainty and entanglement respectively and its mathematics. The second part concentrated on the views of the students concerning the use of metaphors in teaching quantum physics in general and comprised seven questions concerning the relation between metaphors and the treated mathematics or the physical phenomenon or their relevance for understanding the quantum physics content. Examples are: "Metaphors must be transferable directly into the mathematical structures" or "Metaphors could clarify to students, where the difference to classical physics is." One question concerned the generally perceived advantages and disadvantages of metaphors. All questions required open answers. The students should give their opinion together with a reasoning. The students answered the questionnaire during one lesson. The data were analyzed by inductively finding categories for the answers.

Views on teaching quantum physics with metaphors

In accordance with the considerations on metaphors the prospective teachers think that metaphors can give an impression of quantum physics but no precise knowledge (7 out of 18 agree, 5/18 agree partly). They see their use in visualization, in better comprehensibility of concepts and as a possibility to avoid formalism. However, metaphors have to be implemented with a clear goal, to be very specific and build a relation to already well-known content. The drawback is seen in possibly not complete description and the necessary special explanations. Some future teachers (8/18) agree that metaphors can clarify the differences to classical physics because they make its absurdity or contradiction to classical physics apparent. Others (4/18) agree at least partly, because they see the problem to find an understandable representation of the metaphor. Nevertheless the future teachers would use metaphors in their teaching (13/18 agree at least partly), mostly because the formalism is too complex and the metaphors could support understanding. On the other hand, five persons think it is important that the students have to already know quantum physics and that the formalism may not be neglected. 8/18 would their students let invent own metaphors in order to see if they understood the quantum concepts properly. Overall, the participants are positive but indicate conditions for successful use of metaphors. The metaphors would have to be well explained and require pre-knowledge.

Relation between mathematics, physics, and metaphor

Many teacher students hold the formalism in high regard: 6/18 agree that the correct mapping from metaphor to mathematics is necessary, 4/18 think it not necessary in detail, 4/18 state that to make the relation explicit would be too difficult for the students. Overall, they prefer a good agreement with the physical foundation is necessary, but think it is possible only for single aspects (7/18). Concerning the relation of physics and mathematics some believe metaphors could be a help (5/18) because the formalism itself is too complex or that metaphors help in interpreting it, but only if explained adequately (4/18). How well this can be done depends strongly on the metaphor (4/18). On the other hand, some future teachers (4/18) think that metaphors are not useful because they could be puzzling and only give an incomplete picture of the formalism.

Advantages and disadvantages

Most reasons against the use of metaphors in teaching quantum physics are borne from fears that the students might not understand the concepts properly: metaphors could be puzzling (5/18), induce misconceptions (3/18) or their limitations are unclear (6/18).

On the other hand most teacher students see the advantage of metaphors in that they could serve as visualization, simplification or clarification (11/18) if embedded properly into the lesson (especially using clear language and giving good explanation). Metaphors can help in understanding or be motivating because they can involve funny situations, are surprising or can be more easily memorized.

Ability to interpret given metaphors in physics terms

The participants had the task of interpreting some given metaphors known from the seminar: Schrödinger's cat and the metaphors "horses and cows" and "text" described above. The analysis of the pre-service teachers' interpretation of these metaphors highlights their thinking, e.g. that they have a broad interpretation and interconnect uncertainty and the measuring process. This task also revealed learning difficulties concerning the ideas of state and a property of a system. However, the students gave nearly no relation to the mathematical description, they mostly stuck to the physical aspects. The most correct answers were given concerning Schrödinger's cat. The metaphor of "horses and cows" showed to be more difficult because of a confusion of property and state. Hence the explanation of unusual metaphors seems indeed

Conclusion

Concerning the problem of teaching quantum physics with restricted mathematical and physical experience of the learners the use of unusual metaphors could be an additional feature supporting the use of visualizations. Overall, we can identify the following main traits of teacher students: One group of students stresses the possible learning by metaphors: Understanding quantum physics qualitatively and clarity would be central for their teaching. Metaphors have to be explained well and have to mirror as precise as possible the physical relations in order to avoid misconceptions. However, the formalism is in the background and not important for pupils. Letting students find own metaphors can serve as a diagnostic tool. The other group of students attributes a restricted use to metaphors. They can help in explaining uncertainty of entanglement, if they are designed properly. Their usefulness however, strongly depends on the knowledge of students as they can also cause confusion. Metaphors have to be adapted to the problem in question and should fit into the curriculum. Overall, the students react mostly positively to the use of unusual metaphors and agree that metaphors could be a help in grasping the concepts of uncertainty and entanglement of quantum physics. However, they have to be embedded in a careful designed course and to be explained well in order to build a bridge to understanding, especially because of their imaginative character.

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