A developmental research on introducing the quantum mechanics formalism at university level

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Summary

This thesis describes a developmental research conducted in two university level, introductory courses on quantum mechanics: Quantum Physics (QP) for physics majors, and Quantum Chemistry (QC) for chemistry majors. As described in Chapter 1, developmental research has two main aims. The first aim is to develop prototype materials in a real teaching environment. This might also be qualified as a local engineering problem: finding solutions for learning difficulties identified in a concrete situation (i.e. the QC and QP courses in this case). The second aim is to make a scientific contribution by formation of a local model that explains the structure of the developed prototype materials. In other words, the results of a developmental research should be made of use to other contexts as well. Following a developmental research approach, this research is organized in multiple research rounds that have a cyclic character. In a zeroth, exploratory research round an inventory was made of learning and teaching difficulties in both courses. Also, a literature research was conducted to compare our findings to those of others, as well as to find suggestions how to address the observed learning difficulties. The zeroth research round also resulted in preliminary research questions and hypotheses. To answer these questions and test the hypotheses, interventions were planned for a next research round, where the interventions were tried out and their effect was studied. This has led to an adjustment of hypotheses, research questions, and the designed interventions. After the zeroth research round, three additional research rounds have followed for the QP course and four rounds for the QC course. Because of the exploratory character of this research, mainly qualitative research instruments were used. In later research rounds a selection of students were followed throughout the course.

An overview of the relevant education research literature on quantum mechanics and quantum chemistry is given in Chapter 2. In the literature various learning difficulties were found when learning quantum mechanics. Some of these learning difficulties are related to prior education, some to conditions for prior knowledge when learning quantum mechanics. An analysis found frequently in the literature is that due to the difficulties with the interpretation of quantum mechanics and its abstract nature there is a focus on teaching and learning the quantum mechanics machinery first. However, the reviewed literature shows that this method has its drawbacks. It does not prevent stu-
students from forming misconceptions, perhaps even stimulates this, and it elicits surface learning. Some authors see the learning of quantum mechanics as the adoption of a new conceptual framework. Some go further and argue that a paradigm shift is needed. In any case, students seem to have need of a discussion of what the theory is good for, where it comes from, and what it means.

In Chapter 3 we motivate the chosen theoretical framework. Based on the literature review as well as on Ausubelian learning theory, we suggest that introducing quantum mechanics involves the creation of a network of higher-order abstractions for which suitable experiences are needed. We give arguments why verbal reception learning is not appropriate to introduce quantum mechanics, as verbal reception learning relies on this body of higher-order abstractions. Instead we propose to use a guided discovery approach at this stage. The question is how we can guide our students such that this body of higher-order abstractions is formed and what experiences might be used. The Van Hiele level scheme describes how concrete experiences can lead to a network of descriptions and subsequently to theory formation. However, this scheme is very general. It does not yet describe precisely what a teaching sequence might look like and what particular “experiences” are suitable. To organize the teaching-learning sequence, we use the problem posing approach. In short: teaching activities are chosen such that they elicit questions among students that lead them to the next teaching activity and ultimately to quantum theory.

The zeroth research round, described in Chapter 4, revealed several learning difficulties in the two observed courses. First of all, in both courses, students had difficulties with the interpretation of quantum mechanics. Most notably, the meaning of the wave function was unclear and various misconceptions were found, some also reported in the literature (Chapter 2). There were also difficulties due to a lack of understanding of required classical mechanics (for instance, the concept of an energy potential). Furthermore, especially in the QC course, students had difficulties with the mathematics involved. The lecturers also experienced the need to show students why quantum mechanics is needed and where its characteristics come from. In part they had chosen for a motivation based on the historical development of the old quantum mechanics to the formulation of quantum theory. However, this approach was not satisfying, as students were also unaccustomed to the classical physics that is involved in this historical overview.

Before addressing any difficulties related to learning quantum mechanics, it was considered wise to first address chemistry students’ difficulties with the mathematics involved. Chapter 5 describes this effort in the QC course. A remedial mathematics program was set up with which students could brush up on the mathematics needed during the course. Furthermore, students were supported to improve on their study strategies using a Just-in-Time Teaching approach, with which they could prepare for the lectures. For each lecture a diagnostic test was provided with which students could assess whether they
had understood the most important parts of the corresponding lecture. This effort was mostly considered successful.

Based on the design principles (motivated in Chapter 3) as well as on relevant literature (described in Chapter 2), four introductory sessions were designed for the QC course that aimed at guiding students in formulating core concepts of quantum theory. Chapter 6 describes the rationale of the designed teaching materials, thereby focusing on the physics content as viewed by the student. The designed teaching materials discuss several experiments that students analyze and which are used to guide them to introduce quantum mechanics concepts, most importantly the wave function. The sequence starts with a discussion of concrete experiments and ends with the Schrödinger equation along with the wave function as two possible postulates of quantum theory.

An important part of the introductory sessions guides students in hypothesizing the wave function based on a three phase analogical reasoning, described in Chapter 7. The analogical reasoning is set up by letting students study the double slit experiment in three domains: water, light, and electrons. First, students mathematically describe double slit interference of water waves (phase 0 of the analogical reasoning). Students next map their description to the domain of light (phase 1). The light pattern that is visible behind the double slit resembles that of interfering water waves. This motivates students to hypothesize that light is also a wave (phase 2). The mapping of terms and the hypothesis of a wave is repeated for the domain of electrons (again phases 1 and 2). Students are found to hypothesize the wave function to describe electrons. A possible interpretation, found amongst students, is that electrons are waves and that these waves, and thus these electrons interfere. This initial interpretation is fine tuned by considering how the interference pattern builds up due to single electrons that are fired at the double slit (phase 3). Although there is an interference pattern visible, the electrons are fired one at a time at the double slit. It is thus not possible that electrons interfere with each other. Fine tuning the interpretation of the wave function proves to be a difficult part of the sequence. Although students conclude that electrons do not interfere with each other, they cannot reconcile this conclusion with their earlier conclusion that something is interfering. As a result, students do not identify a superposition of two electron waves as describing a single electron. We conclude that the analogical reasoning is successful in letting students hypothesize the wave function, but that phase 3 of the analogical reasoning is not yet finished. Students’ conception of the hypothesized wave function still needs fine tuning.

After the introductory sessions, it remained a question how students’ understanding of the wave function would develop in the QC course. A distinction is made between students’ conceptual understanding of the wave function and students’ procedural fluency in working with the wave function. This is the topic of Chapter 8. After the introductory sessions, the course focuses mainly on procedural fluency. Quantum mechanics is applied in describing chemical
bonding, where the concept of a wave function plays a central role. However, not much conceptual understanding is needed in the problems students work on during the course. The students that were observed during the course were interviewed after the final exam to probe their conceptual understanding of the wave function. It was found that students had a hybrid conception of the wave function: on the one hand they saw it as a trajectory of an electron, on the other hand as a useful tool to do calculations with. Furthermore, students appeared to use self distilled rules in tasks in which the wave function had to be used in reasoning about chemical bonding. Except for one, all these students had passed the final exam. We conclude that a focus on procedural fluency does not lead to conceptual understanding.

For each of the two courses a retention test was designed to measure to what extent students learn important quantum mechanics concepts meaningfully (Chapter 9). Meaningfully learned content is known to be retained better than rotely learned content. Another reason to develop these retention tests is to have an instrument to compare different teaching approaches tried out in different study years. The retention test was conducted in 2006 and 2007 in the QP course and in 2007 and 2008 in the QC course. Unfortunately, in these years there was no significant difference in teaching approach. The cooperation with the QP course ended after 2007, before any large intervention had been carried out. In the QC course, 2007 was the year in which the introductory sessions were first tried out. A null measurement was thus lacking. The test results show no significant decline, nor improvement. This suggests that the test has indeed mainly measured meaningfully learned content. The absolute test results were, however, significantly lower than the exam results. Students’ (conceptual) understanding is thus weak.

In Chapter 10 we draw conclusions and give recommendations based on this research. The main conclusions are that the remedial mathematics activities were successful, but require a lecturer who integrates these activities in his teaching. The introductory sessions were successful to guide students to the wave function concept. However, their interpretation of this term is not yet consistent with the scientifically accepted term. We conclude that phase 3 of the analogical reasoning is not yet finished: there are enough opportunities for students to more critically review their conception of the wave function. Furthermore, we found that a focus on procedural fluency does not seem to be sufficient for the development of students’ conceptual understanding. These findings are a motivation to propose a design for the complete courses QC and QP, not only their introduction. The design we sketch for the two courses is based on our experiences as well as on relevant literature found on this subject. The sequence we describe begins with a top-down (i.e. empirical, inductive) approach and then, when a theory is available, proceeds in a more bottom-up (i.e. theoretical, deductive) fashion. Usually, one starts with the bottom-up approach, after having “motivated” that a new theory (i.e. quantum mechanics) is needed. As found in the zeroth round of this research (Chapter 4), this motivation is not at all convincing for students, and it is certainly not clear
why the theory presented is a solution for the problems that are usually given as an argument for quantum mechanics. The introductory sessions should result in a network of higher-order abstract relations, including a conception of the wave function, the Schrödinger equation as dynamical law, and the notion that operators are needed instead of classical dynamical variables to define observables. Although not in their final form, these notions will appear to be among the axioms of quantum theory. If this network is in place, we argue that the sequence can proceed with a teaching approach based on (verbal) reception learning, instead of guided discovery learning, using recent findings from physics education research.

Chapter 11 concludes this thesis by proposing three different areas in which higher education can be improved. First of all, the development of courses and curricula might be improved by adopting developmental research methods. Importantly, in such a developmental process a clear problem description should be formulated. Furthermore, suitable research instruments need to be chosen to steer the developmental process and assess the quality of the developed course or curriculum. We give examples of universities that use such an approach in developing their courses and curricula. Secondly, we propose ways to improve the quality of written examinations. Exams play an important role in education. Apart from their main function, determining who fails and passes for a course, exams are also used to assess the quality, as well as the efficiency of teaching. But they also influence what students learn and how they learn. Various research (including this research) has found the discrepancy between students’ performance on exams and their conceptual understanding. There are thus enough reasons to monitor and improve the quality of examinations. Currently it is not clear what the quality of our exams is, nor do we have a standard to measure the quality of exams. Finally, we propose to improve the education of existing lecturers and teachers. New lecturers and teachers at our university are obligated to follow an educational training. We propose to extend this program to existing lecturers and teachers such that they are supported in their development as a teacher. Such a training could also address the way in which education can be developed and improved, as well as the importance of the quality of examinations. Another advantage is that existing lecturers and teachers are supported in the time consuming, but important as well as challenging task of teaching our students.