universität wien

DISSERTATION / DOCTORAL THESIS

Titel der Dissertation / Title of the Doctoral Thesis

”Elementary particle physics in early physics education“

verfasst von / submitted by

Mag. rer. nat. Gerfried Wiener

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Doktor der Naturwissenschaften (Dr. rer. nat.)

Wien, 2017 / Vienna 2017

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	A 791 411
Dissertationsgebiet lt. Studienblatt / field of study as it appears on the student record sheet:	Physik / Physics
Betreut von / Supervisor:	Univ.-Prof. Dr. Martin Hopf

Table of contents

Abstract

Elementary particle physics is a fundamental topic in science, and in particular in science education. However, in most countries, the chapter of particle physics is not necessarily fully integrated in the physics curriculum. Indeed, current physics education research is faced with the important question of how best to introduce elementary particle physics in the classroom early on. To investigate the feasibility of such an approach, a doctoral research project was set up and its results are presented in this dissertation.

First, a learning unit on the subatomic structure of matter was developed, which aims to introduce 12-year-olds to elementary particles and fundamental interactions (Wiener et al., 2015). This unit was iteratively developed by means of a design-based research project and the technique of probing acceptance was used in one-on-one interview sessions to evaluate different adaptions of the unit. All interviews were filmed, transcribed in full, and a category-based content analysis was applied to the transcripts. After several iterations, which were tested with a total of 20 grade-6 students, the final version of the learning unit proved to be plausible for all students. Moreover, the promising results showed the unit's key ideas and main concepts to be appropriate for evaluation in the physics classroom. In addition, the development of the learning unit gave rise to a detailed description of CERN's Large Hadron Collider (LHC) as a prime example for the introduction of particle physics in the classroom (Wiener et al., 2016), and also led to the formulation of an alternative proposal for the graphical representation of anticolour charge (Wiener et al., accepted).

Next, the research focus was shifted towards the perspective of teachers to further explore the didactical feasibility of the learning unit. In doing so, a follow-up study was designed to again probe acceptance of the learning unit with a set of 17 grade-6 students (Wiener et al., submitted1). This time, however, the research was conducted by instructed physics teachers to also document their evaluation of the unit's key ideas. Here, the findings of the follow-up study validated the results from the initial study, as all students evaluated the learning unit to be plausible and meaningful, while demonstrating substantial understanding of the unit's key ideas. Furthermore, the teachers' feedback was very positive and showed the learning unit to be well well-

suited for use in the classroom. Thus, the development of the learning unit was concluded successfully and to support its dissemination among teachers, a detailed summary of the unit's key ideas and main concepts was created (Wiener et al., submitted2).

Last, the focus of the doctoral research project was shifted one more time to investigate the potential of the technique of probing acceptance as an effective tool for teachers' professional development. Indeed, during the follow-up study, the teachers' feedback hinted at influences of their pedagogical content knowledge (PCK) about elementary particle physics. Hence, an exploratory study was set up to examine the effect on teachers' PCK when preparing and executing interview sessions based on the technique of probing acceptance (Wiener et al., submitted3). Here, promising findings could be documented as well, hinting especially at influences of teachers' knowledge of learners and knowledge of instructional strategies. Thus, the results of the exploratory study strongly suggested that the transformation of the technique of probing acceptance into a tool for teacher training merits further research.

Overall, the doctoral research project led to successful results and showed the topic of elementary particle physics to be a viable candidate for introducing modern physics in the classroom. Furthermore, thanks to the design-based research methodology, the respective findings have implications for both physics education and physics education research, which are discussed in the final chapter of this dissertation.

Zusammenfassung

Das Kapitel der Elementarteilchenphysik gilt sowohl in der Forschung als auch in der Lehre als grundlegend, ist allerdings noch nicht vollständig in aktuellen Lehrplänen integriert. Tatsächlich stellt sich momentan die fachdidaktische Forschungsfrage, ob und wie man Elementarteilchen frühzeitig im Physikunterricht behandeln kann. Dieser Frage wurde im Rahmen des präsentierten Dissertationsprojekts nachgegangen, und die gesammelten Ergebnisse werden in der vorliegenden Dissertation zusammengefasst.

Zu Beginn des Dissertationsprojekts wurde eine Unterrichtseinheit zum subatomaren Aufbau der Materie entwickelt, welche darauf abzielt, 12-Jährige in die Welt von Elementarteilchen und fundamentalen Wechselwirkungen einzuführen (Wiener et al., 2015). Diese Unterrichtseinheit wurde zyklisch im Sinne fachdidaktischer Entwicklungsforschung erarbeitet und die jeweiligen Versionen wurden mit Hilfe von Akzeptanzbefragungen evaluiert. Nach insgesamt 20 Einzelinterviews mit Jugendlichen der 6. Schulstufe, welche gefilmt, vollständig transkribiert, und kategorienbasiert ausgewertet wurden, erwies sich die finale Version der Unterrichtseinheit für alle teilnehmenden SchülerInnen als adäquat und plausibel. Speziell die der Einheit zugrunde liegenden *key ideas* und Basiskonzepte führten zu vielversprechenden Ergebnissen, welche zukünftige Evaluationen im regulären Physikunterricht nahelegten. Im Rahmen der Entwicklungsphase der Unterrichtseinheit wurde zudem auch eine detaillierte Beschreibung des Large Hadron Collider (LHC) als Paradebeispiel der Grundlagenforschung erarbeitet (Wiener et al., 2016), sowie ein Alternativvorschlag zur graphischen Darstellung von Antifarbladung formuliert (Wiener et al, accepted).

In weiterer Folge wurde der Forschungsfokus des Dissertationsprojekts auf die Sicht der Lehrpersonen gelegt, um so die didaktische Umsetzbarkeit der Unterrichtseinheit zu evaluieren. Dazu wurde eine Folgestudie konzipiert, in der erneut Akzeptanzbefragungen zum subatomaren Aufbau der Materie mit 17 Jugendlichen der 6. Schulstufe durchgeführt wurden (Wiener et al., submitted1). Allerdings wurden diese 17 Akzeptanzbefragungen von instruierten PhysiklehrerInnen geleitet, um so auch deren Einschätzung der Unterrichtseinheit erheben zu können. Vergleichbar mit den Ergebnissen der Originalstudie zeigte sich, dass die teilnehmenden Jugendlichen die

zentralen Konzepte der Einheit erneut als plausibel und sinnvoll beurteilten und deren Bewertung zudem auf ein tiefgreifendes Verständnis der *key ideas* schließen ließ. Darüber hinaus fiel das Feedback der Lehrpersonen ebenfalls sehr positiv aus, wodurch die Entwicklung der Unterrichtseinheit erfolgreich abgeschlossen werden konnte. Zudem wurde, um den Transfer in den Physikunterricht zu unterstützen, eine detaillierte Zusammenfassung der *key ideas* und Basiskonzepte erstellt (Wiener et al., submitted2).

Danach wurde der Fokus des Dissertationsprojekts ein weiteres und letztes Mal adaptiert und basierend auf den Ergebnissen der Folgestudie wurde untersucht, inwiefern sich die Methode der Akzeptanzbefragung als effektive Fortbildungsmethode für Lehrpersonen eignet. Speziell wurde im Rahmen einer explorativen Studie der Frage nachgegangen, ob das Vorbereiten und Durchführen von Akzeptanzbefragungen einen Einfluss auf das fachdidaktische Wissen (*pedagogical content knowledge - PCK*) von PhysiklehrerInnen hat (Wiener et al., submitted3). Hier wiesen die ersten Ergebnisse tatsächlich darauf hin, dass sich einzelne Komponenten des fachdidaktischen Wissens – im Speziellen das Wissen über Lernende und das Wissen über den Lehrplan – beeinflussen lassen, und daher eine weitere Erforschung dieser Methodentransformation vielversprechend ist.

Zusammenfassend führte das Dissertationsprojekt zu erfolgreichen Ergebnissen und unterstrich die Machbarkeit, das Kapitel der Elementarteilchenphysik in adäquater Weise im Physikunterricht einzuführen. Aufgrund der Verortung im Feld der fachdidaktischen Entwicklungsforschung führten die verschiedenen Ergebnisse des Dissertationsprojekts zudem zur Formulierung weiterer Forschungsfragen, die sowohl fachdidaktischer als auch methodischer Natur sind, welche am Ende der Dissertation ausführlich diskutiert werden.

1. Introduction

This cumulative doctoral thesis presents the findings from my research into how best to introduce elementary particle physics in the classroom. I originally grew interested in this question during my undergraduate studies at the University of Vienna. Indeed, as coursework for a didactics seminar, my fellow students and I were prompted to think about which topic from the physics curriculum should be introduced first in the classroom. Our ideas were then discussed among the group. To begin with, most of us favoured one of the two main textbook approaches – introducing physics either via the concept of forces, or from an energy point of view. By the end of the seminar, however, a more radical idea had been born: starting physics education at the very basics, by introducing the fundamental interactions between elementary particles.

Subsequently, this idea stuck with me, and I was lucky enough to give it a try at the end of my studies, when I did my teaching apprenticeship together with a colleague at a high school in Vienna. Here, one of our tasks was to prepare and conduct two consecutive physics lessons covering a topic of our choice at grade-7 level. Obviously, we set out to introduce the core ideas of the Standard Model of particle physics to a class of 13-year-olds and I think it is fair to admit: we failed miserably! Nonetheless, we evaluated and discussed the strengths and weaknesses of our learning unit with the teaching instructor and came to the conclusion that, while our initial approach was too ambitious, introducing elementary particles and fundamental interactions at the beginning of physics education could have merit. Hence, I continued to pursue the idea, both from a theoretical point of view for my masters thesis and in practice, as I had already started teaching physics full-time at a high school in Vienna. Indeed, over the following three years, I frequently used and adapted contents from the original learning unit and introduced them to high school students at various grade levels. However, none of my efforts were in any way research-driven, and at some point the teaching of elementary particle physics simply became part of my standard teaching repertoire.

It was only once I moved to Geneva and started working at CERN, the European Organization for Nuclear Research, that I picked up my idea again. Having briefly discussed it with my supervisor, he invited me for a coffee two weeks later to talk about my approach in detail. This meeting resulted in his proposal for me to properly evaluate and develop the learning unit as my doctoral research project. I happily agreed and, together with my university advisor, I mapped out the rationale of my research to first redesign the learning unit on the subatomic structure of matter based on documented students' conceptions, and then to iteratively develop it with high school students and teachers. The overarching goal of the doctoral research project was to investigate whether elementary particle physics can be introduced in an adequate and meaningful way to high school students at the beginning of their physics education.

Hence, the aim of this dissertation is to provide an overview of the articles written within the scope of the doctoral research project and to put them in a broader context. First, a discussion of the theoretical framework is given in **Chapter 2**. Next, **Chapter 3** presents the research questions that guided the doctoral research project, linking them to the respective articles. The core of this dissertation is then provided by the articles A to F, which are printed in **Chapter 4**. To finish, **Chapter 5** discusses all the articles, focusing on their main outcomes, addressing their limitations, and highlighting potential implications of my doctoral research project for both future research and classroom applications.

2. Theoretical framework

Using the framework of constructivism, the design process of the learning unit started by investigating documented students' conceptions about particles and atoms. Indeed, when considering learning as a constructive process, it is crucial to take learners' pre-existing ideas and conceptions into account to develop adequate and meaningful learning material (Duit, 1996; Duit & Treagust, 2003; Duit et al., 2006). Hence, a detailed literature review was performed to determine the state of research, on which the redesign process was based. This review showed that initial studies about students' conceptions of particles and atoms originate already in the 1980s in the field of chemistry education research (Pfundt, 1981; Novick & Nussbaum, 1981, Stavy, 1991). While these studies were mainly directed at investigating middle and high school students' understanding of particle models when describing the nature of gases, they also indicated that students do not spontaneously tend to use particle models to explain everyday physics phenomena. Later, however, it was shown that students can accept and use particle models for their explanations, if they represent a more meaningful alternative for problem-solving (Harrison & Treagust, 2000; Snir et al., 2003). Furthermore, while high school students seem to accept particle models more easily compared to middle school students (Harrison & Treagust, 1996), students of both age groups show similar misconceptions when it comes to atomic models (Boz, 2006). In addition, more topic-specific students' conceptions and misconceptions about the nature and "appearance" of particles have been documented, which are summarised in the first article of chapter 4 (Wiener et al., 2015).

Taking all documented students' conceptions about the particulate nature of matter into account, the learning unit was redesigned to act as a meaningful learning offer for 12-year-olds. In addition, care was taken to avoid the use of phrasings or illustrations that might trigger potential misconceptions about the nature of particles and atoms. Indeed, the goal of the redesigned learning unit was to adequately introduce the subatomic structure of matter at the beginning of physics education. This approach was motivated by three factors.

First, the particulate nature of matter is considered to be a fundamental topic in science, and in particular in science education (Treagust et al., 2010; Vikström, 2014).

Hence, an early introduction of key terms and main concepts of particle physics could facilitate conceptual change (Duit & Treagust, 2003) and support learners to construct meaningful knowledge about the particulate nature of matter early on. Specifically, the transformation of inadequate conceptions about particles and atoms into scientifically acceptable knowledge might even be supported by the young age of the students. Indeed, one can assume that grade-6 students, having had no or only little physics education, do not possess vast experience-based knowledge in the field of elementary particle physics. Thus, new, to-be-acquired information is less likely to conflict with their existing knowledge structures (Vosniadou et al., 2008).

Second, the recent “Trends in International Mathematics and Science Study” has shown that, in most countries, the chapter of particle physics is only placed at the end of curricula, if at all (TIMSS, Mullis et al., 2012). This indicates that the time devoted to discuss this topic in the classroom is limited and thus one cannot expect physics teachers to possess a rich and diverse pedagogical content knowledge concerning particle physics. For example, it was only in 2014 that the German federal state North Rhine-Westphalia included elementary particle physics, namely the Standard Model of particle physics, in the official curriculum (Ministry of Education, NRW, 2014). This also indicates that educational resources and adequately reconstructed teaching and learning materials are scarce, which in turn highlights the need for empirical studies to investigate the adequacy and feasibility of elementary particle physics to support teachers in the classroom. Therefore, reconstructing the subject matter of elementary particles by means of the “Model of Educational Reconstruction” (Kattmann et al. 1995, 1997) to be used at the beginning of physics education has merit from both a research and a teaching perspective. Furthermore, demonstrating which key ideas can be understood by students with no prior physics education should ideally motivate teachers to also introduce them in their classrooms on a general level.

Third, since, to some extent at least, every physics process can be traced back to fundamental interactions between elementary particles, an early introduction of elementary particle physics in the classroom could also be beneficial for learners’ development of coherent knowledge structures. Indeed, by interlinking the various topics of the physics curriculum through the concept of fundamental interactions, a high degree of coherence and connectedness of learners’ conceptual structures could be achieved. This would be especially promising for physics education, since coherent knowledge structures are considered to be a prominent feature of scientific knowledge. In particular, an expert's knowledge is often described as well-organised, coherent, and consisting of a rich body of knowledge about the subject matter (Bransford et al., 2000; Snyder, 2000; Mestre, 2001; van Zele et al., 2004). Furthermore, this knowledge goes hand-in-hand with a deep understanding of the nature of science and the structure of the scientific method – how hypotheses, theories, predictions, and evidence fit together (McComas et al., 1998; Aydm et al., 2013). Thus, a demand often made of science education is to facilitate the development of coherent knowledge structures in the classroom (Mestre & Cocking, 2002; Koponen & Pehkonen, 2010; Nousiainen & Koponen, 2010). However, it is argued that science education as commonly practiced, focuses too strongly on clarifying facts, while not demonstrating how these facts are related, especially in textbooks (Kosso, 2009; Fortus & Krajcik, 2012). Here, the basics of elementary particle physics can be considered to be a prime candidate to facilitate the connection of different curriculum topics in the physics classroom.

3. Research questions

The evaluation and development of the redesigned learning unit on the subatomic structure of matter was implemented as a design-based research project. This methodology combines the theory-driven design of learning units with educational research and aims at investigating how, when, and why a certain instructional strategy works in practice (Design-Based Research Collective, 2003). Hence, a design-based approach is well-suited and favourable for the development of a new learning environment. Specifically, through a scheme of iterative retesting and redesign phases, successful elements of the instruction in question can be identified, which ultimately leads to the development of a meaningful learning offer. Therefore, the initial phase of the design-based research project was guided by the following research question:

RQ1 | To what extent can grade-6 students understand the learning unit on the subatomic structure of matter and to what extent can they use its key ideas and main concepts for problem-solving?

In order to investigate this research question, the technique of probing acceptance was used. This research method was originally introduced to explore learning processes and consists of the presentation and discussion of information during one-on-one interviews with defined interview phases (Jung, 1992). Indeed, this particular research setting is similar to a quasi-experimental one-on-one tutoring session and has the advantage of giving insight into learning progression, which can thus be documented in detail. For the initial study, the one-on-one interviews were designed to last 40 minutes and followed a precise timeframe. First, the learning unit was presented to the student, whose task it was then to evaluate, paraphrase, and adapt the new information as the interview progressed. Given the ambiguous definition of “acceptance”, however, the name of the research method can be misleading and therefore requires clarification. Indeed, for the purpose of evaluating and developing the learning unit, the aim of “probing acceptance” was redefined to “probing plausibility”. This meant identifying elements of the information input, which the students “accept” as useful and plausible information, and which they can also successfully adapt during the various interview phases. Hence, each one-on-one interview can be seen as a feasibility study of the learning unit on the subatomic structure of matter.

In total, 20 one-on-one interviews were conducted with grade-6 students. All interviews were videotaped, transcribed in full, and analysed by applying the method of qualitative content analysis (Mayring, 2010). Based on a coding manual, the findings were peer-validated with other researchers in science education and the results provided the basis for the iterative redesign of elements of the information input. Indeed, based on the analysis of the first four interviews, the learning unit's key ideas and main concepts were slightly modified and redesigned to be re-evaluated through another set of eight one-on-one interviews with eight different grade-6 students. Again, all transcripts were analysed accordingly and the results indicated that an extensive redesign process of several key ideas was required, which led to major revisions of the learning unit's design. This revised version was then evaluated again through the last series of one-on-one interviews with another eight grade-6 students, with the analysis showing this final version to be plausible for all the students. A detailed description of the final version of the learning unit, a specification of the research setting, and a discussion of the findings from this initial study are given in article A, which was published in the *European Journal of Science and Mathematics Education* (Wiener et al., 2015).

In addition, while working on the development of the revised learning unit, an extensive review of international physics curricula was performed to document potential connections between physics topics and the content of the learning unit. This review was mainly motivated by the unit's overarching rationale of presenting facts by showing their theoretical coherence, to stimulate students' development of coherent knowledge structures. Indeed, the curricula review led to promising results and thus a specific example was elaborated, which shows how high school teachers can promote aspects of the nature of science by linking main topics of physics curricula to fundamental research. Specifically, it was chosen to focus on CERN's Large Hadron Collider (LHC), as its components and the physics behind its operation can be considered to be prototypical for such an approach. Hence, the LHC and its operation were explained in detail, while showcasing the tangled web of science knowledge that undermines such a prime example of fundamental research. In addition, educational resources were referenced to facilitate the transfer into the physics classroom. The complete overview is given in article B, which was published in *Physics Education* (Wiener et al., 2016).

Furthermore, the iterative development of the learning unit also led to the formulation of an alternative proposal for the graphical representation of anticolour charge. Indeed, since the unit introduces antiparticles and systems of particles, a visualisation of anticolour charge was required. Initially, the commonly used complementary-colour method was implemented, whereby anticolour charge is illustrated through the use of the colours complementary to red, green, and blue. However, the students' feedback indicated that this approach can lead to misunderstandings, since it relies on previously-established optics knowledge, namely, additive colour mixing. Therefore, a novel graphical representation was developed, which represents anticolour charge using a stripe pattern instead of a change in colour. Both graphical representations were tested on high school students (ages 16-17, n=78) and physics teachers (n=45) through a questionnaire. The new, alternative proposal gave very successful and promising results, with the clear majority of both students and teachers judging it to be easier to understand, more informative, and simpler. A detailed presentation of the alternative proposal and a discussion of its evaluation are printed in article C, which was accepted for publication in *The Physics Teacher* (Wiener et al., accepted).

Consequently, after the successful investigation of the first research question, which documented the students' evaluation of the learning unit's final version, the research focus was shifted towards the perspective of teachers. Indeed, having developed an appropriate learning unit to introduce the subatomic structure of matter, which proved itself to be promising for use in the classroom, it was the next step to include high school teachers in the development process. Hence, a follow-up study was designed, which was guided by the following research questions:

RQ2 I How do grade-6 students evaluate and make use of the learning unit on the subatomic structure of matter when it is introduced by experienced teachers as opposed to education researchers?

RQ3 I How do teachers evaluate the adequacy and feasibility of the learning unit on the subatomic structure of matter and how do they evaluate its applicability for use in the physics classroom?

Here, the design of the follow-up study mirrored the initial study design (Wiener et al., 2015), but this time the one-on-one interviews were led by experienced teachers, instead of by education researchers. Hence, to facilitate the follow-up study, a new short-term professional development programme for teachers was set up, consisting of a briefing session and an intervention. During the briefing session, the teachers were instructed about the development of the learning unit by showcasing its key ideas and main concepts. Next, based on examples from the initial study, the technique of probing acceptance was presented to and discussed with the group. In addition, all the teachers received their own research manuals, which were developed to guide them through their one-on-one interviews. For the final hour of the briefing, the teachers were enabled to individually and collectively prepare themselves for their intervention by preparing their information inputs and by trying out the use of the research manual.

The intervention took place on the following day and every teacher conducted at least one one-on-one interview with a grade-6 student. Immediately after their final one-on-one interview, semi-structured interviews were conducted individually with the teachers, to document their evaluation of the learning unit. In parallel, the other teachers were invited to share their experiences with their colleagues during a feedback and discussion session, which concluded the professional development programme.

Nine teachers participated in the follow-up study, and in total 17 one-on-one interviews were carried out. Both the one-on-one interviews and the post-intervention interviews were videotaped and transcribed word-for-word, and a qualitative content analysis (Mayring, 2010) was applied to the resulting transcripts. While for the analysis of the one-on-one interviews the same coding manual was used as in the initial study, the analysis of the post-intervention interviews was entirely focused on the teachers' evaluation of the learning unit. Overall, the findings from the follow-up study validated the initial results and showed the learning unit to be adequate and well-suited for a broad evaluation in the classroom. Furthermore, the teachers' feedback was very promising as well, with all teachers evaluating the unit's key ideas and main concepts to be intriguing for use in the classroom. A full description of the professional development programme, the research setting, and an extensive discussion of the findings are given in article D, which was submitted for publication in the *European Journal of Science and Mathematics Education* (Wiener et al., submitted1).

Thus, based on the successful and promising results from the follow-up study, the development of the learning unit on the subatomic structure of matter was concluded. Hence, to facilitate its dissemination among teachers, a detailed summary of the unit's final version was created. This summary includes a discussion of the development of the unit's key ideas, explains the reasoning behind its main concepts, and provides an overview of outcomes of the development process, which are highly promising for classroom application. This summarised version of the learning unit is given in article E, which was submitted for publication in *Physics Education* (Wiener et al., submitted2).

The next and final part of the doctoral research project was an investigation of the professional development programme itself, which was implemented to conduct the follow-up study. Indeed, aside from giving insight into the teachers' evaluation of the learning unit, the analysis of the post-intervention interviews also hinted at potential influences of their pedagogical content knowledge (PCK). Here, PCK is defined as the distinctive component of teachers' knowledge, which was introduced by Shulman (1986, 1987) to distinguish pedagogues from content specialists. Over the past years, the model of PCK has received great attention and its conceptualisation has been elaborated, revised, and extended multiple times (Tamir, 1988; Grossman, 1990; Cochran et al., 1993; Magnusson et al., 1999; Loughran et al., 2006). An extensive overview of the most prominent conceptualisations was given by Park and Oliver (2008), who identified five distinctive dimensions – orientation towards teaching science, knowledge of curriculum, knowledge of learners, knowledge of instructional strategies, and knowledge of assessment – as a working definition of PCK. Therefore, founded on this theoretical framework, a PCK study was designed, to examine the professional development programme by means of the following research question:

RQ4 I To what extent are the dimensions of teachers' PCK influenced by the preparation and execution of one-on-one interviews based on the technique of probing acceptance?

This exploratory study was implemented by replicating the design of the previous study (Wiener et al., submitted1). Again, a professional development programme was set up to further investigate and develop the learning unit on the subatomic structure of matter. This time, however, the research focus was mainly directed at the four teachers who took part in the programme. Specifically, the semi-structured interview guide, which was used to conduct the post-intervention interviews, was revised to incorporate the five dimensions of PCK, and based on this conceptualisation, a qualitative content analysis (Mayring, 2010) was carried out on all transcripts. Following the full cycle of phases for analysing qualitative data (Yin, 2011), the analytic procedure included frequent disassembly and reassembly of the findings, to ensure a transparent and traceable analysis process.

By and large, the findings indicated that all teachers revisited their existing knowledge about the subatomic structure of matter during the professional development programme. Furthermore, various statements were documented, which hinted at influences on the teachers' pedagogical content knowledge, especially with regard to their knowledge of learners and knowledge of instructional strategies. In addition, all teachers evaluated the professional development programme as being very informative and useful for their everyday work in the classroom. Moreover, the programme's short-term character and its design-based research approach, namely, being able to observe learning processes first-hand, appealed greatly to the teachers. A detailed description of the research setting, a discussion of its rationale and limitations, a presentation of the results from the qualitative content analysis, and a summary of the main outcomes and implications of the study are given in article F, which was submitted for publication in the *Journal of Research in Science Teaching* (Wiener et al., submitted3).

4. Articles written within the scope of the dissertation

A

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**2015**). Can Grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education*, 3(4), 313–322.

B

Wiener, G. J., Woithe, J., Brown, A. & Jende, K. (**2016**). Introducing the LHC in the classroom: an overview of education resources available. *Physics Education*, 51(3), 1–7.

C

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**accepted**). An alternative proposal for the graphical representation of anticolor charge. *The Physics Teacher* (accepted: 27 January 2017).

D

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted1**). Why not start with quarks? Teachers investigate a learning unit on the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education* (submitted: 30 January 2017).

E

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted2**). Introducing 12-year-olds to elementary particles. *Physics Education* (submitted: 21 January 2017).

F

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted3**). The technique of probing acceptance as a tool for teachers' professional development: a PCK study. *Journal of Research in Science Teaching* (submitted: 5 March 2017).

A

Can Grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds

Gerfried J. Wiener[1,2], Sascha M. Schmeling[1] and Martin Hopf[2]
[1]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[2]University of Vienna, Austrian Educational Competence Centre Physics

Abstract:

This study introduces a teaching concept based on the Standard Model of particle physics. It comprises two consecutive chapters – elementary particles and fundamental interactions. The rationale of this concept is that the fundamental principles of particle physics can run as the golden thread through the whole physics curriculum. The design process was conducted from a constructivist perspective based on students' documented conceptions. Three pillars underpin the whole teaching concept: a permanent model character, linguistic accuracy, and innovative typographic illustrations. Using the framework of design-based research, microteaching sessions with 20 Grade-6 students were conducted to probe its acceptance. The study focusses on learning processes of 12-year-olds with respect to elementary particles. Our findings indicate broad acceptance of most key ideas, but also avoidance when considering the permanent model character of physics. The most promising outcomes of the study are pure typographic illustrations. Not only were these thoroughly accepted by all students, but they also seem to reduce known misconceptions. Overall, students' understanding of elementary particles improved fundamentally.

Keywords: particle physics, elementary particles, fundamental interactions, acceptance, teaching concept

Introduction

According to the “Trends in International Mathematics and Science Study” (TIMSS, Mullis et al., 2012), in most countries the chapter of modern physics is placed at the end of curricula, if at all. Since these chapters – particularly the Standard Model, the “first full deck of cards to play with” (Griffiths, 2004: 3) – describe processes fundamental to physics, this situation might not support high school students’ development of a coherent knowledge structure. We therefore propose a new teaching concept that reflects particle physics’ position as the basis of all other physics. The proposed concept comprises two short chapters as a starting point for physics teaching. The first chapter tackles the particulate nature of matter by focusing on a state-of-the-art atomic model. This leads to a brief outline from electrons down to quarks. The second chapter introduces the fundamental interactions and their associated bosons. Since it is argued that thinking in and with models is an essential component of an appropriate science knowledge (Mikelskis-Seifert & Fischler, 2003a; Gilbert, 2004), the aim of the proposed concept is to focus on the permanent model character of physics. We consider both chapters to be prototypical for such a model-based approach to physics teaching.

Key to the concept’s design is its independence from today’s curricula. Given that every physics phenomenon can be traced back to fundamental interactions between elementary particles, the integration of the proposed concept could be adequate for any age group. Ideally, one could use this concept from the very beginning of physics teaching by introducing particle physics to 12-year-olds. This allows the fundamental principles of particle physics to run as the golden thread through the whole physics curriculum.

The design process of the teaching concept was approached from a constructivist viewpoint: students are enabled to construct knowledge on their own on the basis of the material provided. This process is based on students’ pre-existing cognitive structures. The exploration and consideration of students’ conceptions is essential to avoid triggering misconceptions. At the same time, this knowledge provides a base for the development of adequate learning opportunities. Thus, an understandable and appropriate offer can be made to the students, enabling them to construct consistent knowledge (Duit, 1996; Duit & Treagust, 2003).

State of research

Studies of students' conceptions about the particulate nature of matter originated in the 1980s, mainly in chemistry research regarding molecules and atoms (Pfundt, 1981; Novick & Nussbaum, 1981; Renstroem, 1987; Andersson, 1990; Stavy, 1991; de Vos & Verdonk, 1996; Harrison & Treagust, 1996; Harrison & Treagust, 2000; Nakhleh & Samarapungavan, 1999). These first studies showed that only few students use a particle model to explain physics phenomena. Especially when dealing with everyday phenomena, a particle model is neglected (Pfundt, 1981; Novick & Nussbaum, 1981; Stavy, 1991). However, when offered as a possible explanation, students broadly accept a particle model (Harrison & Treagust, 2000; Snir et al., 2003). Equally striking is a significant age dependence when it comes to the acceptance of a particle model (Dow et al., 1978; Pfundt, 1981; Harrison & Treagust, 1996). In contrast, a variety of age-independent misconceptions of the atomic structure of matter have been documented (Novick & Nussbaum, 1981; Boz, 2006).

Everyday experience favours a continuous perception of the world. Therefore, most students' conceptions are dominated by a continuum perspective. When introduced to a particle model, most students try to combine both models. This leads to a frequent mixing and overlapping of continuum and discontinuum conceptions, whereby students try to integrate the novel particle model into the framework of the existing continuum model (Pfundt, 1981; Renstroem, 1987; Andersson, 1990; Boz, 2006). These misconceptions can be supported by erroneous illustrations in textbooks. For example, Andersson (1990) describes their impact by discussing an illustration of a glass of water filled with H_2O molecules floating around in the water.

Further studies also show that despite students' acceptance of a particle model, two misconceptions prevail: no reproduction of the permanent motion of particles, and the negation of the existence of empty space (Novick & Nussbaum, 1981; Renstroem, 1987; Andersson, 1990; Harrison & Treagust, 1996). Furthermore, numerous studies have shown that teaching a particle model leads to an automatic transfer of macroscopic aspects and daily life experiences into the world of particles. Students think of particles with faces, while water molecules are thought of as wet and blue (Renstroem, 1987; Andersson, 1990; Boz, 2006; Ozmen, 2011).

Concept design

The concept's design is based on the above documented studies on students' conceptions. Griffith & Preston (1992) gave an overview of 52 different misconceptions related to the properties of atoms and molecules, most of which are supported by erroneous figures and illustrations. To avoid triggering any of these misconceptions and to ensure comprehensiveness and coherence, the teaching concept is based on three pillars:

Permanent model character

A big challenge of teaching particle physics is its abstractness. Therefore, demonstration experiments are limited, the precision of explanations hard to balance with their adequateness, and, due to the inconceivable size ratio, realistic illustrations are doomed to fail. But this abstractness enables one feature to stand out, namely, the permanent model character of science originally defined by Hertz (1899): "When from our accumulated previous experience we have once succeeded in deducing images of the desired nature, we can then in a short time develop by means of them, as by means of models, the consequences which in the external world only arise in a comparatively long time, or as the result of our own interposition." Ever since, modelling has been considered to be a key process in the development of scientific knowledge (Ornek, 2008; Chittleborough & Treagust, 2009; Justi, 2009). That is why we have chosen to focus on the permanent model character of particle physics. Constantly pointing out that everything just said describes a model can enable a proper comprehension of physics.

Consequently, this should lead to setting a tone for the fundamental nature of science and laying foundations for all topics to follow. The phrase "With this model, we describe…" plays a big role in the teaching concept and is frequently repeated and emphasised.

Linguistic accuracy

Another difficulty in the field of modern physics arises when speaking about it. First of all, one has to jump back and forth between a language of science and our everyday language (Rincke, 2010). This requires careful definitions of certain wordings to maintain their original meaning, a process often neglected in classrooms. Secondly, particle physics is still quite a young field of physics. Many of today's wordings and phrasings originate from the early days of particle physics about 100 years ago. For example, any description of “circular orbits” within the Bohr model can be considered to be anachronistic and therefore act as a possible source of misconceptions (Karsten et al., 2011). The same problem applies to the historical accumulation of hundreds of “elementary particles” in the so-called particle zoo. Therefore, clear-cut language is needed to offer valuable teaching material.

Accordingly, linguistic accuracy is a prominent aspect of our concept. This was largely addressed by minor changes to specific phrasings. For instance, when introducing the atomic model, instead of “the nucleus” we refer to “the nucleus-space”. Doing so supports the location aspect of the nucleus-space, while neglecting its manifested aspects. The same idea is applied when the orbital-space is introduced. These areas are then characterised by the phrase “In this space it is possible to locate certain particles”. Thus, these changes aim to increase the probability aspect of particles.

When talking about particles, the proposed concept distinguishes between particles and particle systems. This means that only elementary particles, such as leptons and quarks, are denoted as particles. In contrast, hadrons count as particle systems which are made of particles. However, particle systems can still be described as particle-like objects with particle-like properties.

Pure typographic illustrations

In addition to linguistic accuracy, the concept relies on carefully constructed illustrations. Educational research shows that visual representations are essential for communicating ideas in the science classroom (Carney & Levin, 2002; Cook, 2006). However, as mentioned above, realistic illustrations in the field of particle physics are, by definition, doomed to fail. Two major difficulties prevail: the sheer scale of atoms, and any graphic illustrations of particles and atoms. Using interactive animations (Huang & Huang, 2012) and animated movies (Eames & Eames, 1977) can help to overcome the problem of demonstrating the inconceivable scale of atoms. As for static illustrations, there is no helpful solution in sight.

For the general illustrations of particles and particle systems we propose a typographic approach. Having the permanent model character in mind all particles and particle systems are thus represented by their respective symbol (figure 1). The goal of this approach is to avoid misconceptions of three-dimensional particles, while referring to symbols as defined objects. Furthermore, the underlying colour scheme of the proposed concept is intended to distinguish particles from particle systems. Quarks are blue, green, and red. In the first chapter, this serves the sole purpose to identify quarks as elementary particles. This sets up the notion of colour charge to be introduced in the second chapter. Since antiparticles are also part of the concept, the need for a visualisation of anticolour charge arises. The proposed implementation avoids the commonly-used complementary colours. Instead, antiparticles and antiparticle systems are identified through stripes. This strategy provides a simple distinction while bypassing the use of misleading complementary colours. For instance, white-striped green is used instead of magenta as a more adequate depiction of anti-green.

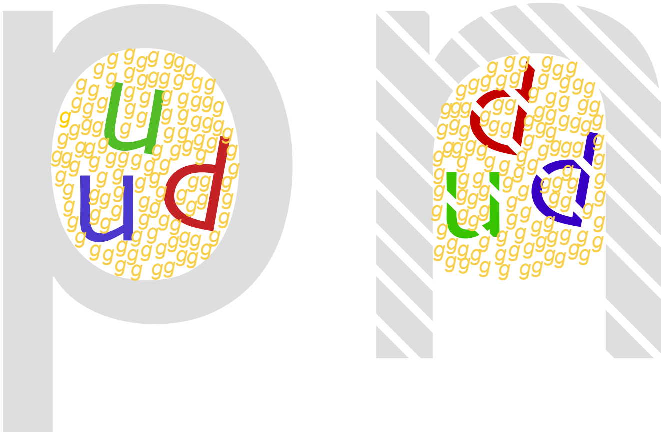


Figure 1. Typographic illustrations of a proton and an antineutron.

A typographic approach is also used to illustrate the atomic model. Both the nucleus-space and the orbital-space are displayed using their names, the latter being made to look spherical. A shift of focus is created by using the two descriptive words themselves to illustrate the different spaces. This gives the impression of a three-dimensional atomic model while reducing the possible misimpression of orbits or shells (figure 2).

Admittedly, this illustration has its limitations. First, the visualisation focuses solely on the quantitative aspects of the atomic model, its aim being to illustrate the distinction between the nucleus-space and the orbital-space. Second, it does not overcome the problem of a realistic size ratio, and it requires a careful introduction by the teacher to explain the underlying model character. Also, it does not convey the notion of different orbital shapes within the specific orbital-space, which must be introduced at a later stage in the physics curriculum.

Figure 2. Typographic illustration of an atomic model.

Methods

A study was performed to evaluate the effects of the teaching concept by probing its acceptance with 12-year-olds. Having only had very little physics education, such students can be considered as novices, especially with respect to particle physics. The main purpose of these teaching experiments was to evaluate students' general understanding of the concept, and to find out whether students use it for problem-solving.

Probing acceptance

The technique of probing acceptance (Jung, 1992) was developed to investigate learning processes. It comprises a set of microteaching sessions, including planned interview phases. Explanations are offered, then observations made regarding students' understanding, valuation, and use of this information in solving problems. The aim is to identify resistances to elements of the instruction. An advantage of this setting compared to conventional problem-centered interviews is the reduction of short-term, ad-hoc constructs (Wiesner & Wodzinski, 1996).

Each microteaching session consists of four steps. First, specific information about the concept being addressed is offered to the student in the form of, for example, an experiment, presentation or short lecture. The student then evaluates the plausibility and comprehensibility of the information offer. This is followed by the task of paraphrasing the presented information "in own words". The student's final task is to apply the new knowledge to concrete examples. Based on the student's reactions, one can then identify obstructive aspects of the original explanations given. Using the framework of design-based research, perpetual redesigning and retesting eventually leads to understandable and valuable teaching material (Design-Based Research Collective, 2003).

Study design, setting and analysis

The method of this study relies on the technique of probing acceptance. We focused on the first chapter of the teaching concept, which introduces the subatomic structure of matter. Based on the atomic model's introduction, several key ideas were formulated. A first test survey was then conducted with four Austrian Grade-6 students to gain insight into the feasibility of the study. As a result, the information offer was slightly revised and modified. This was followed by another set of microteaching sessions with eight Grade-6 students. After evaluation of the transcripts, an extensive redesign process was required. The frequency of references to the permanent model character in the information offer was increased, the typographic illustrations were redesigned more precisely, and the total number of key ideas was reduced to a more feasible amount. The final information input covers these eleven key ideas:

I. Matter is everything that can be touched, practically or theoretically.
II. Reality is described through models.
III. There are atoms (Democritus - *átomos*).
IV. Atoms are divided into two areas: the nucleus-space and the orbital-space.
V. In the nucleus-space there are protons and neutrons.
VI. Protons and neutrons are particle systems made of quarks.
VII. Quarks are indivisible. In this model, these are called elementary particles.
VIII. In the orbital-space electrons can be found.
IX. Electrons are indivisible. In this model, these are called elementary particles.
X. Apart from particles, there is only empty space.
XI. There are (different) atoms, which may combine to form compounds.

The main study took place in spring 2014 at an Austrian high school with another eight Grade-6 students. Each microteaching session lasted about 40 minutes (table 1) and was videotaped using a GoPro® camera. At the beginning, the information was offered through a ten-minute talk. Key descriptive ideas, such as the distinction between nucleus-space and orbital-space, were supported by accompanying typographic illustrations. This presentation was followed by the student's task of evaluating and paraphrasing the information offer, which usually took about five minutes. Of main interest were the intelligibility of the key ideas, and the feasibility of the teaching concept.

Table 1. Timeframe for the microteaching sessions.

#	Phase	Duration
1	Information input	10′
2	Evaluation & Paraphrasing	5′
3	Transfer example 1 & Evaluation	12′
4	Transfer example 2 & Evaluation	12′

Next, two concrete examples were given. At first, some grains of salt were sprinkled across the table. The task was to explain whether salt can be identified as matter, and what it is made of. The second example asked the same question but used droplets of water instead of salt grains. Thus, the student's insight into two different states of matter could be evaluated.

The method of qualitative content analysis (Mayring, 2010) was applied to evaluate the findings. Category-based analysis was carried out on all interviews. Three categories (fully [✓]; partially [~]; not adequate [✗]) were used, with the addition of a fourth non-mention ([ ]) category due to a few omissions. The intercoder-reliability resulted in K=0.725, meeting the required standard.

Results

The final version of the information offer led to quite successful results. The concept's chapter on the atomic model was broadly accepted by all students. Most key ideas were used for problem-solving and most of them were rated to be plausible. We present here the most important and, from a teaching perspective, the most interesting findings.

Key idea I, the crucial introduction of matter as the main subject of the concept was very successful and showed broad acceptance from the beginning (table 2). By linking it to the haptic action of touching, a general understanding of matter was enabled. Doing so allowed for even more difficult questions concerning different materials to be answered correctly. For example, in response to the question whether air qualifies as matter, many students agreed by referring to wind as moving air touching their face. When asked to name the counterpart of matter most students concluded that everything is matter. Additionally, some students even mentioned the absence of matter in outer space, for example as follows: *"If one flies with a rocket into outer space, there is nothing. I believe, there is no matter anymore. Except for stars of course."* (All interview quotes have been translated from the original German version.)

Table 2. Overview of the students' evaluation of key idea I:
Matter is everything that can be touched, practically or theoretically.

Phase	S01	S02	S03	S04	S05	S06	S07	S08
Paraphrasing of the key idea	✓	✓	✓	~	✓	✓	✓	✓
Transfer of the key idea (salt)	✓	✓	✓	✓	✓	✓	✓	✓
Transfer of the key idea (water)	✓	✓	✓	✓	✓	✓	✓	✓

More complex key ideas, such as VII & IX introducing elementary particles, were also accepted to a great extent. Since these two key ideas showed poor acceptance in the test studies, this can be traced back to the revised typographic illustrations. However, the students' acceptance and evaluation differ. While accepting their indivisibility, most students value elementary particles to be difficult to understand, as one student stated: *"Somehow, I always thought that one can divide everything forever."* This goes hand in hand with a healthy scepticism regarding their elementary state, as put so elegantly by another student: *"I can imagine indivisible particles, but I think if our techniques improve maybe we can find something smaller."*

Additionally, key idea X tackling the de facto emptiness of matter, proved to be problematic. Surprisingly, no student seemed to have any problems when talking about empty space itself. Even when describing the atomic model, the empty space was accepted repeatedly. But once it came to everyday objects, most students had to step back. One student mentioned doubts as follows: *"This is really hard to imagine, because the table isn't empty, there are no holes or something else in between."*

Out of the eleven key ideas, only two showed poor acceptance: key idea XI focusing on compounds, such as molecules, and key idea II, which concentrates on the permanent model character. We identified different reasons for their evaluation. As for key idea II the concept's aim to emphasise the permanent model character of physics was not successful. Not only did we encounter poor acceptance, there were also many omissions. During the different stages of the sessions, most students didn't mention the model character at all (table 3). Only when specifically asked about this key idea did some of them evaluate it in an adequate way. At first, it was largely accepted, as one student stated: *"You have to illustrate it somehow."* But as the session progressed, more and more doubts were raised by the students, for example: *"But what does it [the elementary particle] look like?"* In this particular situation, the typographic illustrations proved to be helpful in overcoming the need for a realistic drawing. Overall, though, the question of how to make proper use of the permanent model character of particle physics remains.

Table 3. Overview of the students' evaluation of key idea II:
Reality is described through models.

Phase	S01	S02	S03	S04	S05	S06	S07	S08
Paraphrasing of the key idea		~	✓	✓	✗	✓	✓	✓
Transfer of the key idea (salt)	✓		~	✓		✓	~	
Transfer of the key idea (water)	✓	~				✓	✓	✓

The students' evaluation of key idea XI revealed difficulties in terms of the linguistic accuracy. Most of the new words, such as quarks, orbital-space, and nucleus-space, caused no problems. But at the end of many sessions students mentioned a literary overload, for example: *"Well, there are certainly some terms, for example, mole-, molec-, molep-, molecule, yes, molecule, which are definitely difficult to memorise. These special terms are really complicated."* However, only a few salient transformations of elements of the explanation were observed. Most key words were used consistently as originally introduced. The only exception was the use of nucleus-space and orbital-space. Here the nucleus-space proved to appeal a lot more to students than the orbital-space. All students referred to the nucleus-space and made use of it in all repetitions. In contrast, the orbital-space was almost always transformed into "the orbital". But when asked specifically about "the orbital" the transformation vanished and the orbital-space was used again. We therefore believe it is safe to say this transformation occurs for practical reasons, but it highlights the uphill nature of the battle for linguistic accuracy.

Discussion

The explicit question motivating this work was whether Grade-6 students can understand and make use of the proposed subatomic particle concept. Indeed, we might claim that the results presented above can be judged as satisfactory. The typographic illustrations especially had a promising impact on students' learning processes. However, there are specific details that need to be addressed.

First, our aim of conveying a permanent model character was not fulfilled. Although the information input was carefully constructed from a model-based point of view, it showed little success. Only a few students adopted the proposed model-based perspective. This should come as no surprise, as other findings suggest that students need more experience using models as intellectual tools (Grosslight et al., 1991). Even with acceptance, many paraphrases exposed only a naive epistemological model character. Mostly, the students' interpretations focused on a model as a physical copy of reality. Thus, the descriptive model was accepted but never seriously questioned. One improvement could be to start with a specific course about models (Mikelskis-Seifert & Fischler, 2003b), potentially leading to a more stable base upon which to build more complex chapters, such as fundamental interactions. However, for our research, the question remains as to whether the particle physics concept sufficiently supports a model-based approach of teaching physics.

Second, the linguistic modifications within the teaching concept seemed to appeal to all students. The clear distinction between particles and particle systems resulted in very positive evaluations and led to broad acceptance. In particular, the notion of protons and neutrons as particle systems made of particles recurred consistently. Nevertheless, our study has limitations in terms of linguistic accuracy. The timeframe of 40 minutes did not allow for a proper discussion of all the modified phrasings during the planned interview phases. Indeed, the literary overload noted at the end of most sessions demonstrates the need for future linguistic modifications of the teaching concept, especially given the latter's reliance on the introduction of novel terms and phrasings.

Third, the typographic illustrations proved to be comprehensible and adequate. All students evaluated them to be understandable and showed broad acceptance. Especially when it came to the distinction between particles and particle systems, the illustrations turned out to be very helpful. The underlying colour pattern, supported by the careful use of wording led to a clear distinctness. We observed no confusion regarding electrons and quarks during any session. No students showed any difficulty when talking about elementary particles, except with respect to their indivisibility. A more astonishing side effect was the observed impact on known misconceptions. Regarding the topics of empty space or the scale of atoms, we still found persistent misconceptions in accordance with documented research (Novick & Nussbaum, 1981; Renstroem, 1987; Andersson, 1990; Harrison & Treagust, 1996). However, over the course of two test studies and the main study, everyday descriptions of particles almost vanished. In the end, we hardly encountered any transfer of macroscopic aspects onto the properties of subatomic objects. The students' evaluations suggest this is mostly due to the revised typographic illustrations. Upcoming challenges include how to improve and implement these when introducing fundamental interactions. For future directions, we suggest typographic illustrations as the most promising outcome of this study.

Last, we want to give a brief outline of how the particle physics concept relates to previous research and how it can be used in classrooms. Its aim is to introduce elementary particles and fundamental interactions by linking them through their respective charges. This enables an early introduction of key terms such as quark, electron, charge, and interaction. One can then build the whole physics curriculum upon these fundamental principles. For obvious reasons, not all physics chapters can be explained extensively enough through particle physics. But the vast majority is adequately suited. Particularly when looking at central topics of the curriculum and how to link them to particle physics, one already finds plenty of intriguing proposals. These include, for instance, a photon-based approach of teaching optics (Gjurchinovski, 2013), an introduction of electromagnetism by using particle accelerators (Sinflorio et al., 2006), Newton's laws of motion explained through quantum physics (Ogborn & Taylor, 2005; Pinto 2007), a course on quantum physics supported by GeoGebra simulations (Malgieri et al., 2014), and, of course, a couple of CERN-based explanations of particle physics (Long, 2011; Cid-Vidal & Cid, 2011; Johansson, 2013; Johansson & Watkins, 2013). This list is not exhaustive, but it serves to give a general impression. Ideally, our concept supports and enables future work to facilitate integrating particle physics into modern physics curricula.

Conclusion

In this paper, we have presented a new teaching concept based on particle physics. It comprises two consecutive chapters – elementary particles and fundamental interactions. The main motivation originates from the idea of particle physics linking the whole physics curriculum as the fundamental basis of physics. The concept's aim is to introduce modern physics at an earlier stage than is currently the case in most countries. The design process was conducted from a constructivist perspective based on documented students' conceptions. Three main pillars – a permanent model character, linguistic accuracy, and innovative typographic illustrations – support the whole teaching concept. To evaluate students' general understanding of the concept, a study was conducted. Based on the concept's first chapter on elementary particles, eleven key ideas were formulated. The acceptance of these key ideas was then investigated over the course of two test and one main study with 20 Grade-6 students. Our findings were quite successful with two main outcomes of the study. On the one hand, the permanent model character was poorly accepted and barely used for problem-solving. Here, the concept needs to be adapted for future studies. On the other hand, the typographic illustrations led to broad acceptance and, in combination with linguistic accuracy, to a reduction of known misconceptions. Signs of everyday descriptions of particles largely vanished during the repetitions. We consider this to be the most interesting result of the presented study and the most promising application for teaching particle physics.

Future research will concentrate on the teachers' opinions concerning the teaching concept. A follow-up study is being designed to again probe acceptance of the concept with Grade-6 students. This time, instead of education researchers, the microteaching sessions will be led by experienced teachers to evaluate their implementation of the concept. Combined with the students' acceptance, the teachers' evaluation should provide detailed information on the didactical feasibility of the teaching concept.

Acknowledgements

We thank Prof. Michael Kobel for useful discussions and Prof. Rodney Jory for valuable suggestions.

References

Andersson, B. (**1990**). Pupils' Conceptions of Matter and its Transformations (age 12-16). *Studies in Science Education*, 18, 53-85

Boz, Y. (**2006**). Turkish Pupils' Conceptions of the Particulate Nature of Matter. *Journal of Science Education and Technology*, 15, 203-213

Carney, R. N. & Levin, J. R. (**2002**). Pictorial Illustrations Still Improve Students' Learning From Text. *Educational Psychology Review*, 14, 5-26

Chittleborough, G. D. & Treagust, D. F. (**2009**). Why Models are Advantageous to Learning Science. *educación química*, 12-17

Cid-Vidal, X. & Cid, R. (**2011**). How to count 300 trillion protons travelling at the speed of light. *Physics Education*, 46(3), 309-311

Cook, M. P. (**2006**). Visual Representations in Science Education: The Influence of Prior Knowledge and Cognitive Load Theory on Instructional Design Principles. *Science Education*, 90, 1073-1091

Design-Based Research Collective (**2003**). Design-based Research: an emerging paradigm for educational inquiry. *Educational Researcher*, 32, 5-8

de Vos, W. & Verdonk, A. H. (**1996**). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching*, 33, 657-664

Dow, W., Auld, J. & Wilson, D. (**1978**). Pupils' Concepts of Gases, Liquids and Solids. Dundee College of Education

Duit, R. (**1996**). The constructivist view in science education – what it has to offer and what should not be expected from it. *Investigações em Ensino de Ciências*, 1, 40-75

Duit, R. & Treagust, D. F. (**2003**). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, 25(6), 671–688

Eames, C. & Eames, R. (**1977**). Powers of Ten. [Online], Available: www.youtube.com/watch?v=0fKBhvDjuy0 [24.3.2015]

Gilbert, J. (**2004**). Models and modelling: routes to more authentic science education. *International Journal of Science and Mathematics Education*, 2, 115–130

Gjurchinovski, A. (**2013**). Reflection from a moving mirror - a simple derivation using the photon model of light. *European Journal of Physics*, 34, 1-4

Griffith, A. & Preston, K. (**1992**). Grade-12 Students' Misconceptions Relating to Fundamental Characteristics of Atoms and Molecules. *Journal of Research in Science Teaching*, 29, 611-628

Griffiths, D. (**2004**). Introduction to elementary particles. Weinheim: Wiley-VCH

Grosslight, L., Unger, C., Jay, E., & Smith, C. (**1991**). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching*, 28, 799–822.

Harrison, A. G. & Treagust, D. F. (**1996**). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education*, 80, 509-534

Harrison, A. G. & Treagust, D. F. (**2000**). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry. *Science Education*, 84, 352-381

Hertz, H. (**1899**). The principles of mechanics. London: Macmillan and Co. Ltd

Huang, C. & Huang, M. (**2012**). The scale of the universe 2. [Online], Available: htwins.net/scale2 [24.3.2015]

Johansson, K. E. (**2013**). Exploring quarks, gluons and the Higgs boson. *Physics Education*, 48(1), 96-104

Johansson, K. E. & Watkins, P. M. (**2013**). Exploring the standard model of particles. *Physics Education*, 48(1), 105-114

Jung, W. (**1992**). Probing acceptance, a technique for investigating learning difficulties. In R. Duit, F. Goldberg & H. Niedderer (Eds.), Research in physics learning: Theoretical issues and empirical studies. Kiel: IPN, 278-295

Justi, R. (**2009**). Learning how to model in science classroom: key teacher's role in supporting the development of students' modelling skills. *educación química*, 32-40

Karsten, F., Koch, T., Kranzinger, F. & Theis, M. (**2011**). Planeten, Wolken oder schwarze Kisten? Wie können wir Atome in der Schule didaktisch sinnvoll beschreiben? *Physik Journal*, 10, 11, 39-42

Long, L. (**2011**). More 'hands-on' particle physics: Learning with ATLAS at CERN. *Physics Education*, 46(3), 270-280

Malgieri, M., Onorato, P. & De Ambrosis, A. (**2014**). Teaching quantum physics by the sum over paths approach and GeoGebra simulations. *European Journal of Physics*, 35, 1-21

Mayring, P. (**2010**). Qualitative Inhaltsanalyse. Grundlagen und Techniken. Weinheim: Beltz

Mikelskis-Seifert, S. & Fischler, H. (**2003a**). Die Bedeutung des Denkens in Modellen bei der Entwicklung von Teilchenvorstellungen – Stand der Forschung und Entwurf einer Unterrichtskonzeption. *Zeitschrift für Didaktik der Naturwissenschaften*, 9, 75-88

Mikelskis-Seifert, S. & Fischler, H. (**2003b**). Die Bedeutung des Denkens in Modellen bei der Entwicklung von Teilchenvorstellungen – Empirische Untersuchung zur Wirksamkeit der Unterrichtskonzeption. *Zeitschrift für Didaktik der Naturwissenschaften*, 9, 89-103

Mullis, I., Martin, M., Minnich, C., Stanco, G., Arora, A., Centurino, V. & Castle, C. (**2012**). TIMSS 2011 Encyclopedia: Education Policy and Curriculum in Mathematics and Science, Volumes 1 and 2. Chestnut Hill, MA: TIMSS & PIRLS International Study Center, Boston College.

Nakhleh, M. B. & Samarapungavan, A. (**1999**). Elementary school children's beliefs about matter. *Journal of Research in Science Teaching*, 36, 777-805

Novick, S. & Nussbaum, J. (**1981**). Pupils' Understanding of the Particulate Nature of Matter: A Cross-Age Study. *Science Education*, 65, 187-19

Ogborn, J. & Taylor, E. F. (**2005**). Quantum physics explains Newton's laws of motion. *Physics Education*, 40, 26-34

Ornek, F. (**2008**). Models in Science Education: Applications of Models in Learning and Teaching Science. *International Journal of Environmental & Science Education*, 3(2), 35 – 45

Ozmen, H. (**2011**). Turkish primary students' conceptions about the particulate nature of matter. *International Journal of Environmental & Science Education*, 6, 99-121

Pfundt, H. (**1981**). Das Atom - Letztes Teilungsstück oder erster Aufbaustein? Zu den Vorstellungen, die sich Schüler vom Aufbau der Stoffe machen. *chimica didactica*, 7, 75-94

Pinto, M. B. (**2007**). Introducing the notion of bare and effective mass via Newton's second law of motion. *European Journal of Physics*, 28, 171–181

Renstroem, L. (**1987**). Pupils Conceptions of Matter. A phenomenographic approach. Proceedings of the 2. Int. Seminar "Misconceptions and Educational Strategies in Science and Mathematics", 3, 400-414

Rincke, K. (**2010**). Alltagssprache, Fachsprache und ihre besonderen Bedeutungen für das Lernen. *Zeitschrift für Didaktik der Naturwissenschaften*, 16, 235-260

Sinflorio, D. A., Fonseca, P., Coelho, L. F. S. & Santos, A. C. F. (**2006**). Teaching electromagnetism to high-school students using particle accelerators. *Physics Education*, 41(6), 539-541

Snir, J., Smith, C. L. & Raz, G. (**2003**). Linking phenomena with competing underlying models: A software tool for introducing students to the particulate model of matter. *Science Education*, 87, 794-830

Stavy, R. (**1991**). Children's Ideas About Matter. *School Science and Mathematics*, 91(6), 240-244

Wiesner, H. & Wodzinski, R. (**1996**). Akzeptanzbefragungen als Methode zur Untersuchung von Lernschwierigkeiten und Lernverläufen. *Lernen in den Naturwissenschaften*, 250-274

B

Introducing the LHC in the classroom: an overview of education resources available

Gerfried J. Wiener[1,2], Julia Woithe[1,3], Alexander Brown[1,4] and Konrad Jende[1,5]
[1]CERN, European Organization for Nuclear Research, Geneva
[2]Austrian Educational Competence Centre Physics, University of Vienna
[3]Department of Physics/Physics Education Group, University of Kaiserslautern
[4]Institut Universitaire pour la Formation des Enseignants, University of Geneva
[5]Institute of Nuclear and Particle Physics, TU Dresden

Abstract:

In the context of the recent re-start of CERN's Large Hadron Collider (LHC) and the challenge presented by Unidentified Falling Objects (UFOs), we seek to facilitate the introduction of high energy physics in the classroom. Therefore, this paper provides an overview of the LHC and its operation, highlighting existing education resources, and linking principal components of the LHC to topics in physics curricula.

Keywords: CERN; Large Hadron Collider; Unidentified Falling Objects; High energy physics; Education resources; Physics curricula

Introduction

Early in 2015, CERN's Large Hadron Collider (LHC) was awoken from its first long shutdown to be re-ramped for Run 2 at unprecedented beam energy and intensity. Intense scrutiny was required to verify the full and proper functioning of all systems. This included a special run of the machine to ensure a well-scrubbed LHC [1]. However, due to the increased beam currents, a critical but familiar issue reared its head during the run. Interactions between the beams and Unidentified Falling Objects – so called UFOs – led to several premature protective beam dumps (see figure 1).

These infamous UFOs are presumed to be micrometre-sized dust particles and can cause fast, localised beam losses with a duration on the order of 10 turns of the beam. This is a known issue of the LHC which has been observed before. Indeed, between 2010 and 2011, about a dozen beam dumps occurred due to UFOs and more than 10000 candidate UFO events below the dump threshold were detected [2]. Thus, UFOs presented more of an annoyance than a danger to the LHC, by reducing the operational efficiency of the machine. However, as beam currents increase, so does the likelihood of UFO-induced magnet quenches at high energy, creating a possible hazard to the machine. Therefore, particular care is taken to keep an eye on the timing and frequency of UFO occurrences. As the experience with UFOs during run 1 decreased over time, it is hoped that this will be the same in Run 2.

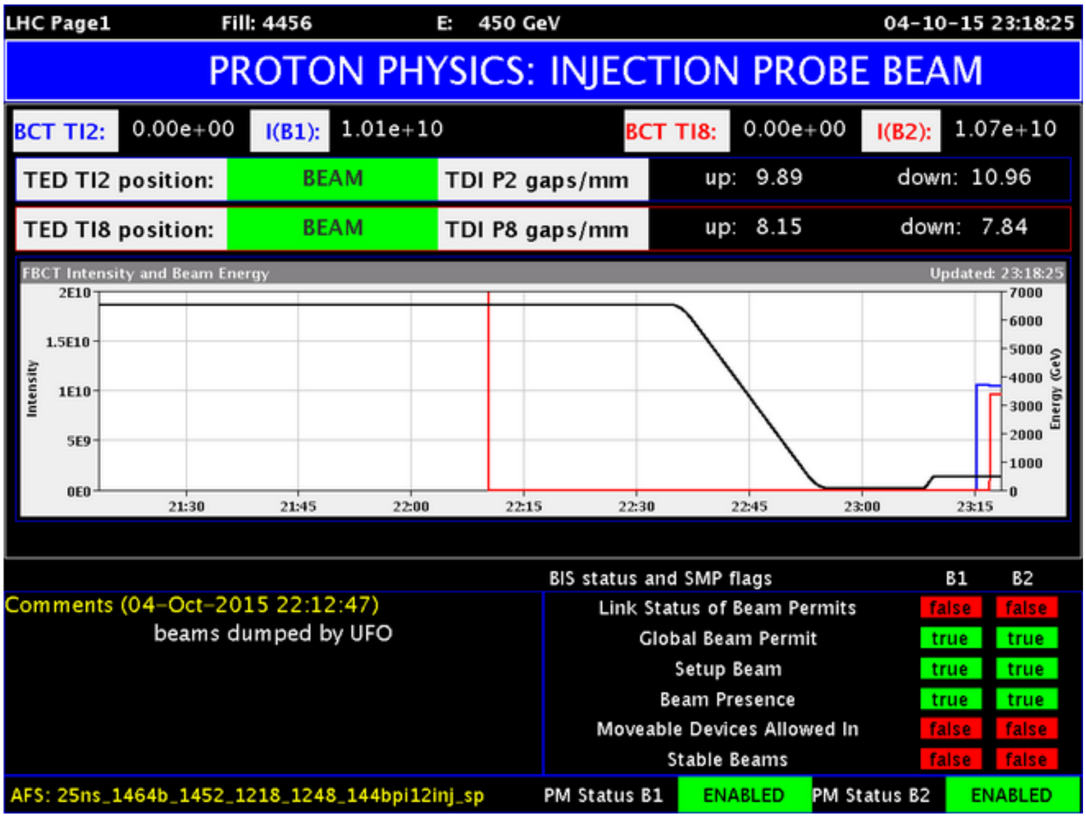


Figure 1. Screenshot of LHC Page1 after a beam dump by a UFO (image courtesy of CERN). This display of current activities of the LHC, as well as details about all the other particle accelerators at CERN, can be found online [3].

The recent re-start of the LHC at higher collision energies and rates presents high school teachers with a unique opportunity: to use the LHC as a prime example of fundamental research, further integrating modern physics into their physics classes. We consider the re-start of the LHC, in combination with the intriguing phenomenon of UFOs, to be well-suited to engage students with high energy physics. Therefore, the aim of our paper is to give a broad overview of the LHC and its operation and to link each aspect of these to a range of existing educational resources. In addition, we highlight specific connections to physics curricula to facilitate the integration of high energy physics in the classroom.

The operation of the LHC

The ultimate goal of the LHC is to collide beams of electrically charged particles at unprecedented energies and luminosities. Large detectors are installed around the collision points in order to explore the structure of matter, better understand the evolution of the Universe, and unambiguously discover new particles [4].

Particle beams

CERN's historic accelerator complex [5, 6] provides beams of either protons or, about one month per year, lead ions. Interconnected particle accelerators speed up these particles to energies of up to 7 TeV. Particles are taken from sources, marking the beginning of the complex. One of the sources is an ordinary bottle of hydrogen gas. Molecular hydrogen is fed from the bottle into a chamber, where its protons are separated from its electrons by an electron gun. These protons are guided by electric fields through vacuum chambers into the first accelerating machines. The last of these take care of the final beam structure, which is not a continuous stream of particles but consists of packages of protons, known as "bunches" (see figure 2a). In the LHC, this leads to the ultimate fill with about 2800 bunches of ultra-relativistic protons for each of the counter-rotating beams at a bunch spacing of 25 ns. A bunch contains about a hundred billion protons while being a few centimetres long and having a horizontal spread between millimetres and a few micrometres. In order to provide the detector experiments with high-quality collisions for a sufficient period of time, an ultra-high vacuum, on the order of 10^{-10} mbar, must be imposed on the chambers surrounding the beams.

Various papers have been published encouraging the use of the LHC as an educational resource. Among these, relevant to the teaching of particle beams, are descriptions and calculations of the vacuum system [7] and the energy stored in individual LHC components [8]. In addition, a new set of state-of-the-art animations by CERN's MediaLab illustrates many aspects of the operation of the LHC, including the process of producing particle beams for the LHC [9]. When introducing particle beams in the classroom, these can all be combined to cover several topics. Ionisation, a phenomenon described by quantum physics, is the dominant production process of electrically charged particles in accelerators. Their properties and behaviour after being accelerated to ultra-relativistic energies are described by special relativity. The record-breaking numbers describing the LHC beams, such as the energy of 7 TeV applied to protons, allow the introduction of physics quantities in mechanics, including energy, velocity, momentum, and mass. The astonishing quality of the vacuum in the LHC beam pipes can be used to discuss thermal physics. Phenomena of electricity, such as electromagnetic induction, are used in the LHC in several instances, e.g., determination of the LHC beams' positions and intensities by beam position monitors [10]. Particle beams represent a source of ionising radiation and therefore possible hazard to humans. Their penetrating power, however, can also be used in medical applications, such as cancer treatment. Thus, particle beams invite one to speak about interdisciplinary topics, e.g., radiation protection [11] and medical applications [12]. When being smashed together as they are in the LHC, particles interact in numerous ways. Three of the four fundamental interactions in Nature – namely, the strong, weak, and electromagnetic interactions – and their laws can be studied, which gives an opportunity to introduce particle physics into the classroom.

Radiofrequency cavities

The beams of electrically charged relativistic particles described above are delivered to the LHC at an injection energy of 450 GeV [5]. Thus, to produce collisions at the desired energy of 14 TeV (7 TeV per colliding proton), the beams must be further accelerated. Moreover, due to synchrotron radiation, the particles constantly lose energy which must be fed back to them, even once they reach their final energy. This is achieved through the use of radiofrequency (RF) cavities, hollow copper structures coated with a 1.5 µm thick niobium layer on the inside. The outside of the cavities is cooled with liquid helium to an operating temperature of 4.5 K. At this low temperature, the niobium is superconducting, allowing a more cost-effective operation compared to normally conducting cavities [13]. The cavities are hosted alongside cryogenic and RF equipment in mechanical support structures called "cryomodules" (see figure 2b). There are four cryomodules containing four cavities each, all grouped together at one of the straight sections of the LHC, with two cryomodules per beam. High-power RF generators, called klystrons, feed each cavity with an electromagnetic field via waveguides. This field oscillates at a period compatible with the duration of the particles' passage around the LHC. As a result of the superposition of electromagnetic waves moving back and forth inside the cavities at their resonant frequency of 400 MHz, standing electromagnetic waves are generated. Their associated electromagnetic fields produce longitudinal electric fields of about 5 MV/m along the beams' directions. Provided ideal timing of the particles' arrival at the cavities, these alternating electric fields can be used to transfer energy to the particle beams each time they pass through. With each lap around the LHC, every proton thus gains on average 485 keV in energy. The process of acceleration from injection to collision energies takes about 20 minutes, or about 1 million laps of the ring [6, 13].

Introducing the process of accelerating particles is supported by many educational resources, for example a simple calculation on the sheer amount of protons circulating in the LHC [14], which is well-suited for high school students. Additionally, hands-on experiments allow for more practical engagement by enabling students to build models of particle accelerators in the classroom [15]. The operation and functioning of the RF cavities used for the LHC is illustrated in another CERN MediaLab animation [16]. High school teachers can use RF cavities to illustrate several topics of physics curricula. For example, principles of electricity, such as electrodynamics, are fundamental to the functioning of RF cavities. Furthermore, discussions of the electromagnetic waves used to accelerate particles can underpin discussions of mechanics, specifically regarding oscillations and waves. Finally, superconductivity, being a macroscopic effect of quantum mechanics, can serve as an example of quantum physics aspects of particle physics.

Dipole magnets

Key to every circular particle accelerator are magnetic fields. To bend accelerated particle beams into closed paths, magnetic dipole fields are essential. These uniform fields have a pure bending effect on electrically charged particles by the virtue of Lorentz force. The movement of an electrically charged particle in a magnetic dipole field thus depends on the particle's velocity and the properties of the magnetic field. In the case of the LHC, the state-of-the-art version of a synchrotron, the guiding magnetic field is produced by high electric current in superconducting coils, which are placed close to the beam pipes (see figure 2c). A total of 1232 so-called "dipoles" are installed in the LHC tunnel. Each dipole is 15 metres long and their coils are made of niobium-titanium (NbTi) cables, which must be operated at a fraction of their critical temperature

(10 K) to ensure superconductivity. The required operating temperature of 1.9 K is reached by using superfluid helium [17]. Thus, superinsulation and thermal shields are key components of each dipole to maintain the challenging temperature gradient between the cold mass and the outside. In addition, shrinking vessels also play a big role during cool-down, as every dipole contracts with temperature, yielding a total shortening of approximately 80 metres of the LHC's circumference [6]. When cooled down and operational, the dipoles can produce a magnetic field of up to 8.3 T by suitable distribution of a nominal electric current of around 12 kA through the superconducting cables [4]. At the designed maximum collision energy of 14 TeV, this magnetic field is required to keep the proton bunches on their intended trajectory.

Every dipole produced needed to be tested thoroughly before being installed at the LHC tunnel. Therefore, all dipoles were transported to CERN's magnet testing facility hall, where each was individually attached to a test bench to simulate operational conditions. Of main interest during the testing were the vacuum in the beam pipes and the insulation vacuum. Only once it was shown that the cryostat's insulation was sufficient could the magnet be cooled down. Once the dipole reached operation temperature, electric voltage was applied to the coils to scrutinise the magnetic field produced [18].

As for classroom application, we believe that by going through the described testing process and discussing the physics behind the dipoles, one can demonstrate the variety of physics phenomena coming into play. We identified three main curriculum topics standing out when discussing dipoles: starting with thermal physics to describe the cool-down process and operation, then making the link to electromagnetism when explaining how the magnetic field is produced through superconducting coils, and finally leading to mechanics for the discussion of the Lorentz force and the circular motion of the accelerated particle beams. Here, useful resources have already been published, mainly focusing on LHC's dipoles by providing calculations of their impedance [8], as well as of the Lorentz force and the magnetic energy required [19]. Once again, an animation is also available, showing the operation and functioning of the LHC's dipoles [20].

Quadrupole magnets

In addition to dipole magnets, which ensure the circular paths of the particle beams, many other superconducting electromagnets with a variety of configurations are used to keep the trajectories of the electrically charged particles close to the ideal orbit [21]. Among these are quadrupole magnets, which consist of four coils arranged around the beam pipes (see figure 2d). The strength of the resulting magnetic quadrupole field increases linearly with displacement from the centre. The resulting linearly increasing Lorentz force leads to a focusing effect on a beam of electrically charged particles like protons [6]. Because of the shape of the magnetic field, one quadrupole magnet will always focus in one direction, e.g., horizontally, and defocus in the other direction, e.g., vertically. To produce radially focused beams, a combination of focusing and defocusing quadrupole magnets is used.

In a circular collider like the LHC, focusing is not only needed to continuously compensate the repulsion between particles of the same electric charge due to Coulomb forces, but also to dramatically reduce the beams' diameters to a minimum size of 16.7 µm as the beams approach each interaction point [13]. Small beam diameters are crucial for high collision rates inside the LHC detectors. To achieve the necessary magnetic field gradients of up to 205 T/m inside the quadrupole magnets, the same superconducting NbTi cables are used as in the LHC dipole magnets [21].

Especially when placed close to an interaction point where particle interactions take place about 800 million times per second, magnets must be designed taking into account the flux of emerging secondary particles. Up to 30 W of thermal load is produced in a quadrupole magnet when energy of secondary particles is deposited inside the magnet material. To prevent the magnets from quenching and thereby losing their superconducting properties, heat exchanger pipes carry superfluid helium at 1.9 K, which absorbs heat through vaporisation [22]. In addition, radiation damage due to an accumulated dose of approximately 23 MGy during the first ten years of operation had to be considered in the design process [23].

Discussing quadrupole magnets allows a variety of connections to the physics curriculum. To guide and focus beams of electrically charged particles, scientists have adapted many concepts from optics, e.g., quadrupole magnets are often compared to lenses. In the classroom, focusing and defocusing effects of quadrupole magnets can easily be demonstrated by using four identical coils and a cathode ray tube [24]. A simple visualisation of complex multi-pole magnetic fields can be realised by using cheap magnetic toys, such as GEOMAG™ [25]. Thermal physics is key in describing enthalpy of vaporisation and the importance of cryogenic plants at the LHC, whereas interactions of secondary particles with the magnets themselves are described by applying fundamentals of particle physics. To illustrate the operation and functioning of the LHC's quadrupoles, teachers can make use of yet another animation, made available online by CERN's MediaLab [26].

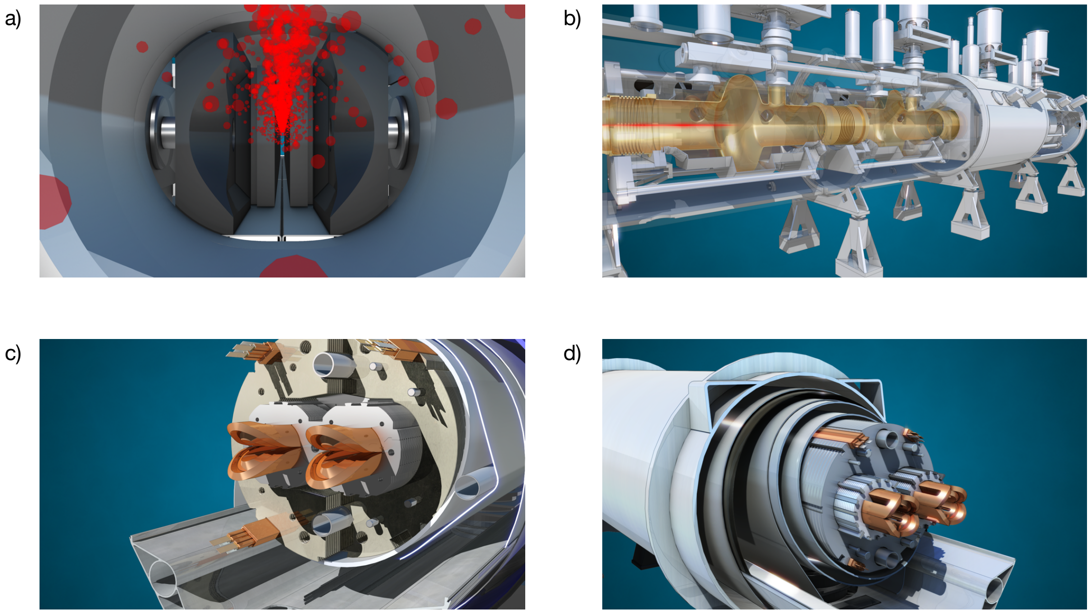


Figure 2. Graphical visualisations of (a) a particle beam; (b) two of the four radiofrequency cavities inside a cryomodule; and coils of superconducting NbTi cables in (c) dipole and (d) quadrupole magnets (images courtesy of CERN).

Conclusion

Over the last few years, CERN's Large Hadron Collider (LHC) has become widely known as the most powerful particle accelerator of our generation and has sparked significant interest in high energy physics. To help high school teachers respond to this demand, we have given an overview of the LHC and its operation while linking it to resources which could be of use in the classroom. Furthermore, we have introduced a current challenge facing operators of the LHC, Unidentified Falling Objects (UFOs), which may spark high school students' interest in high energy physics.

Furthermore, we want to stress that several educational outreach programmes have been established, prompting a multitude of approaches towards the introduction of the physics behind the LHC into the classroom. For instance, in coordination with CERN's LHC outreach group, every major LHC detector collaboration runs their own education and outreach programme, facilitating the creation and distribution of helpful material and useful resources on particle detection for high school teachers [27-30]. Indeed, many resources on the LHC and its detectors are available online in various degrees of quality, scope, and elaboration. The International Particle Physics Outreach Group (IPPOG) maintains a database of resources [31] containing an extraordinary and ever-growing range of tools and materials, such as teaching and exhibition material, educational games, podcasts, and many more. A prominent example is IPPOG's programme of International Masterclasses [32], enabling high school students to perform hands-on measurements on real data from the four main LHC experiments. This goes hand-in-hand with CERN's open data portal [33], which acts as an access point to research data produced at CERN. As the LHC enters Run 2, this is an exciting time for high energy physics and a prime opportunity for high school teachers to introduce this modern topic in the classroom. We hope, therefore, that the resources referenced above and our overview of the LHC and the challenges involved in its operation will support high school teachers in this endeavour.

Acknowledgments

We would like to thank Rhodri Jones, head of the CERN beam instrumentation group, Sarah Aull of the CERN RF group, and Hugo Day of the CERN accelerator beam transfer group for feedback on our manuscript. We are indebted to Daniel Dominguez and Arzur Torres from CERN's MediaLab for providing us with the LHC graphics.

References

[1] CERN Bulletin **2015** LHC report: intensity ramp-up – familiar demons. Retrieved October 12, 2015, from https://cds.cern.ch/journal/CERNBulletin/2015/30/News%20Articles/2034985

[2] Baer T et al **2012** UFOs in the LHC after LS1 Proc. of workshop on LHC performance, Chamonix 294–298

[3] CERN **2015** OP Vistars. Retrieved October 12, 2015, from https://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php

[4] Baconnier Y, Brianti G, Lebrun P, Mathewson A G, and Perin, R **1993** LHC: the Large Hadron Collider accelerator project. Geneva: CERN

[5] Benedikt M et al (eds.) **2004** LHC Design Report Volume 3: the LHC Injector Chain. Retrieved October 12, 2015, from http://cdsweb.cern.ch/record/823808

[6] Meyers S **2012** The engineering needed for particle physics *Philosophical Transactions of the Royal Society A* 370 3887–3923

[7] Cid-Vidal X and Cid R **2011** LHC: the emptiest space in the solar system *Physics Education* 46(1) 45–49

[8] Cid X. and Cid R **2009** Taking energy to the physics classroom from the Large Hadron Collider at CERN *Physics Education* 44(1) 78–83

[9] CERN **2014** Duoplasmatron. Retrieved October 12, 2015, from http://cern60.web.cern.ch/en/exhibitions/duoplasmatron

[10] Jones O R **2007** LHC Beam Instrumentation. 22nd Particle Accelerator Conf., Albuquerque, NM, USA, 25–29 Jun 2007, 2630

[11] Haran B **2010** Putting your hand into the Large Hadron Collider... Retrieved October 12, 2015, from https://www.youtube.com/watch?v=_NMqPT6oKJ8

[12] CERN **2013** ENVISION, innovative medical imaging tools for particle therapy. Retrieved October 12, 2015, from https://cds.cern.ch/record/1611721

[13] Brüning O S et al (eds.) **2004** The LHC Design Report Volume 1: the LHC Main Ring. Retrieved October 12, 2015, from http://cdsweb.cern.ch/record/782076

[14] Cid-Vidal X and Cid R **2011** How to count 300 trillion protons travelling at the speed of light *Physics Education* 46(3) 309–311

[15] CERN **2015** Salad Bowl Accelerator Retrieved October 12, 2015, from http://ippog.web.cern.ch/resources/2014/salad-bowl-accelerator

[16] CERN **2014** LHC RF cavity. Retrieved October 12, 2015, from http://cds.cern.ch/record/1750705

[17] Wyss C **1999** LHC arc dipole status report. Retrieved October 12, 2015, from https://cds.cern.ch/record/410778/files/lhc-project-report-288.pdf

[18] CERN Courier **2007** LHC magnet tests: the Indian connection. Retrieved October 12, 2015, from http://cerncourier.com/cws/article/cern/30145

[19] Cid R **2005** Contextualized magnetism in secondary school: learning from the LHC (CERN) *Physics Education* 40(4) 332–338

[20] CERN **2014** Dipole. Retrieved October 12, 2015, from http://cds.cern.ch/record/1750706

[21] Siegel N **2000** Overview of the LHC magnets other than the main dipoles 7th European Particle Accelerator Conf., Vienna, Austria, 26–30 June 2000

[22] Bertinelli F et al **2004** Design and Fabrication of Superfluid Helium Heat Exchanger Tubes for the LHC Superconducting Magnets Proc. of EPAC 2004, Lucerne, Switzerland

[23] Mokhov N V et al **2006** Superconducting Magnets in High-Radiation Environment at Supercolliders. Fermilab-Conf-06-244-AD (2006)

[24] CERN Teachers Lab **2007** Cathode Ray Tube. Retrieved October 12, 2015, from http://project-physicsteaching.web.cern.ch/project-physicsteaching

[25] Defrancesco S, Logiurato F and Karwasz G **2007** GEOMAG™ Paradoxes *The Physics Teacher* 45 542–545

[26] CERN **2014** Quadrupole. Retrieved October 12, 2015, from http://cern60.web.cern.ch/en/exhibitions/quadrupole

[27] ALICE Matters. Retrieved October 12, 2015, from http://alicematters.web.cern.ch

[28] ATLAS for Students and Teachers. Retrieved October 12, 2015, from http://atlas.ch/students-teachers.html

[29] CMS Public Data. Retrieved October 12, 2015, from http://cms.web.cern.ch/content/cms-public-data

[30] LHCb Outreach Materials. Retrieved October 12, 2015, from http://lhcb-public.web.cern.ch/lhcb-public/en/LHCb-outreach

[31] IPPOG Resources. Retrieved October 12, 2015, from http://ippog.web.cern.ch/resources

[32] IPPOG International Masterclasses. Retrieved October 12, 2015, from http://physicsmasterclasses.org

[33] CERN Open Data Portal. Retrieved October 12, 2015, from http://opendata.cern.ch

C

An alternative proposal for the graphical representation of anticolor charge

Gerfried J. Wiener[1,2], Sascha M. Schmeling[1] and Martin Hopf[2]
[1]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[2]University of Vienna, Austrian Educational Competence Centre Physics

Keywords: particle physics, anticolor charge, graphical representation

We have developed a learning unit based on the Standard Model of particle physics, featuring novel typographic illustrations of elementary particles and particle systems[1]. Since the unit includes antiparticles and systems of antiparticles, a visualization of anticolor charge was required. We propose an alternative to the commonly used complementary-color method, whereby antiparticles and antiparticle systems are identified through the use of stripes instead of a change in color. We presented our proposal to high school students and physics teachers, who evaluated it to be a more helpful way of distinguishing between color charge and anticolor charge.

Education research shows that carefully designed images can improve students' learning[2]. However, in practice, illustrations commonly contain elements limiting students' learning, as underlined by Cook[3]: *“Visual representations are essential for communicating ideas in the science classroom; however, the design of such representations is not always beneficial for learners.”* To determine what aspects of the typographic representations used in our learning unit (fig. 1) hinder or promote learning, we tested and adapted them in the context of design-based research[4] using Jung’s technique of probing acceptance[5]. In the course of developing our unit, we also formulated this proposal regarding the graphical representation of anticolor charge.

In the Standard Model of particle physics, elementary particles are sorted according to their various charges. A “charge” in this context is the property of a particle whereby it is influenced by a fundamental interaction. In quantum field theory, the electromagnetic, weak, and strong interactions are each associated with a fundamental charge. The abstract naming of the strong interaction's associated charge as “color charge” originated in the work of Greenberg[6] and Han & Nambu[7] in the 1960s. They introduced red, green, and blue as the “color charged” states of quarks and antired, antigreen, and antiblue for antiquarks. According to this model, quarks only have a color charge, whereas antiquarks are defined by having an anticolor charge. In addition, particle systems must be color neutral, i.e. “white”. This includes mesons, composed of two quarks each, and baryons, made of three. In each case, the distribution of color charge must “balance out” among the quarks. For mesons, this can only be achieved if a color charged quark is bound to an antiquark with the respective anticolor charge. In the case of baryons, all three (anti)color charge states must be present, one per (anti)quark.

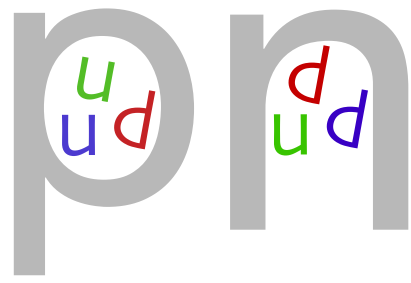


Fig.1. Typographic illustrations of a proton and a neutron.

When it comes to graphical representation of color charge, one is faced with a challenge, particularly when considering anticolor charge. Looking at standard physics textbooks, one finds that such graphical representations are almost completely neglected at university level. Instead, (anti)color charge is only explained through text and accompanying Feynman diagrams, if at all.

Nonetheless, there have been sporadic attempts to illustrate the abstract concept of anticolor charge. These can be found in selected textbooks and mainly in educational resources available online, in which the common solution is the use of the colors complementary to red, green, and blue (fig. 2). However, this relies on previously established optics knowledge, namely, additive color mixing. The overlapping of such content can be expected to be detrimental to learning.

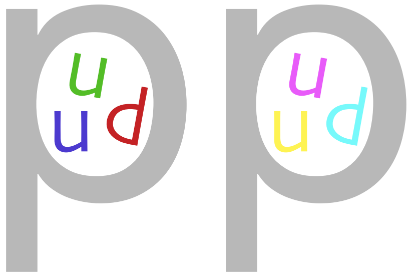


Fig. 2. Traditional illustrations of a proton and an antiproton, relying on readers' prior knowledge of the relevant color wheel. Obviously, using colors complementary to the quarks' red, green, and blue presents a challenge for identifying anticolor charges, e.g. cyan as antired.

Furthermore, the complementarity of colors must always be defined as a function of the color wheel being applied in a given model of color. This inevitably leads to problems, especially given the existence of multiple models of color, such as those of Newton[8] or Goethe[9]. The following quote, gathered during the evaluation of our proposal, illustrates this: *"Is not the complementary color of blue, orange, of green, red, and of yellow, pink?"* [student, age 17; translated by the authors from the original German]. To avoid the overlapping of this prerequisite knowledge from optics, our proposal represents anticolor charge using a stripe pattern (fig. 3).

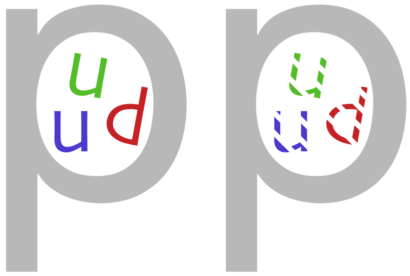


Fig. 3. Alternative illustrations of a proton and an antiproton, using a stripe pattern to denote anticolor charge. This representation clearly shows corresponding color and anticolor charge states while doing away with any requirement for prior knowledge of complementary colors.

Doing so preserves the original colors red, green, and blue for antiquarks, and it is only the stripe pattern that identifies the anticolor charged state and thus distinguishes quarks from antiquarks. By giving up complementary colors, this method of representation purposefully avoids the notion that particles with opposite color charge states cancel out in a "color neutral" way. While this idea is clearly elegant, it is problematic to introduce it at an early stage in the physics curriculum, because the metaphorical use of additive color mixing for the "cancelling out" of color charge states could promote the transfer of macroscopic properties into the world of quarks.

Therefore, we have decided to avoid any notion of color mixing within our reconstructed alternative proposal. Instead, the model character of physics is taken into account by emphasizing that the illustrations are only graphical representations, which thus cannot be attributed real-world characteristics. In this way, possible misconceptions regarding elementary particles' "appearance" should a priori be avoided, while unequivocally enabling the distinction between particles and antiparticles.

The final version of the alternative proposal presented here was tested on high school students (ages 16-17, n=78) and physics teachers (n=45). Each group was given a short written summary of color charge, including both forms of representation of anticolor charge. These were then evaluated using a questionnaire, composed of multiple-choice questions, where each correct anticolor charge was to be selected. Each question was asked when using complementary colors for antiquarks as well as when using the stripe pattern (fig. 4). Rather than probing understanding of the concept of color charge, the aim of the questionnaire was solely to evaluate the two graphical representations and how they appeal to students and teachers.

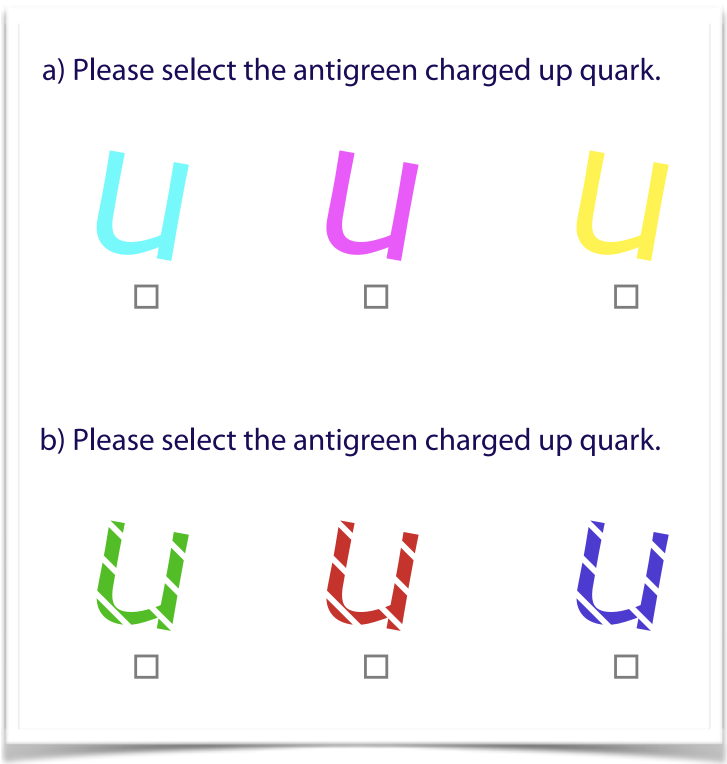


Fig. 4. Excerpt from the questionnaire used to evaluate the two different graphical representations of anticolor charge. The full questionnaire is available on request.

The testing of the alternative proposal proved to be very successful. Both students and teachers answered considerably more questions correctly when using the stripe pattern illustrations as opposed to complementary color illustrations. In addition, individuals' assessment of each method of illustration was gathered using binary questions regarding their understandability, informativeness, simplicity, and thinking time requirement. A clear majority of students (fig. 5) and teachers (fig. 6) judged the use of the stripe pattern to be easier to understand, more informative, and simpler, as underlined by the following quote from the evaluation: *"From the point of view of pure understanding, the complementary colors are logical, given that they illustrate an opposition. But, for me, the stripe version is simpler, because it is easier to recognize."* [student, age 16; translated by the authors from the original German].

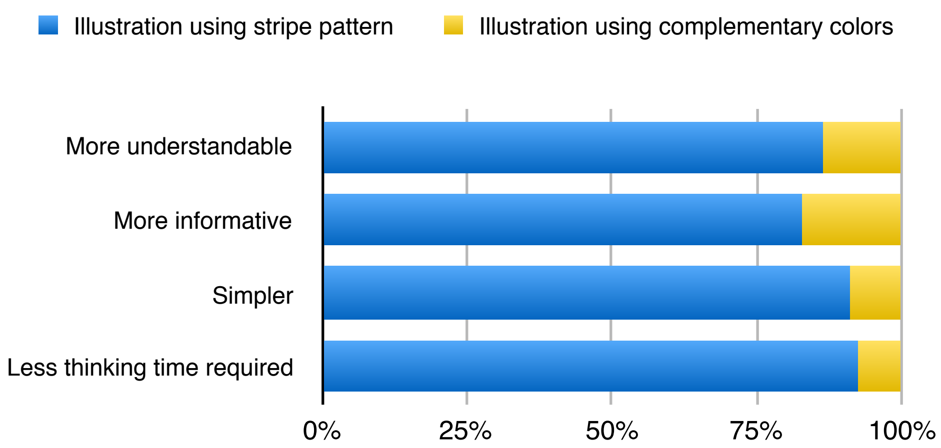


Fig. 5. Students' assessments of the two illustration methods (ages 16-17, n=78).

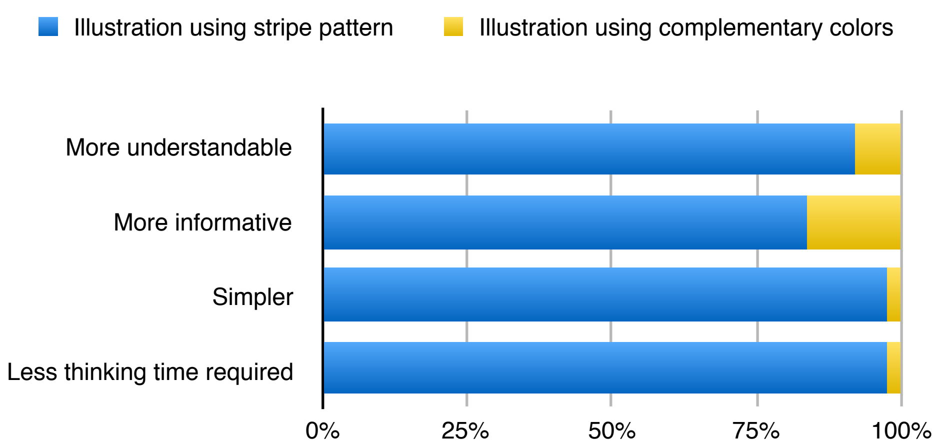


Fig. 6. Teachers' assessments of the two illustration methods (n=45).

Of particular note is the drastic reduction in the perceived amount of time needed to answer the questions. It is in this sense that our alternative proposal proves itself to be particularly helpful for learning and extremely promising for future applications. We therefore strongly recommend the use of a stripe pattern in representations of anticolor charge.

References

1. G. J. Wiener, S. M. Schmeling, and M. Hopf, "Can grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds," European Journal of Science and Mathematics Education 3(4), 313–322 (October 2015).
2. R. N. Carney and J. R. Levin, "Pictorial illustrations still improve students' learning from text," Educational Psychology Review 14, 5–26 (March 2002).
3. M. P. Cook, "Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles," Science Education 90, 1073–1091 (April 2006).
4. Design-Based Research Collective, "Design-based Research: an emerging paradigm for educational inquiry," Educational Researcher 32, 5–8 (January 2003).
5. W. Jung, "Probing acceptance, a technique for investigating learning difficulties," in R. Duit, F. Goldberg, and H. Niedderer (Eds.), Research in Physics Learning: Theoretical Issues and Empirical Studies (IPN, Kiel 1992), 278–295
6. O. W. Greenberg, "Spin and unitary-spin independence in a paraquark model of baryons and mesons," Phys. Rev. Lett. 13(20), 598–602 (November 1964)
7. M. Y. Han and Y. Nambu, "Three-triplet model with double SU(3) symmetry," Phys. Rev. 139(4B), 1006–1010 (August 1965)
8. I. Newton, The Optical Papers of Isaac Newton. Vol. 1: The Optical Lectures, 1670-1672 (U. Press, Cambridge, 1984)
9. J. W. Goethe, Theory of Colours (MIT Press, Cambridge, 1982)

D

Why not start with quarks? Teachers investigate a learning unit on the subatomic structure of matter with 12-year-olds

Gerfried J. Wiener[1,2], Sascha M. Schmeling[1] and Martin Hopf[2]
[1] CERN, European Organization for Nuclear Research, Genève 23, Switzerland
[2] Austrian Educational Competence Centre Physics, University of Vienna, Austria

Abstract:

This paper describes the second in a series of studies exploring the acceptance of the subatomic structure of matter by 12-year-olds. The studies focus on a novel learning unit introducing an atomic model from electrons down to quarks, which is aimed to be used at an early stage in the physics curriculum. Three features are fundamental to the unit's design: conveying the central role of models in physics, focusing on linguistic accuracy, and the use of novel typographic illustrations. An initial study saw the iterative redesign and retesting of the unit through 20 one-on-one interviews with grade-6 students. Findings indicated broad acceptance of most of the unit's key ideas, hinting that the unit's final version is plausible for 12-year-olds. Subsequently, the research was focused on the perspective of teachers to gain insight into their evaluation of the unit's adequacy and didactic feasibility. Therefore, the current follow-up study was designed to introduce the proposed unit to grade-6 students. This time, instead of education researchers, 13 teachers conducted a set of 17 one-on-one interviews. The teachers had been introduced to the learning unit and the research method during a professional development programme. Our analysis showed that the unit's key ideas were broadly accepted by all the students, who adequately used them for problem-solving during the one-on-one interviews. Overall, the documented results validate our findings from the initial study and indicate that the learning unit is adequate and well-suited for a broad evaluation in the classroom.

Keywords: Elementary particle physics, Learning unit, Design-based research, Probing acceptance

Introduction

The particulate nature of matter is considered to be a fundamental topic in science, and in particular in science education (Snir et al., 2003; Boz an Boz, 2008; Treagust et al., 2010; Vikström, 2014). However, studies of students' conceptions about the particulate nature of matter have repeatedly shown that middle and high school students have significant difficulties in establishing an adequate understanding of a particle model. Documented findings show that, in addition to conceptions based on everyday experience, students can develop misconceptions about the particulate nature of matter due to disadvantageous learning materials and interpretations potentially derived from these (de Posada, 1999; Ferk et al., 2003). This is often accompanied by erroneous illustrations in textbooks and over-drawn animations (Andersson, 1990; Adbo and Taber, 2009). Students' conceptions of matter are dominated by a continuum perspective, and the confrontation with a particle model frequently leads to a mixing and overlapping of continuum and discontinuum conceptions, whereby students try to integrate the novel particle model into the framework of the existing continuum model (Pfundt, 1981; Andersson, 19990; Renström et al., 1990; de Vos and Verdonk, 1996; Snir et al., 2003). Furthermore, when introducing a particle model, an automatic transfer of macroscopic aspects into the world of particles occurs, with students thinking of particles with faces and specific colours (Andersson, 1990; Renström et al., 1990; Boz, 2006; Ozmen, 2011; Özalp and Kahveci, 2015). Persistent misconceptions also include the ignoring of the permanent motion of particles and the negation of the existence of empty space (Novick and Nussbaum, 1981; Andersson, 1990; Renström et al., 1990; Harrison and Treagust, 1996).

Middle and high school students' documented difficulties with learning about particle models have prompted extensive theoretical and empirical work on how properly to introduce the particle model in the classroom (Talanquer, 2009). To contribute to the large body of research on the introduction of particle models, we have developed a learning unit on the subatomic structure of matter, which aims to introduce an atomic model from electrons down to quarks at an early stage in the physics curriculum (Wiener et al., 2015). The unit's design process was approached from a constructivist viewpoint by taking into account students' pre-existing cognitive structures (Duit, 1996; Duit and Treagust, 2003). The rationale of the teaching and learning material thus developed is to enable students to construct knowledge about the subatomic structure without prior physics knowledge.

The unit was developed within the framework of design-based research (Design-Based Research Collective, 2003) through a scheme of iterative retesting and redesign phases by using the technique of probing acceptance (Jung, 1992). This research method relies on the presentation and discussion of information during one-on-one interviews, with defined interview phases aiming to investigate learning processes. In total, we conducted 20 one-on-one interviews with grade-6 students during the development phase of the unit. We chose 12-year-olds because such students, having been exposed to very little physics education, can be considered to be novices, especially with respect to particle physics. The first testing phase with four students gave insight into the feasibility of the study and the unit's adequacy. As a result, the content of the unit was slightly revised and modified. The new version was then used for a set of eight one-on-one interviews with different students, which prompted an extensive redesign process. Finally, the revised unit was presented to another group of 12-year-olds through a set of eight one-on-one interviews, which led to the final version of the unit (Wiener et al., 2015).

This final version of the unit resulted in a description of the subatomic structure of matter, from which we prepared two different documents: one for students, and one to be used by teachers. The student document is intended to act as a stand-alone version of the unit, which can be used as learning material by grade-6 students. We then developed a set of documentation for teachers, which, in addition to the student document, contains an annotated version of the learning unit with highlighted key ideas and detailed explanations of their respective uses. The aim of the teacher document is to guide teachers when introducing subatomic particles into the classroom. As a next step, to evaluate the adequacy and didactic feasibility of the learning unit, we focused our research on the perspective of teachers. Therefore, the presented follow-up study was designed to have experienced physics teachers conduct another set of one-on-one interviews with grade-6 students. The teachers took part in a professional development programme, in which they were instructed about the content, aims, and goals of the learning unit and trained to use the technique of probing within the one-on-one interview. Given that these interviews and their outcomes are strongly tied to the content of the learning unit itself, we first give a brief overview about its main concepts, before explaining the rationale and methods of the follow-up study in detail.

The final version of the learning unit is based on ten key ideas, which are fundamental to the introduction of the subatomic structure of matter (Table I). These elementary steps were reconstructed to adequately introduce the topic to 12-year-olds at the beginning of their physics education. Peer validation was sought from education researchers and experts in particle physics, who found that these reconstructed elementary steps are suitable for such an introduction. As shown in Table I, the set of key ideas can be divided in two sections: key ideas I & II as general ideas, and key ideas III-X as particle model ideas, which illustrate the specific model of particle physics examined in the learning unit.

Table I. Key ideas of the learning unit on the subatomic structure of matter.

#	Key ideas
I	Matter is everything that can be touched, practically or theoretically.
II	Reality is described through models. For example the model of particle physics.
III	In the model of particle physics, there are atoms, which may combine to form compounds.
IV	In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.
V	In the nucleus-space, protons and neutrons are located.
VI	Protons and neutrons are particle systems, which are made of quarks.
VII	Quarks are indivisible. In this model, these are called elementary particles.
VIII	In the orbital-space, it is possible to find electrons.
IX	Electrons are indivisible. In this model, these are called elementary particles.
X	In this model, apart from particles, there is only empty space.

This model presents electrons and quarks as elementary particles, while stating that protons and neutrons are particle systems, which are made of quarks. In contrast to elementary particles the notion of empty space is introduced. Here, the model purposely omits the introduction of vacuum fluctuations, as documented students' conceptions show that the introduction of the concept of empty space is already a challenging task in the classroom. Hence, to avoid unnecessary confusion, this specific key idea (X) was formulated solely to introduce empty space as the counterpart to elementary particles. We consider this a suitable reconstruction for 12-year-olds, which can be expanded in a meaningful way at a later stage in the curriculum.

Furthermore, the model in question uses a simplified depiction of hadrons as combinations of only quarks. The rationale of this approach is to start with elementary particles and then – in the unit's second chapter – introduce fundamental interactions and their associated bosons. However, since the second chapter is beyond the scope of the study presented, we intentionally excluded every notion of fundamental interactions within the model examined in the learning unit. Nonetheless, we want to highlight the intended possibility of further building upon the learning unit to combine both elementary particles and fundamental interactions as the basics of the Standard Model of particle physics.

In addition to the ten key ideas, over the course of the initial study, three features turned out to be essential to the unit's design: conveying the central role of models in physics, focusing on linguistic accuracy, and the use of novel typographic illustrations. While the three features were originally introduced only to ensure comprehensiveness and coherence, they also seemed to have a major impact on avoiding triggering any of the documented misconceptions about the particulate nature of matter (Wiener et al., 2015). Below is a brief overview of the three features, highlighting their main objectives and how they are used in the final version of the learning unit.

Model-building has been considered to be a key process in the development of scientific knowledge, and it is argued that thinking in and with models is an essential component of appropriate science knowledge (Hestenes, 1987; Ornek, 2008; Chittleborough and Treagust, 2009; Justi, 2009). In the 1990s, both the National Science Education Standards and National Council of Teachers of Mathematics Standards as well as Benchmarks for Science Literacy recommended 'models and modelling' as the unifying theme for science and mathematics education in the US, which has been reflected in the development of a modelling instruction programme (Wells et al., 1995; Hestenes, 2003; Jackson et al., 2008). However, when looking at common practice, education research shows that neither modelling nor thinking in models are sufficiently developed by either students (Danusso et al., 2010; Grünkorn et al., 2011; Khan, 2011; Krell et al., 2012; Krell et al., 2015) or teachers (Gilbert, 2004; Koponen, 2007; Topcu, 2013). Bearing this in mind and addressing models as "effective pedagogical tools" for teaching scientific literacy (Halloun, 2007: 653), the proposed unit focuses strongly on conveying the central role of modelling in physics by emphasising its model aspect. We consider the chapter of elementary particles to be prototypical for a model-based approach to physics teaching and the phrase “With this model, we describe …” thus plays a big role in the unit. Furthermore, as the learning unit is intended to be used at the beginning of the physics curriculum, the ‘model of particle physics’ is introduced to serve both as a prominent example of a commonly-used model in physics, and as the overarching theme of the unit. Consequently, the notion of the model aspect is frequently repeated and emphasised in the final version of the unit's key ideas.

The second prominent aspect of the proposed unit is linguistic accuracy. The unit's design relies on careful definitions of key words and key phrases (Table II) to distinguish everyday language from a language of science, a distinction thought to be beneficial to learners (Brown and Ryoo, 2008; Rincke, 2011). For instance, when talking about particles, the proposed unit distinguishes between ‘particles’ and ‘particle systems’, which is reflected in key ideas VI, VII & IX. This means that only elementary particles, such as leptons and quarks, are denoted as particles. In contrast, hadrons count as particle systems, which are made of particles. However, particle systems can still be described as particle-like objects with particle-like properties. When introducing the atomic model, instead of 'the nucleus', the unit refers to 'the nucleus-space'. Doing so avoids the potential misconception that one can 'touch the nucleus', while unambiguously reinforcing the location aspect of the nucleus-space. The same idea is applied when the 'orbital-space' is introduced, emphasising the probability aspect of particles while avoiding any anachronistic descriptions of 'circular orbits' as a possible source of misconceptions (Karsten et al., 2011).

Table II. Overview of key words central to the unit and how they are used in phrasings.

Key word	Key phrasing
Description	Reality is described through models, e.g. the model of particle physics.
Particle	In the model of particle physics, electrons and quarks are elementary particles.
Particle System	Protons and neutrons are particle systems, which are made of quarks.
Nucleus-space	Protons and neutrons are located in the nucleus-space.
Orbital-space	In the orbital-space, it is possible to find electrons.

Conveying the probability aspect is also supported by the use of certain key phrasing. For instance, instead of introducing electrons that 'are' in the orbital-space, the unit’s key idea VIII emphasises that 'it is possible to find' electrons in the orbital-space, and thus avoids any notion of movement of electrons. While still a challenging step, this key idea serves as a basic concept and adequate reconstruction of probability distributions for 12-year-olds. Furthermore, it can be meaningfully linked to at a later stage in the physics curriculum, as it introduces the notion of orbitals early on. Another prominent example of linguistic accuracy is used for the unit's key idea I, which introduces the key word 'matter' through the defining property of 'touching'. Here, we discovered that it is necessary to specify that matter can be touched practically (for example, ordinary matter such as a table, the wall, or clothes) and theoretically (for example, the moon or *"a lion, because I think I can touch it, but I would never do it"*. [Quote from one of the grade-6 students taking part in the initial study; all quotes translated by the authors from the original German])

In addition to linguistic accuracy, the unit relies on carefully constructed illustrations, since education research shows that visual representations are essential for communicating ideas in the science classroom (Carney and Levin, 2002; Cook, 2006). However, due to the inconceivable size ratios in the field of particle physics, it is challenging to produce even adequate illustrations, let alone realistic ones. Therefore, to avoid triggering misconceptions, and bearing in mind the central role of models in physics, we propose a novel typographic approach. Herein, instead of misleading visualisations as spheres, particles are represented by their respective symbol. The same applies to particle systems, with their respective symbols enveloping those of their respective constituent elementary particles (Figure 1).

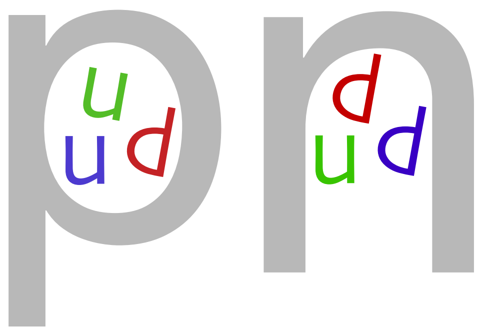


Figure 1. Typographic illustrations of a proton and a neutron.

These illustrations were iteratively tested and modified during the initial study. By the end of this process, we hardly encountered any transfer of macroscopic aspects onto the properties of subatomic objects. As the students' evaluations suggest this was mostly due to the revised typographic illustrations, we consider them to be an essential feature of the unit discussed. To further distinguish particles from particle systems, the underlying colour scheme has been thoroughly thought through: the symbols of particle systems are kept in grey, while particles' symbols are drawn in colour. For instance, the symbols of quarks are blue, green, and red. For our research, this serves the sole purpose to identify quarks as particles, but it sets up the notion of colour charge to be used when introducing fundamental interactions in future additions to the unit.

A typographic approach was also developed to illustrate the atomic model. This visualisation displays the names of both the nucleus-space and the orbital-space, the latter being made to look spherical (Figure 2). This gives the impression of a three-dimensional atomic model while reducing the possible misimpression of orbits or shells. As our unit is designed to be used at the beginning of the physics curriculum, this visualisation of the atomic model aims only to illustrate the distinction between the nucleus-space and the orbital-space introduced through key idea IV. However, it sets up the notion of different orbital shapes within the specific orbital-space, which must be introduced at a later stage in the physics curriculum. Furthermore, the visualisation requires a careful introduction by the teacher to explain its underlying model aspect, as it does not overcome the problem of a realistic size ratio, which can be demonstrated additionally using interactive animations, simulations, and animated movies.

Figure 2. Typographic illustration of the atomic model.

Research Question

The aforementioned initial study saw the iterative redesigning and retesting of the proposed learning unit through 20 one-on-one interviews with grade-6 students. Findings indicated broad acceptance of most key ideas, hinting that the unit's final version can indeed be understood by 12-year-olds. The most promising outcomes of the initial study are pure typographic illustrations. Not only were these accepted by all grade-6 students, but they also led to a reduction of known misconceptions. The illustrations turned out to be particularly helpful when it came to the distinction between particles and particle systems. The underlying colour pattern, supported by the careful wording, led to a clear distinction. Overall, the students who took part in the study displayed a greatly improved understanding of elementary particles, but occasionally showed avoidance when considering the role of models in physics (Wiener et al., 2015). However, these initial results only showed that students could make use of the unit's final version and accept its key ideas when it was introduced by the research team. Therefore, as a next step, we focused our research on the perspective of teachers, to gain insight into their evaluation of the unit's adequacy and didactic feasibility. Hence, the present article addresses this topic through the following research question:

> *How do grade-6 students evaluate and make use of the learning unit on the subatomic structure of matter when it is introduced by experienced teachers as opposed to education researchers?*

To evaluate the research question, a follow-up study was designed to investigate the proposed unit with grade-6 students. This time, the one-on-one interviews were led by experienced teachers, instead of by education researchers. The rationale of this approach was to compare their results with those of the initial study, to evaluate whether broad acceptance of the unit's key ideas can be achieved by teachers as well. Ultimately, this would demonstrate the unit's applicability and prepare the ground for a broad field study to facilitate its integration in the classroom.

Methods

Theoretical framework

To investigate the research question, the follow-up study was designed in accordance with our previous study (Wiener et al., 2015). Specifically, the study design was based on the technique of probing acceptance, which was developed by Jung (1992) to investigate learning processes. This research method relies on students' evaluation, paraphrasing, and adaptation of information presented during a one-on-one interview with defined student-centred interview phases. This particular setting is similar to a quasi-experimental one-on-one tutoring session with several tasks to be completed by the student during each interview phase. An advantage of this setting compared to conventional problem-centred interviews when seeking to identify resistances to elements of the information input is the reduction of short-term, ad hoc constructs (Wiesner and Wodzinski, 1996). Thus, we consider the technique of probing acceptance to be well-suited to develop adequate teaching and learning material. Depending on the definition of 'acceptance', however, the name of the research method can be misleading and therefore needs clarification. For the purpose of developing our unit, we focused the research method on evaluating the plausibility of our unit and whether it makes sense to students. Probing acceptance then means identifying elements of the instruction that students accept as useful and meaningful information, and which they can successfully adapt during the one-on-one interview.

Study design

We invited teachers to take part in education research to further evaluate the developed learning unit on the subatomic structure of matter from a teaching point of view. Hence, the study was implemented in a professional development programme for teachers, formed of two parts: a briefing session, and an intervention (Figure 3). The briefing session took place the day before the intervention and lasted about three hours. Its design was based on the assumption that all teachers participating in the study would have basic knowledge of particle physics. For our Austrian and German teachers, this turned out to be true, as all of them had received a university-level physics degree. Furthermore, all teachers participating in the study had vast experience in teaching basic concepts of particle physics, such as the subatomic model of matter. Since particle physics is part of both the Austrian and German physics curricula for grade 12, it did not come as a surprise that all teachers also showed considerable understanding of the Standard Model of particle physics during the briefing session. In addition, we noted that all teachers were very interested in learning about alternative instructional strategies regarding particle physics. However, we found that none of the teachers had deep knowledge of students' existing conceptions about particle physics. Hence, instead of updating the teachers' content knowledge, the briefing focused on instructing them about the key ideas of the novel learning unit and on helping them prepare for the intervention. The main idea of the briefing was to highlight the approach of the learning unit, by confronting teachers with documented students' conceptions of the particulate nature of matter. Therefore, a presentation on the concepts of the unit was given, which explained its development, gave an overview of students' documented conceptions of the structure of matter, and highlighted the unit's key ideas. This presentation took one hour and was followed by the introduction of the research method.

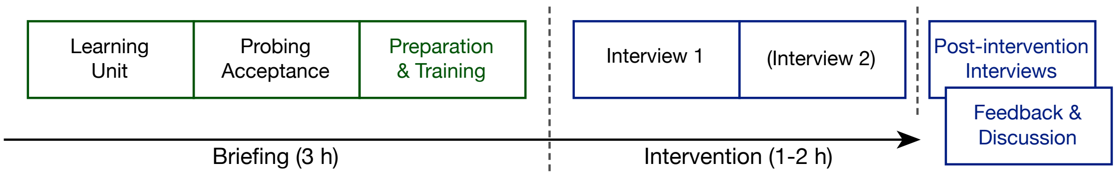


Figure 3. Design of the professional development programme with a briefing session followed by an intervention. During the intervention, each teacher conducted at least one one-on-one interview. Additionally, where time and planning allowed, teachers conducted a second one-on-one interview with a different grade-6 student immediately after their first interview. The intervention was concluded by post-intervention interviews, which were conducted individually with every teacher. In parallel, a feedback and discussion session enabled the remaining teachers to collectively reflect on their experiences and discuss main outcomes of their one-on-one interview(s).

During this next hour, the technique of probing acceptance was explained in detail by presenting representative examples from our previous study, which were then discussed among the teachers. Additionally, all teachers received their own research manuals, which we developed to enable teachers to conduct the one-on-one interview in accordance with the setting of the study and to ensure comparability among all teachers. It contained a set of anchor phrases to facilitate conducting the interview (Table III), a list of the ten key ideas, and the general timeframe of the interview. The research manual was discussed and worked through with the teachers to summarise the presentation of the technique of probing acceptance.

For the last hour of the briefing, it was the teachers' task to prepare themselves for the intervention, individually and collectively, by trying out the handling of the research manual and practicing specific parts of the one-on-one interviews with their colleagues. This part of the briefing session also included time for the preparation of the information input. The latter was left to the discretion of each teacher, making it possible to analyse how they each adapted elements of the learning unit. However, while all teachers were asked to prepare their own information input based on the unit's key ideas individually, teachers were encouraged to discuss their ideas with colleagues while preparing for their instruction during the intervention. To ensure comparability among the teachers and with the setting of our previous study, a general time constraint of 8-10 minutes was given for the duration of the information input, as well as the requirement for teachers to mention every key idea at least once during their instruction. Aside from these conditions, individual preparation, including optional use of digital visualisation (e.g., PowerPoint©, Prezi©), was then left to the discretion of each teacher.

Table III. Examples of anchor phrases in the research manual (translated from the original German).

Phase	Key phrases
Evaluation	• How does this sound to you? • Was the presented information easy to understand? • Can you recall any details that you could not understand at all? • What is your general impression of this information input?
Paraphrasing	• Can you tell me again – in your own words – everything you remember from what I have just presented to you? • How would you explain this to a friend?
Transfer example	• How does this example relate to what you just heard? • How do you picture this 'in reality'? • Can you think of another, different way of explaining this?

The intervention took place on the day following the briefing session and lasted between one and two hours. Every teacher conducted at least one one-on-one interview with a grade-6 student. Since the intervention took place at the students' and teachers' own school, during school time, we reserved one full hour for each interview session, which only lasted a maximum of 40 minutes. This planning allowed for a relaxed setting and minimised any potential influences due to time pressure or stress for both the teachers and the students. Where given constraints allowed, teachers were encouraged to conduct a second one-on-one interview with a different student during the second hour of the intervention. The rationale of this approach was to give teachers the opportunity to learn from their experience gained during the first interview and thus enable them to adapt their instructional strategies and research phrases for the second interview. While still limiting the whole Intervention to a feasible duration, this schedule allowed for a more detailed analysis regarding the applicability of the unit discussed. Following the intervention, we conducted semi-structured interviews individually with teachers immediately after their one-on-one interview(s). These post-intervention interviews lasted about 15 minutes and were designed to document the teachers' evaluation of both the learning unit and the novel research experience of conducting the one-on-one interview(s). In parallel, the other teachers were enabled to collectively reflect on their experiences with the preparation and execution of their one-on-one interviews. This feedback and discussion session concluded the whole intervention.

Setting of the one-on-one interview

Mirroring the original setting of the initial study, the one-on-one interviews were designed to comprise four interview phases with a maximum interview duration of 40 minutes (Figure 4). All teachers were guided through their one-on-one interview by the research manual. Key to the manual's design was the list of the ten key ideas, which had to be worked through by the teachers. During each interview phase, every key idea was to be addressed, discussed, and explained by the student, and then ticked off the list. Only once all key ideas had been discussed could the next interview phase begin. The research manual's checklist can be found in the appendix to this article.

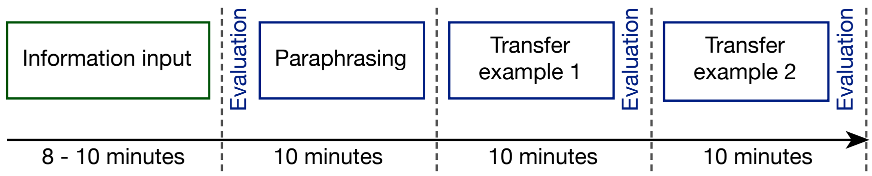


Figure 4. Setting and timeframe of the one-on-one interview.

Each one-on-one interview started with the presentation of the information input, which was individually prepared by each teacher. This was followed by a first evaluation of the student to document immediate feedback on the novel information. For example, they were asked by the teacher, "What do you think about this topic?" and, "Was there anything that you could not understand? Or anything that you really liked?". This evaluation also marked the beginning of the second interview phase. The teacher was then prompted by the manual to ask their student to paraphrase the presented information "in their own words". Here, the student was tasked with recalling as much of the initial information input as possible. This paraphrasing concluded the second interview phase. Next, as a first transfer example, it was the teacher's task to sprinkle some grains of salt across the table and ask the student to apply the new knowledge to this concrete example by solving the problem of whether salt can be identified as matter, and to explain what salt is made of. To conclude the third interview phase, this transfer example was followed by the student's second evaluation of the information input.

For the fourth and final phase of the one-on-one interview, it was the teacher's task to guide the student through the second transfer example. This example set the same challenge as the first transfer example, but instead of using grains of salt the teacher dripped some droplets of water on the table. It was then the student's task to explain whether water qualifies as matter and to further give a description of what it is made of. While both transfer examples focused on the same question, the rationale of this approach was to document the students' reasoning for the two different aggregate states, solid (salt) and liquid (water). For the final task, each student was asked to give a third and final evaluation of the information input, which concluded the fourth interview phase and marked the end point of the one-on-one interview.

Data collection and analysis

The follow-up study took place at one Austrian and four German middle schools (Gymnasium, age group: 10-18 years) with a total of 13 teachers (6 female & 7 male) and 17 Grade-6 students (10 female & 7 male), all of whom volunteered to participate in the study. Furthermore, all teachers received the support from their principals to participate in the study, enabling them to clear their schedules for four consecutive lessons, which allowed for a continuous and harmonic data collection. The group of teachers can be seen as a typical sample of Austrian and German middle school teachers. Every teacher had received an academic degree from a university with physics as their main subject. The individual teaching experience varied from 2 to 32 years and thus represents a diverse segment of the population of teachers. During the briefing session all teachers attributed a serious importance to the topic of particle physics and indicated that they felt comfortable discussing particle physics in the classroom.

All told, 17 one-on-one interviews were carried out in German, the native language of all participants. Nine teachers conducted one interview each. A further four teachers conducted two interviews each. To avoid conflicts of interest, most teachers conducted their one-on-one interview(s) with students who were usually taught by another teacher. All students, as well as their parents, gave their informed consent in written form. The participating students were randomly chosen by the teachers, the only limitation being that they be interested in trying out new teaching material. We view this attitude as necessary for the setting of the one-on-one interviews, which we consider to be feasibility studies, to ensure that the students are motivated and confident to take part in the different tasks during the respective interview phases. One might expect teachers to select only their best students to take part in the study. Therefore, we asked all teachers to characterise their student(s) during the post-intervention interviews. As foreseen, most teachers rated their student(s) to be among the best in the class. However, four teachers explicitly mentioned that, due to timing issues, this was not necessarily the case. Instead, they stated that they were lucky to find students, who would even be interested in taking part in the study. In addition, three of the four teachers, who conducted two interviews each, even mentioned that they purposely tried to select two students of different abilities. The motivation behind this approach was explained for example by one of the teachers as follows: *"I am always a bit sceptical about education research results, because most of these studies do not really show the real world. So I thought I would invite two students who would clearly talk a lot [laughs], but one of them is way smarter than the other."*

Based on our analysis, we believe it is safe to say that the students who participated in this study represent a diverse yet positive sample. However, since the students were mainly self-selected and showed considerable interest towards physics, care should be taken in generalising from our findings. Indeed, we want to add the cautionary note that our results are limited to the setting of our study and especially to the students who participated in it. Each one-on-one interview was videotaped using GoPro© cameras and transcribed word by word. To evaluate the findings, the method of qualitative content analysis (Mayring, 2010) was applied by carrying out a category-based analysis on all transcripts. This rule-based, traceable process is based on categories, which meet the research interest and fulfil the standard of reliability. For the evaluation of the transcripts we used the same three categories as in the initial study. Specifically, criteria were defined for each of the ten key ideas to rate statements as either fully adequate, partially adequate, or not adequate. The criteria were developed and peer-validated with other researchers in science education and explicitly formulated in a coding guide. This guide was then used to analyse and evaluate all transcripts. Thirty representative passages, one for each of the three categories of the ten key ideas, served as accompanying examples (Table IV). The complete coding guide can be found in the appendix to this article.

Table IV. Excerpt from the coding guide for key idea number one:

"Matter is everything that can be touched, practically or theoretically."

(A statement was rated as fully adequate if and only if all criteria were met.)

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention of matter • Explanation of touching as the defining property of matter • Distinction between touching something practically and theoretically	• Mention of matter • Transformation of touching as the defining property into the notion of the solid state of matter • Incomplete distinction between touching something practically and theoretically	• No mention of matter • No or wrong explanation of touching as the defining property of matter
Examples	*"Matter is everything. Well, everything I can touch. Even the air, because, theoretically, it is touching me all the time."*	*"Matter is all the stuff that is solid and compact."* *"Air and water are not matter because we cannot grab them."*	*"I don't know what matter is."* *"If I touch something it becomes matter."*

For each interview phase, the transcripts were analysed in accordance with the coding guide. Thus, each student's level of acceptance of the unit's key ideas could be identified for each interview phase separately, resulting in a documentation of the learning processes for the entire interview. The analysis was carried out on all transcripts by two independent researchers. Their inter-coder reliability resulted in a Cohen's Kappa of $\kappa = 0.86$, meeting the required standard of values higher than 0.8, which are characterised as an almost perfect agreement (Landis and Koch, 1977).

Results

The 17 one-on-one interviews led to very positive results. Our analysis showed that all teachers conducted their research session in accordance with the guidelines provided. Our analysis of the one-on-one interviews showed that the unit's key ideas were broadly accepted by all 12-year-olds and all key ideas were used to solve the problems presented by the transfer examples. Overall, the documented results validate our findings from the initial study (Wiener et al., 2015) and evaluate the learning unit to be adequate and well-suited for use by teachers.

In particular, when looking at the ten key ideas, the qualitative content analysis indicated broad acceptance of all key ideas throughout every interview phase. As all ten key ideas were addressed in each of the three interview phases (paraphrasing, transfer example 1, transfer example 2), each one-on-one interview generated 30 key idea mentions. For the 17 one-on-one interviews this resulted in a total of 510 codes. Aside from the vast majority of fully-adequate statements in accordance with the coding guide (494 out of 510; 96.9%), we documented only a few partially-adequate statements (16 out of 510; 3.1%) and no inadequate statement. Most partially adequate statements were given during the paraphrasing at the beginning of the interview but were transformed over time to fully adequate statements during the transfer examples. For instance, at the beginning of the one-on-one interview, key words such as 'nucleus-space' and 'orbital-space' were sometimes neglected by the student, but as the interview progressed, these were frequently used for their explanations. In most cases, all key ideas were accepted from the beginning and turned out to be persistent during the entire interview. Here we give a detailed overview of the evaluation of the ten key ideas, and then present the results from our analysis regarding the three features of the learning unit.

Key idea I, which acts as the starting point of the unit by introducing the key word 'matter' through the defining property of 'touching', was broadly accepted by all students. All teachers used key idea I to start their information input and most of them invited their student to brainstorm about different examples of matter. Here, all students immediately displayed understanding that solid objects are examples of matter, but occasionally a discussion with the teacher was required to transfer this knowledge onto liquids and gases. In these cases, all teachers used Socratic questioning, which always led to understanding by the student, for example as follows: *"Ah, I never thought of it this way. But of course, when the wind is flowing through my hair it is touching me. So, yes, air is also matter, because it touches us all the time."*

Key idea II, which introduces the key word 'model' by linking it to the distinction made in key idea I that matter can be touched either practically or theoretically, was mainly accepted by all students. Specifically, the fact that the unit introduces the 'model of particle physics' which aims to describe reality seemed to appeal to most of the students, as one student emphasised during the paraphrasing phase: *"Well, this model of particle physics, as it is called, is one way of describing what is going on in nature.*

But scientists still need to figure out whether this is really the best way to explain the world." However, during four interviews we noted partially-adequate statements regarding the model aspect of the unit. All four statements occurred during the paraphrasing phase of the one-on-one interview, and all four of them were rated partially-adequate in accordance with the coding guide due to the absence of the key word 'description', as is the case in the following example: *"In this model of particles, well, there are particles which make up atoms, and scientists conduct experiments to find even smaller particles of this model."*

Key idea III, which introduces the key word 'atom' to the previously mentioned model of particle physics, seemed to appeal greatly to all students. At some point during the information input, every teacher asked their student whether they know what atoms are. In most cases students claimed that they had already heard of atoms, and five students even mentioned that they associated *"something very small"* or *"something really tiny"* with atoms. Nonetheless, no student could give an adequate ad hoc explanation of atoms at the beginning of the one-on-one interview. As the interviews progressed, however, we only noted fully-adequate statements of the key idea during every interview phase.

Key idea IV, which features the crucial division of the atomic model into the nucleus-space and the orbital-space, also showed no difficulties for the students. Our analysis revealed that during the 17 one-on-one interviews, all criteria of the key idea were met by all students, who consistently made use of the division of the atomic model. Throughout all phases of the interviews we noted frequent use of the key words 'nucleus-space' and 'orbital-space', and only occasionally did we encounter mentions of *"the nucleus"* and *"the orbital"*.

Key idea V, which introduces the key words 'proton' and 'neutron' by specifying that protons and neutrons are located in the nucleus-space, turned out to be understandable for all students. During most interviews we only encountered correct statements with respect to the location of protons and neutrons in accordance with the coding guide. However, we also noted a few variations of the key word 'nucleus-space', for example *"proton-space"* and *"atomic-space"* (In the original German: *Atom-Bereich* instead of *Atomkern-Bereich*), which resulted in a total of eight partially-adequate ratings of the respective statement.

Key idea VI, which explains that protons and neutrons are made of quarks by introducing the key word ‘particle system’, was accepted and adequately used by all students. Our analysis revealed frequent use of the key word ‘particle system’ during all interview phases. Overall, the idea behind the key word 'particle system' seemed to appeal greatly to most of the students. For example, one student explained the connection between quarks, protons, and neutrons in their own words as follows: *“So, here in the nucleus-space [points to illustration] we have protons and neutrons. They are shown as ‘p’ and ’n’. And they are similar to particles, [ehm] but we describe them as particle systems, because they are made of smaller particles. [Hm] Yes, and these smaller particles have a very funny name, I think it was [ehm] something like [ehm] quark, yes, quarks.“* In addition to the frequent use of the key word ‘particle system’, our analysis showed that no student displayed the conception that quarks are inside of protons or neutrons. Instead, the key phrasing ‘protons and neutrons are made of quarks’ was frequently used when discussing the key idea, and no misconceptions concerning the description of protons or neutrons were documented.

Key idea VII, which introduces the key word ‘elementary particles’ and attributes it to quarks, was similarly well received. Not only did all students evaluate the novel term ‘quark’ to be funny and interesting but ten students even mentioned the indivisibility of elementary particles to be intriguing. In these cases our analysis showed that all teachers started to ask specific questions about the nature of elementary particles, trying to get more specific statements from their student. For example, consider the following statement made by one student: *“Well, I mean, I think it is really interesting that there are particles that are elementary particles. But, I mean, [ehm] ok, this is just this model, [ehm] maybe there are even smaller particles and we just do not know them yet.”* Furthermore, most students used the key word ‘elementary particle’ as the intended counterpart to particle systems, as shown by one student who asked the following question during the paraphrasing phase: *“Do I understand that correctly, there are only elementary particles and they can form to make particle systems? But if this is the case, there are only elementary particles and these [ehm] protons and neutrons are just groups of those quarks?”*

Key idea VIII, which introduces the key word ‘electron' by stating that it is possible to find electrons in the orbital-space, proved to be understandable to all students. Our analysis showed that all students used the key word ‘orbital-space' for their explanations and the key phrase 'it is possible to find' was used frequently by most of the students. Among all one-on-one interviews we only encountered the following partially-adequate rated statement about the location of electrons within the atomic model: *“And here, these electrons, they fly around in the orbital-space.”* Aside from this statement, all other statements focused on the intended probability aspect of electrons, in some cases even merged with the model aspect of the atomic model, as follows: *“In the orbital-space, here [points to illustration] this is where we could find electrons. So, we do not know where they are precisely, but according to the model [ehm] they have to be somewhere in this area [points to illustration].“* While the probability aspect of electrons remains a challenging concept, especially with regard to linguistic accuracy of its description, our analysis showed that all grade-6 students attributed electrons to the orbital-space which resulted in a clear distinction between the orbital-space and the nucleus-space, as intended by the learning unit.

Key idea IX, which attributes the key word 'elementary particle' to electrons in the same way as key idea VII did to quarks, led to similar understanding by the students. This did not come as a surprise, as our analysis showed that 12 out of the 13 teachers combined both key ideas at some point during their information input to summarise the notion of elementary particles. Therefore, we almost only noted fully-adequate statements in accordance with the coding guide. However, we did encounter three cases where the student’s explanation was lacking linguistic accuracy and the key word 'elementary particle' was either neglected or even transformed, for example into *“elementary particle system”*. In addition, we noted two cases where the similarity of the first syllable of the key words ‘electron’ and ‘elementary particle’ caused confusion, for example as follows: *“And these quarks, they are also called electrons. [Hm] No… no… not electrons, these are different particles, [ehm] el-em-entary particles, yes, elementary particles. They are indivisible. Quarks and electrons are indivisible and they are called elementary particles [laughs].”* Nonetheless, both statements were still rated as fully-adequate in line with the coding guide.

Key idea X, which introduces the key word ‘empty space' as the counterpart to particles, seemed to appeal greatly to most students. All students made use of the key word 'empty space' and showed no difficulties when using it during the different interview phases. In contrast to our previous study, we found that no student compared empty space to air. Overall, we only noted fully-adequate statements of the key idea.

Following the evaluation of the ten key ideas, we focused our analysis on the three features of the unit: conveying the central role of models in physics, focusing on linguistic accuracy, and the use of novel typographic illustrations. Here, we also took into account statements made during the respective evaluation of each interview phase. As all three features are strongly linked to the ten key ideas, we were pleased to find promising results here as well, as discussed below.

Model aspect

All 13 teachers successfully conveyed the model aspect of particle physics throughout their one-on-one interviews. Many grade-6 students adopted the proposed viewpoint of a model as a current description of nature and made frequent use of the key word 'description' (In the original German: *Beschreibung*) throughout the sessions. For example, one student explained their take on the theory behind the model-based approach of physics as follows: *"This is how we describe things right now. But if we continue to do research, it is possible that we will have to change it again."* Even when asked to explain the subatomic structure of salt grains and water droplets during the transfer examples, most 12-year-olds automatically mentioned the model of particle physics and referred to the discussed key ideas.

This was also the case when it came to the conceptions known to be especially difficult, such as the indivisibility of elementary particles and the notion of empty space. During every interview phase, many teachers consistently focused on the fact that on a subatomic scale, everything is made of elementary particles. This was broadly accepted by all students and widely used for their explanations of the subatomic structure of salt and water during the transfer examples. Most of the students' descriptions were even merged with key idea number ten, which introduces empty space as the counterpart to elementary particles, as put so elegantly by a student: *"Since everything is made of electrons, up-quarks, and down-quarks, this has to be the case here as well. If this [salt] does not consist of these three things, there would be nothing."* When asked to evaluate the same fact, another student reacted similarly: *"That is absolutely clear to me, because what else would it be made of?"* In general, to our surprise, the abstract concept of empty space was fairly well accepted and seemed to appeal to most students, as one student formulated during their final evaluation: *"Well, I really liked it, because I did not know anything about it. In particular, [I did not know anything] about this empty space and that there are only a few electrons in the* *orbital-space. This is really fascinating."* However, some students felt puzzled by the indivisibility of elementary particles and the notion of empty space, where their acceptance and evaluation differed. Here, the teachers' focus on the unit's model aspect played a key role, since the grade-6 students' questions were mostly expressed from a model-based perspective, as follows: *"It is just, as I said, very hard to imagine. But one can orientate oneself based on the model, which helps a lot."*

Linguistic accuracy

In addition to the model aspect of the learning unit we paid particular attention to linguistic accuracy, the unit's second feature. Of specific interest was the teachers' use of key words, such as 'orbital-space' and 'nucleus-space', and how it affected and motivated their respective grade-6 students' use of them. Our findings show that seven teachers used all key words consistently throughout their sessions, which had a considerable impact on their student's paraphrasing of the information input. These students repeatedly and consistently used key words as originally introduced during their respective information inputs. In contrast, during the sessions of the other six teachers, both the teachers and the students transformed key words or neglected some of them. Salient transformations on both sides included *"the orbital"* and *"the nucleus"*, which may merely have been used as practical shorthand forms. On the students' side, however, we also documented transformations such as *"the nucleus-orbital"* and *"elementary particle systems"*, which hint at confusion resulting from the lack of linguistic accuracy in these interviews.

When comparing one-on-one interviews of different degrees of linguistic accuracy, our analysis showed no differences regarding the students' acceptance of the unit's key ideas. However, we found connections between the extent to which key words and phrases were used during the one-on-one interviews and the students' attitude towards the learning unit. In interviews with a high degree of linguistic accuracy, our analysis showed that the evaluation of the unit was focused entirely on the content of the subatomic structure of matter. We found that the students still rated aspects of the unit's key ideas to be abstract, but, having no obstructive linguistic elements to discuss, their overall evaluation of the proposed unit was notably positive.

During interviews with a lack of linguistic clarity, on the other hand, the confusion regarding novel terms had a considerable impact on the students' evaluation. Here, their feedback was hugely directed at the linguistic difficulties and only little notice was given regarding the content of the unit. Their evaluations were less profound than those in the aforementioned interviews and only rarely reached a meta-level at which the content itself was evaluated. Our analysis indicates that, while not showing any impact on the students' acceptance of the unit's key ideas, the degree of linguistic clarity drastically influenced the student's evaluation of the proposed unit. Only when teachers followed the guidelines regarding linguistic accuracy by consistently using the unit's key words and phrases were students able to give their evaluation from a cognizant point of view. This highlights the fact that clear-cut language is indeed needed to offer valuable teaching material.

Typographic illustrations

Twelve teachers delivered their information input through a talk, accompanied by typographic illustrations printed out on paper, while one teacher had even prepared a presentation, which was shown on a laptop. During the respective interview phases, all teachers made frequent use of the illustrations and referred back to them when responding to questions from the student. All students evaluated the typographic illustrations to be understandable, and their use proved to be comprehensible and adequate. As in our initial study, we did not encounter any 'everyday' descriptions of particles, and no transfer of macroscopic aspects onto the properties of subatomic objects was documented.

Furthermore, the issue of how to properly illustrate particles and particle systems was addressed by several teachers during their interviews. One teacher, for example, chose to focus on the infamous illustration of a glass of water filled with H2O molecules floating around in the water. This illustration, which Andersson (1990) used to describe the impact of erroneous illustrations, was presented to the teachers to justify the use of typographic illustrations. The teacher in question used the illustration at the end of their session as the starting point of the final evaluation. The 12-year-old evaluated it as follows: *"Well, somehow this line [water level] up here is also strange, because theoretically everything is made of atoms. So, all the water would have to consist of particles. Actually, the glass… this is probably not so important… but the glass would have to be made of particles as well."*

Conclusions

The explicit motivation for this work was to have instructed teachers introduce the subatomic structure of matter to 12-year-olds by using the key ideas and typographic illustration of our proposed learning unit. The presented findings strongly support the results from our initial study (Wiener et al., 2015). Once again, the learning unit, which introduces the subatomic structure of matter, was broadly accepted by 12-year-olds during the one-on-one interviews. Although the evaluated information inputs were prepared and presented individually by experienced teachers in different ways, all of them achieved comparable results and acceptance of key ideas by the grade-6 students. This supports our assumption that the presented key ideas (Table I) and typographic illustrations are well-suited and adequate for an evaluation in the classroom. However, there are specific details that need to be addressed.

First, key idea II, which focuses on the model-based description of nature, appealed greatly to all the teachers. Thus, the central role of models in physics received numerous mentions throughout every interview. Our findings suggest that this is mainly due to the extensive emphasis placed on the model aspect throughout the unit's key ideas. This is backed up by feedback from the teachers, who, despite being well-trained and qualified physics teachers, evaluated this constant emphasis to be a helpful reminder. Indeed, during the post-intervention interviews, most teachers mentioned that this was helpful during their one-on-one interview(s), and that they would seek to apply it to their own classroom contexts. We consider this to be a very promising detail of our study, as education research shows that science teachers today have often not been explicitly educated and trained in the theme of models and modelling in science (Gilbert, 2004). In turn, the numerous mentions and explanations were highly appreciated by all students, who consistently displayed an epistemological understanding of the model aspect of physics throughout the interviews. This came as a surprise, as our initial study showed that most students accepted a model only as a physical copy of reality. The model itself was then never seriously questioned, which, according to the pioneering study of Grosslight et al. (1991), who divided students' understanding of the 'nature of model' into three different levels, correlated only with a Level 1 understanding. However, compared to our previous findings, the teachers managed to convey a greatly improved model-based description of nature. All students showed acceptance of the viewpoint that a model is created to test ideas, while still accepting this model's potential for change, which corresponds to a Level 3 understanding.

When trying to trace back the reason for this improvement in understanding, we face limitations in our study. Clearly, the teachers' ongoing emphasis of the central role of models in physics had a huge impact on the one-on-one interviews and how the students perceived and evaluated the presented information input. However, the teachers' achievement in doing so does not necessarily relate to the learning unit or the research manual developed here. While we are tempted to do so, we are unable to link the grade-6 students' improved understanding of model-based thinking to the developed unit alone, as our data do not contain any information about the teachers' experience with model-based teaching. Here, we are lacking the possibility to compare the teachers' performance during the one-on-one interviews to their daily teaching practice. Therefore, while having noted strong hints, for our future research, the question remains as to whether our particle physics unit sufficiently supports a model-based approach to teaching physics.

Second, regarding documented students conceptions about the particulate nature of matter, we hardly encountered any persistent misconceptions at any point during the individual one-on-one interviews. By and large, the indivisibility of elementary particles and the notion of empty space were rated as abstract, which did not come as a surprise, as these conceptions are known to be difficult for students (Novick and Nussbaum, 1981; Andersson, 1990; Renström et al., 1990; Harrison and Treagust, 1996; Boz and Boz, 2008). But, in accordance with our previous findings, we did not document any 'everyday' descriptions of particles or any transfer of macroscopic aspects onto their properties. The students' evaluations suggest this is again mostly due to the typographic illustrations, which subtly underline the unit's model aspect, while preventing any macroscopic attributions onto particles. All students evaluated the typographic illustrations to be understandable, and their use proved to be comprehensible and adequate. We therefore suggest typographic illustrations of particles and particle systems as a suitable solution for a model-based approach of teaching particle physics.

Third, we want to stress the fact that while our results are satisfying, there remain aspects of the learning unit that we believe could be further developed and investigated. When looking at the unit's key ideas IV and VIII, for instance, we see the potential of refining both the notion of electrons and the introduction of the orbital-space. For the purpose of our research, these key ideas served as an adequately reconstructed explanation to be used when introducing the theory of orbitals to 12-year-olds. Our results showed that grade-6 students could make use of the key ideas in their current form. However, without further clarification of their simplicity and an additional refinement at a later stage in the physics curriculum, these key ideas carry the risk of inducing misconceptions about the nature of atoms. This goes hand in hand with the limitations of the typographic illustration of the atomic model (Figure 2). Its intended use was to distinguish the orbital-space from the nucleus-space. Hence, within the learning unit the orbital-space is introduced in spherical form. However, without the introduction of other possible configurations of the orbital-space, which, for instance, can be elegantly demonstrated via animations and interactive visualisations, this approach will most certainly show shortcomings at a later stage in the physics curriculum. Therefore, we see the potential of further modifications through future implementations of the learning unit with older high school students.

Fourth, the young age of our student sample deserves some comment. As mentioned above, we have chosen 12-year-olds for our studies, as such students, having only had very little physics education, can be considered as novices, especially with respect to particle physics. Thus, for our one-on-one interviews, the minimised pre-existence of instructional misconceptions enabled us to trace back possible documented students' conceptions to the information input discussed. In addition, our results support the hypotheses of Nakhleh & Samarapungavan (1999) and Johnson & Papageorgiou (2010), who mention the possibility of introducing particle theory at an earlier, rather than later, stage in the curriculum. The feasibility of such a successful application on the classroom level, however, requires much further research. Ideally, our learning unit will support preparation of a broad field study to shed light on the applicability and usefulness of introducing subatomic particles at the beginning of physics education.

Last, we want to present the research goal for our future work derived from the study presented above. Our analysis revealed that preparing experienced teachers to successfully conduct one-on-one interviews in accordance with our guidelines also enabled them to observe the learning processes of each of their respective grade-6 students. During the post-intervention interviews, which were conducted immediately after the one-on-one interview(s) to document the teachers' evaluation of the learning unit, all teachers mentioned this very detail to be interesting and informative. In particular, being able to observe how their information input affected their student's performance during the interview phases appealed greatly to the teachers. As education research shows that theory does not necessarily help teachers apply teaching strategies that work on a daily basis in the classroom (Appleton, 2003; Vikström, 2014), we consider the setting of one-on-one interviews to be very promising for bridging this research-teaching gap. Indeed, Nuthall (2004) argues that this effort requires continuous, detailed data on the experience of individual students. Therefore, future research will concentrate on the development and improvement of the technique of probing acceptance as a form of teacher training with respect to teachers' knowledge about students' conceptions and instructional strategies.

References

Adbo, K., and Taber, K. S., (**2009**). Learners' mental models of the particle nature of matter: a study of 16-year-old Swedish science students. *International Journal of Science Education*, 31(6), 757-786.

Andersson, B., (**1990**). Pupils' conceptions of matter and its transformations (age 12-16). *Studies in Science Education*, 18, 53-85.

Appleton, K., (**2003**). How do beginning primary school teachers cope with science? Toward an understanding of science teaching practice. *Research in Science Education*, 33, 1-25.

Boz, Y., (**2006**). Turkish pupils' conceptions of the particulate nature of matter. *Journal of Science Education and Technology*, 15, 203-213.

Boz, N., and Boz, Y., (**2008**). A qualitative case study of prospective chemistry teachers' knowledge about instructional strategies: introducing particulate theory. *Journal of Science Teacher Education*, 19, 135-156.

Brown, B. A., and Ryoo, K., (**2008**). Teaching science as a language: a "content-first" approach to science teaching. *Journal of Research in Science Teaching*, 45(5), 529-553.

Carney, R. N., and Levin, J. R., (**2002**). Pictorial illustrations still improve students' learning from text. *Educational Psychology Review*, 14, 5-26.

Chittleborough, G. D., and Treagust, D. F., (**2009**). Why models are advantageous to learning science. *educación química*, 12-17.

Cook, M. P., (**2006**). Visual representations in science education: the influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education*, 90, 1073-1091.

Danusso, L., Testa, I., and Vicentini, M., (**2010**). Improving prospective teachers' knowledge about scientific models and modelling: design and evaluation of a teacher education intervention. *International Journal of Science Education*, 32(7), 871-905.

Design-Based Research Collective, (**2003**). Design-based research: an emerging paradigm for educational inquiry. *Educational Researcher*, 32, 5-8.

Duit, R., (**1996**). The constructivist view in science education – what it has to offer and what should not be expected from it. *Investigações em Ensino de Ciências*, 1, 40-75.

Duit, R., and Treagust, D. F., (**2003**). Conceptual change: a powerful framework for improving science teaching and learning. *International Journal of Science Education*, 25(6), 671–688.

Ferk, V., Vrtacnik, M., Blejec, A., and Gril, A., (**2003**). Students' understanding of molecular structure representations. *International Journal of Science Education*, 25, 1227-1245.

Gilbert, J., (**2004**). Models and modelling: routes to more authentic science education. *International Journal of Science and Mathematics Education*, 2, 115–130.

Grosslight, L., Unger, C., Jay, E., and Smith, C., (**1991**). Understanding models and their use in science: conceptions of middle and high school students and experts. *Journal of Research in Science Teaching*, 28, 799–822.

Grünkorn, J., zu Belzen, A. U., and Krüger, D., (**2011**). Design and test of open-ended tasks to evaluate a theoretical structure of model competence. In A. Yarden & G. Carvalho (Eds.), Authenticity in biology education. Benefits and challenges (pp. 53–65). Braga: CIEC, Universidade do Minho.

Halloun, I. A., (**2007**). Mediated modeling in science education. *Science & Education*, 16, 653-697.

Harrison, A. G., and Treagust, D. F., (**1996**). Secondary students' mental models of atoms and molecules: implications for teaching chemistry. *Science Education*, 80, 509-534.

Hestenes, D., (**1987**). Toward a modeling theory of physics instruction. *American Journal of Physics*, 55(5), 440-454.

Hestenes, D., (**2003**). Oersted medal lecture 2002: reforming the mathematical language of physics. *American Journal of Physics*, 71(2), 104-121.

Jackson, J., Dukerich, L., and Hestenes, D., (**2008**). Modeling instruction: an effective model for science education. *Science Educator*, 17(1), 10-17.

Johnson, P., and Papageorgiou, G., (**2010**). Rethinking the introduction of particle theory: a substance-based framework. *Journal of Research in Science Teaching*, 47(2), 130-150.

Jung, W., (**1992**). Probing acceptance, a technique for investigating learning difficulties. In R. Duit, F. Goldberg & H. Niedderer (Eds.), Research in physics learning: Theoretical issues and empirical studies (pp. 278-295). Kiel: IPN.

Justi, R., (**2009**). Learning how to model in science classroom: key teacher's role in supporting the development of students' modelling skills. *educación química*, 32-40.

Karsten, F., Koch, T., Kranzinger, F., and Theis, M., (**2011**). Planeten, Wolken oder schwarze Kisten? Wie können wir Atome in der Schule didaktisch sinnvoll beschreiben? *Physik Journal*, 10, 39-42.

Khan, S., (**2011**). What's missing in model-based teaching. *Journal of Science Teacher Education*, 22, 535-560.

Koponen, I. T., (**2007**). Models and modelling in physics education: a critical re-analysis of philosophical underpinnings and suggestions for revisions. *Science & Education*, 16, 751-773.

Krell, M., zu Belzen, A. U., and Krüger, D., (**2012**). Students' understanding of the purpose of models in different biological contexts. *International Journal of Biology Education*, 2(2), 1-34.

Krell, M., Reinisch, B., and Krüger, D., (**2015**). Analyzing students' understanding of models and modeling referring to the disciplines biology, chemistry, and physics. *Research in Science Education*, 45, 367-393.

Landis, J. R., and Koch, G. G., (**1977**). The measurement of observer agreement for categorical data. *Biometric*, 33, 159-174.

Mayring, P., (**2010**). Qualitative Inhaltsanalyse. In G. Mey & K. Mruck (Eds.), Handbuch Qualitative Forschung in der Psychologie (pp. 601-613). Wiesbaden: Springer.

Nakhleh, M. B., and Samarapungavan, A., (**1999**). Elementary school children's beliefs about matter. *Journal of Research in Science Teaching*, 36, 777-805.

Novick, S., and Nussbaum, J., (**1981**). Pupils' understanding of the particulate nature of matter: a cross-age study. *Science Education*, 65, 187-19.

Nuthall, G., (**2004**). Relating classroom teaching to student learning: a critical analysis of why research has failed to bridge the theory-practice gap. *Harvard Educational Review*, 74(3), 273-306.

Ornek, F., (**2008**). Models in science education: applications of models in learning and teaching science. *International Journal of Environmental & Science Education*, 3(2), 35-45.

Özalp, D., and Kahveci, A., (**2015**). Diagnostic assessment of student misconceptions about the particulate nature of matter from ontological perspective. *Chemistry Education Research and Practice*, 16, 619-639.

Ozmen, H., (**2011**). Turkish primary students' conceptions about the particulate nature of matter. *International Journal of Environmental & Science Education*, 6, 99-121.

Pfundt, H., (**1981**). Das Atom - Letztes Teilungsstück oder erster Aufbaustein? Zu den Vorstellungen, die sich Schüler vom Aufbau der Stoffe machen. *chimica didactica*, 7, 75-94.

de Posada, J. M., (**1999**). The presentation of metallic bonding in high school science textbooks during three decades: science educational reforms and substantive changes of tendencies. *Science Education*, 83, 423-447.

Renström, L., Andersson, B., and Marton, F., (**1990**). Students' conceptions of matter. *Journal of Educational Psychology*, 82(3), 555-569.

Rincke, K., (**2011**). It's rather like learning a language. Development of talk and conceptual understanding in mechanics lessons. *International Journal of Science Education*, 11(2), 229-258.

Snir, J., Smith, C. L., and Raz, G., (**2003**). Linking phenomena with competing underlying models: a software tool for introducing students to the particulate model of matter. *Science Education*, 87, 794-830.

Talanquer, V., (**2009**). On cognitive constraints and learning progressions: the case of "structure of matter". *International Journal of Science Education*, 31(15), 2123-2136.

Topcu, M. S., (**2013**). Preservice teachers' epistemological beliefs in physics, chemistry, and biology: a mixed study. *International Journal of Science and Mathematics Education*, 11, 433-458.

Treagust, D. F., Chandrasegaran, A. L., Crowley, J., Yung, B. H. W., Cheong, I. P.-A., and Othman, J., (**2010**). Evaluating students' understanding of kinetic particle theory concepts relating to the states of matter, changes of state and diffusion: a cross-national study. *International Journal of Science and Mathematics Education*, 8, 141-164.

Vikström, A., (**2014**). What makes the difference? Teachers explore what must be taught and what must be learned in order to understand the particulate character of matter. *Journal of Science Teacher Education*, 25, 709-727.

de Vos, W., and Verdonk, A. H., (**1996**). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching*, 33, 657-664.

Wells, M., Hestenes, D., and Swackhamer, G., (**1995**). A modeling method for high school physics instruction. *American Journal of Physics*, 63(7), 606-619.

Wiener, G. J., Schmeling, S. M., and Hopf, M., (**2015**). Can grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education*, 3(4), 313-322.

Wiesner, H., and Wodzinski, R., (**1996**). Akzeptanzbefragungen als Methode zur Untersuchung von Lernschwierigkeiten und Lernverläufen. *Lernen in den Naturwissenschaften*, 250-274.

Appendix

Coding guide

Table A1. Coding guide with criteria and examples for key idea number one: "Matter is everything that can be touched, practically or theoretically."

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention of matter • Explanation of touching as the defining property of matter • Distinction between touching something practically and theoretically	• Mention of matter • Transformation of touching as the defining property into the notion of the solid state of matter • Incomplete distinction between touching something practically and theoretically	• No mention of matter • No or wrong explanation of touching as the defining property of matter
Examples	*"Matter is everything. Well, everything I can touch. Even the air, because, theoretically, it is touching me all the time."*	*"Matter is all the stuff that is solid and compact."* *"Air and water are not matter because we cannot grab them."*	*"I don't know what matter is."* *"If I touch something it becomes matter."*

Table A2. Coding guide with criteria and examples for key idea number two: *"Reality is described through models. For example the model of particle physics."*

	Fully adequate	Partially adequate	Not adequate
Criteria	• Explanation of the use of models in science • Use of the key word 'description' • Mention of the model of particle physics	• Explanation of the use of models in science • Mention of the model of particle physics • No or wrong use of the key word 'description'	• No mention of modelling • No or wrong explanation of the use of models
Examples	*"We have no idea what reality is, but we have to describe it somehow. That is why we need models, for example the model of particles in particle physics."*	*"A model tells us how reality works."* *"In particle physics the particles are the models we use."*	*"I did not understand what this [modelling] is about."* *"I think scientists conduct experiments, but I do not know why they need models for that."*

Table A3. Coding guide with criteria and examples for key idea number three: "In this model, there are atoms, which may combine to form compounds"

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention of atoms • Explanation that atoms may combine to form compounds • Acknowledgment that atoms are part of the model of particle physics	• Mention of atoms • No or wrong explanation that atoms may combine to form compounds	• No mention of atoms • No or wrong explanation that atoms may combine to form compounds
Examples	*"So, in the model of particle physics, scientists invented atoms. Everything is made of atoms because they can connect with each other."*	*"The model of particle physics uses atoms to describe what everything is made of."*	*"I don't know atoms"* *"An atom can swallow other atoms and then it gets bigger and bigger. This is how matter is created."*

Table A4. Coding guide with criteria and examples for key idea number four: *"In this model, atoms are divided into the nucleus-space and the orbital-space."*

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention that atoms are divided into two areas • Mention of the nucleus-space and the orbital-space • Acknowledgment that this division is part of the model of particle physics	• Mention that atoms are divided into two areas • No or wrong mention of the nucleus-space and the orbital-space	• Wrong explanation of the division within the atomic model • No or wrong mention of the nucleus-space and the orbital-space
Examples	*"This atom can be divided into the nucleus-space, which is super, and then there is the orbital-space around it, which is super big. But this is just how we picture it with the model."*	*"An atom has some kind of a substructure. There are these two areas. But I forgot their names."*	*"[hm] I don't really know, no, I don't think these atoms can be divided."*

Table A5. Coding guide with criteria and examples for key idea number five:
“In the nucleus-space, protons and neutrons are located."

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention of protons and neutrons • Explanation of the nucleus-space as the location of protons and neutrons	• Mention of protons and neutrons • No or wrong explanation of the nucleus-space as the location of protons and neutrons	• No mention of protons and neutrons • No or wrong explanation of the nucleus-space as the location of protons and neutrons
Examples	*“And as I said, there is the nucleus-space, which is just the location in the middle. This is were we have the protons and the neutrons.”*	*"In an atom, there are even smaller things. For example, these, which are called [ehm] protons and [ehm] neutrons. They are somewhere in it.”*	*"I think there was something special about this nucleus-orbital, but I can’t remember it anymore.”*

Table A6. Coding guide with criteria and examples for key idea number six:
“Protons and neutrons are particle systems, which are made of quarks."

	Fully adequate	Partially adequate	Not adequate
Criteria	• Use of the key word ‘particle system’ • Mention that protons and neutrons are particle systems • Explanation that particle systems are made of quarks	• Use of the key word ‘particle system’ • Mention that protons and neutrons are particle systems • No or wrong explanation that particle systems are made of quarks	• No or wrong mention that protons and neutrons are particle systems • No or wrong explanation that particle systems are made of quarks
Examples	*“Protons, [ehm], and neutrons also, are not really particles. They are some kind of particle system, because there are these [ehm] quarks, yes, quarks, and three of these make one proton or neutron.”*	*“So, these particles, they are called proton and neutron. But they only look like particles. There are smaller particles because they [proton and neutron] are particle systems. But I forgot their names. I only know that it was a funny name.”*	*"In the nucleus-space we have protons and neutrons. And they are the smallest particles that we know of.”* *“These protons and neutrons can combine and then they form particle systems which are called [ehm] quark.”*

Table A7. Coding guide with criteria and examples for key idea number seven: *"Quarks are indivisible. In this model, these are called elementary particles."*

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention that quarks are indivisible • Use of the key word 'elementary particle' • Acknowledgment that elementary particles are part of the model of particle physics	• Mention that quarks are indivisible • No or wrong use of the key word 'elementary particle'	• No or wrong mention that quarks are indivisible • No or wrong use of the key word 'elementary particle'
Examples	*"Quarks are the smallest particles that we have found so far. We think they are indivisible, but this can change if we have to change the model. We call them elementary particles."*	*"Quarks are the smallest particles. And they have a second special name, but I think I forgot it. Something with e [hm]."*	*"Quarks are made of protons and sometimes also neutrons."* *"Quarks are also called electron particles"*

Table A8. Coding guide with criteria and examples for key idea number eight: *"In the orbital-space, it is possible to find electrons."*

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention of electrons • Explanation of the orbital-space as the location of electrons • Use of the key phrase 'it is possible to find'	• Mention of electrons • No or wrong explanation of the orbital-space as the location of electrons • No or wrong use of the key phrase 'it is possible to find'	• No or wrong mention of electrons • No or wrong explanation of the orbital-space as the location of electrons
Examples	*"So, and then we have the big orbital-space around the nucleus-space. This big area is made of nothing, it is just the space where it would be possible to find electrons. But we don't know where exactly they are."*	*"Aside from protons and neutrons, well and quarks also, there are electrons around."* *"Electrons are in the orbital-space."*	*"Next to the protons, in the nucleus-space, there are also electrons."*

Table A9. Coding guide with criteria and examples for key idea number nine: *"Electrons are indivisible. In this model, these are called elementary particles."*

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention that electrons are indivisible • Use of the key word 'elementary particle' • Acknowledgment that elementary particles are part of the model of particle physics	• Mention that electrons are indivisible • No or wrong use of the key word 'elementary particle'	• No or wrong mention that electrons are indivisible • No or wrong use of the key word 'elementary particle'
Examples	*"Electrons are, as far as we know, indivisible. Same as the quarks. That's why, for now, we call them elementary as well. But this is just a model."*	*"Electrons are indivisible, we can't split them anymore."*	*"These electron particles are elementary, which means we can divide them further."*

Table A10. Coding guide with criteria and examples for key idea number ten: *"In this model, apart from particles, there is only empty space."*

	Fully adequate	Partially adequate	Not adequate
Criteria	• Mention of empty space • Distinction between particles and empty space • Acknowledgment that particles and empty space are part of the model of particle physics	• Mention of empty space • No or wrong distinction between particles and empty space	• No mention of empty space • No or wrong distinction between particles and empty space • Comparison of empty space with air
Examples	*"There are only some particles, which are very small. Everything else is empty. Apart from particles, there is nothing else."*	*"In the orbital-space, [ehm] and in the nucleus-space, there is nothing."*	*"An atom is essentially empty. There is nothing we can touch, only air."*

10 minutes | 20 minutes | 30 minutes | 40 minutes

	Key Ideas	**Paraphrasing** "in own words"	**Transfer example 1** Grains of salt	**Transfer example 2** Droplets of water
1.	Matter is everything that can be **touched**, practically or theoretically.	☐	☐	☐
2.	Reality is **described** through models. For example the model of particle physics.	☐	☐	☐
3.	In this **model**, there are atoms, which may combine to form compounds.	☐	☐	☐
4.	In this model, atoms are divided into two **areas**: the nucleus-space and the orbital-space.	☐	☐	☐
5.	In the **nucleus-space**, protons and neutrons are located.	☐	☐	☐
6.	Protons and neutrons are particle systems, which are **made of quarks**.	☐	☐	☐
7.	Quarks are indivisible. In this **model**, these are called elementary particles.	☐	☐	☐
8.	In the **orbital-space**, it is possible to find electrons.	☐	☐	☐
9.	Electrons are indivisible. In this **model**, these are called elementary particles.	☐	☐	☐
10.	In this **model**, apart from particles, there is only empty space.	☐	☐	☐

☐ Evaluation | ☐ Evaluation | ☐ Evaluation

E

Introducing 12-year-olds to elementary particles

Gerfried J. Wiener[1,2], Sascha M. Schmeling[1], Martin Hopf[2]
[1]CERN, European Organization for Nuclear Research, Geneva
[2]Austrian Educational Competence Centre Physics, University of Vienna

Abstract:
We present a new learning unit, which introduces 12-year-olds to the subatomic structure of matter. The learning unit was iteratively developed as a design-based research project using the technique of probing acceptance. We give a brief overview of the unit's final version, discuss its key ideas and main concepts, and conclude by highlighting the main implications of our research, which we consider to be most promising for use in the physics classroom.

Keywords: Elementary particles, Subatomic structure of matter, Learning unit, Design-based research, Technique of probing acceptance

Introduction

Integrating modern physics into the curriculum is a question that has recently received ever increasing attention. This is especially true since in most countries the topic of modern physics is usually added at the end of physics education – if at all [1]. However, since these chapters – and here especially the Standard Model of particle physics – are considered to be the fundamental basics of physics, this situation might hinder the development of coherent knowledge structures in the physics classroom. Hence, one is faced with the question of whether it makes sense to introduce elementary particle physics early in physics education. Therefore, to investigate this research question, we have developed a learning unit, which aims to introduce 12-year-olds to elementary particles and fundamental interactions [2].

The learning unit consists of two consecutive chapters. It starts with an accurate description of the subatomic structure of matter by showcasing an atomic model from electrons to quarks. This first chapter is followed by the introduction of fundamental interactions, which on the one hand complete the discussion of the atomic model, and on the other hand set up possible links to other physics phenomena. An integral component of the learning unit is its independence from the physics curriculum and students' prior knowledge about particle physics. Indeed, since every physics process can be traced back to fundamental interactions between elementary particles, the use of the learning unit is not restricted to a certain age-group. Ideally, it can even be used at the beginning of physics education to enable an early introduction of key terms and principal concepts of particle physics in the classroom.

Following the framework of constructivism [3], the initial version of the learning unit was based on documented students' conceptions. Taking these into account enabled us to avoid potential difficulties for students, which might occur due to inadequate information input. As a next step, the initial version was developed by means of a design-based research [4] project with frequent adaptions of the learning unit. Here, we used the technique of probing acceptance [5] to conduct one-on-one interviews with 12-year-olds to evaluate the material developed. Based on the students' feedback, the learning unit was iteratively modified and evaluated until we arrived at the final version [2].

In this article, we give an overview of documented students' conceptions, which were relevant to the development of our learning unit. Next, we present the key ideas and main concepts of the learning unit by discussing its first chapter, which introduces the subatomic structure of matter. We then summarise the results from our development of the learning unit before concluding with a brief summary of suggestions, deduced from our research results, which we consider to be adequate and promising for use in the classroom.

State of research

When it comes to students' conceptions about the atomic model of matter, one finds initial studies, conducted in chemistry education research in the 1980s. Here, it was already shown that middle and high school students use particle models mainly to describe the nature of gases, but do not consider it to be their first choice when discussing everyday physics phenomena [6-8]. However, if a suitable particle model is offered as a meaningful alternative, most students accept and use it [9,10]. In addition, when looking at various age groups, one finds that high school students tend to accept particle models more easily compared to middle school students [6, 11]. However, concerning the understanding of the atomic model, the same misconceptions can be documented in both age groups [7, 12].

Since everyday life suggests a continuos rather than particular nature of matter – after all, ordinary matter usually appears to be compact and not at all corpuscular – it does not come as a surprise that students tend to prefer a continuos description of matter [6, 12-15]. Moreover, after introducing a particle model in the classroom, a mixing of both conceptions can be documented. This can be interpreted as the attempt of students to integrate the novel particle model into their existing continuos conception of matter [6, 12, 13]. The development of such inadequate conceptions can even be supported by erroneous textbook illustrations. For instance, this is the case in the infamous illustration of a glass of water, which shows H2O-molecules floating around in water [13].

Last, even if middle and high school students accept a particle model, this neither includes the notion of the constant motion of particles nor the idea of empty space. These two concepts are both only rarely documented with students, which instead leads to persistent misconceptions [7, 11, 13]. In addition, students also tend to anthropomorphise particles by imbuing them with everyday characteristics, such as colours and faces [12, 13, 15].

Learning unit

As mentioned above, our learning unit on the subatomic structure of matter was developed based on documented students' conceptions. The rationale of the unit is to enable 12-year-olds to construct knowledge on their own. Here, we encountered challenges due to the abstract nature of particle physics, which hinders the development of a correct and adequate learning unit. However, we found that by constantly putting the focus of the unit's content on the model aspect of physics, the abstractness of elementary particles can be incorporated in a meaningful way. In addition, to avoid triggering potential misconceptions, we also focused on linguistic accuracy when formulating the contents of the learning unit. Third, since education research has identified erroneous graphical representations as a main source for students' misconceptions, the learning unit is supported by the use of novel typographic illustrations. All told, the following three concepts are fundamental to the design of the learning unit:

- Model aspect of particle physics
- Linguistic accuracy
- Typographic illustrations

To illustrate the essential character of these three main concepts, we now give a brief overview of the learning unit's first chapter, which introduces the subatomic structure of matter. The aim of this first chapter is to outline an adequate atomic model, which mentions Democritus as the originator of the idea of atoms, but otherwise focuses on a modern description of atoms. Hence, it incorporates electrons and quarks as elementary particles, while protons and neutrons are introduced as particle systems, which are made of particles. Since gluons are only introduced in the unit's second chapter, which focuses on fundamental interactions, they are omitted at this early stage. However, through the careful use of colours for the typographic illustrations, the introduction of colour charge is already set up to be introduced in the second chapter. Furthermore, the unit's first chapter is based on the following ten key ideas, which are fundamental to the introduction of the subatomic structure of matter:

1. Matter is everything that can be touched, practically or theoretically.
2. Reality is described through models. For example the model of particle physics.
3. In the model of particle physics, there are atoms, which may combine to form compounds.
4. In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.
5. In the nucleus-space, protons and neutrons are located.
6. Protons and neutrons are particle systems, which are made of quarks.
7. Quarks are indivisible. In this model, these are called elementary particles.
8. In the orbital-space, it is likely to find electrons.
9. Electrons are indivisible. In this model, these are called elementary particles.
10. In this model, apart from particles, there is only empty space.

These key ideas were reconstructed together with education researchers and teachers, and iteratively modified and refined based on the students' evaluations during the one-on-one interviews. This led to the final version, which was validated by particle physicists and proved itself to be adequate and well-suited to introduce the subatomic structure of matter to grade-6 students [2]. However, our results also indicate that students only find it easy to accept and use these key ideas if the main concepts of the learning unit are also taken into account. Indeed, focusing on the model aspect of physics and on linguistic accuracy is prominently reflected in the phrasing of the ten key ideas and our findings show that they are essential for the successful implementation of the learning unit. The same goes for the typographic illustrations, which accompany the learning unit. Therefore, we give a brief overview of the three main concepts to highlight their importance for the unit's design.

Model aspect of particle physics

One of the biggest challenges when it comes to teaching particle physics is its abstractness. Hence, it does not come as a surprise that this topic is only rarely introduced in the physics classroom. After all, explanatory hands-on experiments are limited, physically precise explanations are hardly adequate for high-school level, and, due to the inconceivable dimensions involved, graphical representations fail to convey a realistic image. However, this allows the model aspect of particle physics to stand out. Indeed, the learning unit strongly focuses on conveying the idea that the use of models is essential in science, particularly in particle physics. The rationale of this approach is to highlight the key process of model-building, since it is argued that thinking in and with models is an essential component of appropriate science knowledge [16, 17]. Specifically, the phrasing "With this model, we describe…" plays a big role and is being used frequently throughout the unit's key ideas and key phrasings. Instead of the Standard Model of particle physics, however, we use a simplification and introduce "the model of particle physics". During first iterations of the learning unit, this modification proved itself to be very successful, since students showed difficulties with the term "Standard Model". Hence, the original term was omitted and replaced by its simplified version, which appealed greatly to all students during further evaluations. This example leads to the discussion of the second main concept, linguistic accuracy, which played a significant role in the development of the learning unit as well.

Linguistic accuracy

Another challenge in particle physics is how best to talk about particles and atoms in general. Since in the classroom one needs to jump back and forth between technical jargon and everyday language [18], this is especially problematic in the case of inconceivable particles. Hence, to prepare a meaningful learning unit, careful definitions of key terms and the rephrasing or avoidance of misleading terms are required. Indeed, the rapid pace of discovery in the early days of particle physics led to the establishment of key terms, which now convey an outdated description of modern particle physics, and should therefore be avoided in the classroom. Here, the so-called "particle zoo", which was used to describe the dozens of newly discovered "elementary particles" is a prominent example. This unfortunate term originates from a time when, in the absence of a complete quark theory, each newly discovered combination of quarks was classified as an elementary particle. Nowadays, following the modern description of only leptons and quarks as elementary particles, the notion of a "particle zoo" can be seen as anachronistic and thus detrimental to students' understanding.

Hence, we consider linguistic accuracy to be a very important aspect of the learning unit. Indeed, at the beginning of the development of our learning unit, we identified several terms and phrasings, which students evaluated to be difficult to understand. However, we also found that, by making minor adjustments to these terms and phrasings, or by rephrasing them, students showed broad acceptance. For instance, instead of using the "nucleus", the learning unit introduces the "nucleus-space". Doing so highlights the location aspect of the nucleus-space and minimises any potential misconceptions of a nucleus as an entity in its own right. In a similar way, the "orbital-space" is introduced, which defines the space "where it is likely to find electrons". This aims at reenforcing the probability aspect of the orbital-space, while unambiguously avoiding any misleading notion of electrons orbiting around in planet-like circles.

In addition, within the learning unit, we make a clear distinction between "particles" and "particle systems". This means that only elementary particles – leptons and quarks – are denoted as particles, while hadrons and mesons are introduced as particle systems "which are made of particles". Our findings showed that, thanks to this minor modification, any potential misconceptions of protons enveloping quarks like jelly could be avoided. The important aspect of linguistic clarity is also supported by the use of typographic illustrations, which we present next.

Typographic illustrations

Since education research shows that visual illustrations are essential to communicate scientific ideas in the classroom [19, 20], we developed new graphical representations of particles and particle systems to include in our learning unit. With the model aspect of particle physics in mind, these illustrations aim at visualising subatomic objects, while avoiding triggering any misconceptions about their potential appearance. Therefore, instead of using spheres or any other misleading symbols, we represent particles and particle systems by using their respective letters (see figure 1). To enable a clear distinction, elementary particles are drawn in colour, while particle systems are grey. Specifically, red, green, and blue are reserved for quarks, to set up the notion of colour charge early on, which will then be introduced within the learning unit's second chapter.

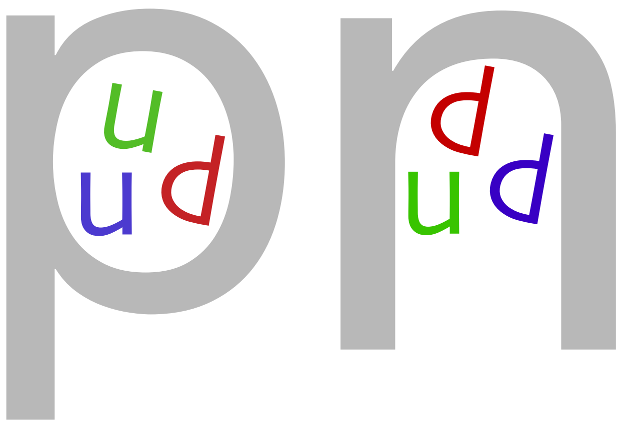


Figure 1. Typographic illustration of a proton and a neutron, as used in the first chapter of the learning unit.

Furthermore, since the learning unit also includes the notion of antiparticles and systems of antiparticles, a graphical visualisation of anticolour charge was required. Here, we developed an alternative to the commonly used complementary-colour method, whereby antiparticles and antiparticle systems are identified through the use of stripes instead of a change in colour (see figure 2). The rationale of this novel approach is to avoid any overlapping of the content with previously established optics knowledge, as this can be expected to be detrimental to learning. Instead, by using stripes, a clear distinction between particles and antiparticles is given, which also facilitates students' understanding of the model aspect of particle physics. Indeed, our alternative representation of anticolour charge was tested with high school students (age group 16-17 years, n=42) and physics teachers (n=38), who evaluated it to be a more helpful way of distinguishing between colour charge and anticolour charge [21].

To represent the atomic model, which is introduced in the learning unit's first chapter, a typographic illustration is used as well (see figure 3). Its aim is to qualitatively represent an atom and to highlight the difference between the nucleus-space and the orbital-space. In subsequent steps, this illustration of the atomic model allows the introduction of different orbital shapes within the orbital-space, without using inadequate terms, such as orbits or shells. To demonstrate a more realistic size ratio, however, the additional use of interactive animations and animated movies may be required.

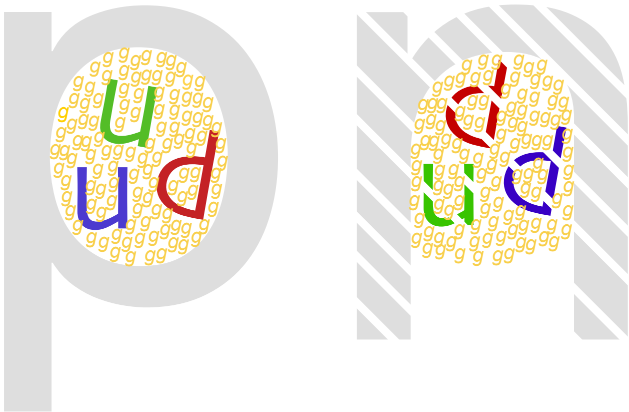


Figure 2. Typographic illustration of a proton and an antineutron, as used in the second chapter of the learning unit.

Figure 3. Typographic illustration of the atomic model, which highlights the distinction between the nucleus-space and the orbital-space.

Conclusions and Implications

The learning unit on the subatomic structure of matter presented here was developed and evaluated with 12-year-olds over the course of several iteration cycles [2]. In addition, we also introduced the final version of the learning unit to experienced physics teachers within designed professional development programmes to document their assessment of the unit. During these programmes, teachers were instructed about the main concepts and key ideas of the learning unit, and were encouraged to discuss students' conceptions about particles among each other. Next, based on a research manual, teachers were introduced to the technique of probing acceptance, which we used to develop the learning unit. This enabled them to conduct one-on-one interviews with grade-6 students during the last part of the professional development programme to evaluate the feasibility of the learning unit on their own. The analysis of the teachers' one-on-one interviews led to comparable results as documented during our initial study and showed the learning unit to be adequate for a broad evaluation in the classroom. In addition, all teachers provided us with very positive feedback and evaluated the unit's key ideas and main concepts to be promising for classroom application [22]. Specifically, the typographic illustrations and the use of certain key words and key phrasings, for example to distinguish between particles and particle systems, appealed greatly to all teachers and were identified as important for the introduction of subatomic particles in the classroom. Hence, based on our results, we concluded that it is indeed possible and useful to introduce elementary particles in early physics education.

However, we want to stress the fact that we do not limit our learning unit to the use with 12-year-olds. In fact, since the contents of the unit were developed with grade-6 students, who had no prior knowledge about the subatomic structure of matter, we consider the use of the learning unit to be independent of age. Furthermore, our findings highlight that to provide learners with adequate and meaningful learning offers, an iterative development of such learning material by means of design-based research is essential.

Last, we want to conclude by giving a brief overview of the most important implications of our research, which we consider to be highly promising for classroom application:

- Before discussing the topic of particle physics in the classroom, care should be taken to properly introduce and define the term "particle". We suggest to only use it for the description of elementary particles, since our results showed that students have difficulties to imagine particles “within” particles. Instead, so-called “composite particles” can be elegantly introduced as particle systems, which are made of particles.

- Abstract symbols, like the typographic illustrations presented here, are well-suited for the graphical representation of particles. Specifically, compared to the commonly used spheres, their use minimises the triggering of misconceptions about the appearance of particles. Furthermore, avoiding any pseudo-realistic illustrations and instead focusing on abstract symbols supports an adequate introduction of the model aspect of science in the classroom.

- Introducing the “nucleus-space”, instead of the standard description of the “nucleus”, greatly facilitates the discussion of a modern atomic model. Indeed, adding the word “space” to the key term “nucleus” emphasises its location aspect, while at the same time hindering the formation of potential misconceptions about the nucleus as an entity in and of itself. Consequently, this enables an elegant introduction of protons und neutrons, which are located in the nucleus-space.

- In a similar way, the introduction of the key term “orbital-space” turned out to be very helpful for students’ understanding of an accurate atomic model. Specifically, to avoid triggering any misconceptions of shells or orbits, it is worthwhile to introduce the notion of orbitals from the beginning. The “orbital-space” is then defined as the space in which it is likely to find electrons. Doing so emphasises the probability aspect of the description of subatomic particles and facilitates the development of a coherent theory of orbitals at a later stage in the curriculum.

- Dividing the atomic model into two different areas and thus highlighting its location and probability aspect also allows to elegantly introduce empty space as the counterpart to elementary particles. Our findings showed that emphasising the nucleus-space and the orbital-space as empty spaces, where it is likely to find particles, appealed greatly to students. Indeed, during our research we did not document any statements questioning the “fabric” of atoms and most students even evaluated the notion of empty space to be intriguing rather than difficult to accept.

Literature

[1] Mullis I, Martin M, Minnich C, Stanco G, Arora A, Centurino V and Castle C **2012** TIMSS 2011 Encyclopedia: Education Policy and Curriculum in Mathematics and Science, Volumes 1 and 2 (Chestnut Hill, MA: TIMSS & PIRLS International Study Center, Boston College)

[2] Wiener G J, Schmeling S M and Hopf M **2015** Can Grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds *Eur. J. Sci. Math. Educ.* 3(4) 313–22

[3] Duit R and Treagust D F **2003** Conceptual change: a powerful framework for improving science teaching and learning *Int. J. Sci. Educ.* 25(6) 671–88

[4] Design-Based Research Collective **2003** Design-based research: an emerging paradigm for educational inquiry *Educ. Res.* 32 5–8

[5] Jung W 1992 Probing acceptance, a technique for investigating learning difficulties Research in Physics Learning: Theoretical Issues and Empirical Studies, ed R Duit, F Goldberg and H Niedderer (Kiel: IPN) p 278–95

[6] Pfundt H **1981** Das Atom – Letztes Teilungsstück oder erster Aufbaustein? Zu den Vorstellungen, die sich Schüler vom Aufbau der Stoffe machen *Chimica Didactica* 7 75–94

[7] Novick S and Nussbaum J **1981** Pupils’ understanding of the particulate nature of matter: a cross-age study *Sci. Educ.* 65 187–96

[8] Stavy R **1991** Children’s ideas about matter *Sch. Sci. Math.* 91(6) 240–4

[9] Harrison A G and Treagust D F **2000** Learning about atoms, molecules, and chemical bonds: a case study of multiple-model use in grade 11 chemistry *Sci. Educ.* 84 352–81

[10] Snir J, Smith C L and Raz G **2003** Linking phenomena with competing underlying models: a software tool for introducing students to the particulate model of matter *Sci. Educ.* 87 794–830

[11] Harrison A G and Treagust D F **1996** Secondary students' mental models of atoms and molecules: implications for teaching chemistry *Sci. Educ.* 80 509–34

[12] Boz Y **2006** Turkish pupils’ conceptions of the particulate nature of matter *J. Sci. Educ. Technol.* 15 203–13

[13] Andersson B **1990** Pupils' conceptions of matter and its transformations (age 12-16) Stud. *Sci. Educ.* 18 53–85

[14] Nakhleh M B and Samarapungavan A **1999** Elementary school children's beliefs about matter *J. Res. Sci. Teach.* 36 777–805

[15] Ozmen H **2011** Turkish primary students' conceptions about the particulate nature of matter *Int. J. Environ. Sci. Educ.* 6 99–121

[16] Grosslight L, Unger C, Jay E and Smith C **1991** Understanding models and their use in science: conceptions of middle and high school students and experts *J. Res. Sci. Teach.* 28 799–822.

[17] Gilbert J **2004** Models and modelling: routes to more authentic science education *Int. J. Sci. Math. Educ.* 2 115–30

[18] Rincke K **2011** It's rather like learning a language. Development of talk and conceptual understanding in mechanics lessons *Int. J. Sci. Educ.* 11 229–58

[19] Carney R N and Levin J R **2002** Pictorial illustrations still improve students' learning from text *Educ. Psychol. Rev.* 14 5–26

[20] Cook M P **2006** Visual representations in science education: the influence of prior knowledge and cognitive load theory on instructional design principles *Sci. Educ.* 90 1073–91

[21] Wiener G J, Schmeling S M and Hopf M (**in press**) An alternative proposal for the graphical representation of anticolor charge *The Phys. Teach.*

[22] Wiener G J, Schmeling S M and Hopf M (**submitted**) Why not start with quarks? Teachers investigate a learning unit on the subatomic structure of matter with 12-year-olds *Eur. J. Sci. Math. Educ.*

F

The technique of probing acceptance as a tool for teachers' professional development: a PCK study

Gerfried J. Wiener[1,2], Sascha M. Schmeling[1], Martin Hopf[2]
[1]CERN, European Organization for Nuclear Research, Geneva
[2]Austrian Educational Competence Centre Physics, University of Vienna

Abstract:

This article presents a study that examined an innovative short-term program for the professional development of teachers. The program design is based on the technique of probing acceptance, which is aimed at investigating student learning processes. During the professional development program, teachers are introduced to a novel learning unit that focuses on the subatomic structure of matter. In addition, the teachers are instructed in how to use the technique of probing acceptance during one-on-one interviews to evaluate the concepts of the unit. The rationale of the professional development program is that the preparation and execution of the one-on-one interviews based on the technique of probing acceptance should have an impact on certain dimensions of teachers' pedagogical content knowledge (PCK). Four teachers from one Austrian high school participated in this exploratory study, and each teacher conducted two one-on-one interviews with two different grade-6 students. Post-intervention interviews were conducted with all the teachers to document the potential influences on the teachers' PCK. The interviews were transcribed word for word, and a category-based content analysis was applied to the transcripts. Our results indicate that during the professional development program, all the teachers revisited their existing knowledge about the subatomic structure of matter and left with an updated PCK, especially regarding their knowledge of learners and of instructional strategies. Overall, we show the technique of probing acceptance to be a promising tool for short-term professional development programs, and we suggest that our findings have implications for both professional development designers and educators.

Keywords: professional development program, pedagogical content knowledge (PCK), technique of probing acceptance, design-based research, subatomic structure of matter

Introduction

Over the past 50 years, the concept of teacher knowledge has received ever-increasing attention from education researchers, and it is widely agreed that teachers are central to educational processes (Wallace & Loughran, 2012). However, the ways in which we view teacher knowledge and its development have changed profoundly. In the 1960s, teacher knowledge, much like a qualification or competency, was considered a static component of teacher characteristics. The initial studies compared these variables with teacher practice (Smith & Cooper, 1967; Bruce, 1971) or student outcomes (Rothmans et al., 1969; Northfield & Fraser, 1977) and thus tried to evaluate the "formal knowledge" that was needed for teaching. In general, this formal knowledge overlapped greatly with teachers' subject matter knowledge. In the 1980s, however, research on teachers shifted towards a more dynamic orientation. Instead of assessing subject matter knowledge per se, researchers acknowledged the importance of its transformation into subject matter knowledge for teaching and directed their research at examining teachers' "practical knowledge". This shift was stimulated mainly by Shulman (1986, 1987), who proposed a model that distinguishes pedagogues from content specialists by introducing the concept of pedagogical content knowledge (PCK) as a distinct component of teacher characteristics: *"It represents the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction. Pedagogical content knowledge is the category most likely to distinguish the understanding of the content specialist from that of the pedagogue"* (Shulman, 1987, p. 8).

By and large, PCK refers to the knowledge that is developed by teachers to help others learn. According to Abell (2007), this developmental process is grounded mainly in three other knowledge bases: subject matter knowledge, pedagogical knowledge, and knowledge of context. By means of their PCK, teachers transform subject matter knowledge into useful educational instruction, which is delivered to their students in a meaningful way based on the pedagogical knowledge of the teacher. This instruction is situated in the teachers' knowledge of context, which includes knowledge of communities, schools, and students' backgrounds (Grossman, 1990).

Since its introduction, Shulman's model has received much attention and has been explicated, revised, and extended many times (Tamir, 1988; Grossman, 1990; Cochran et al., 1993; Magnusson et al., 1999; Loughran et al., 2006). Starting from the original conceptualization, different aspects of PCK have been identified that now represent a more detailed view of the knowledge base. However, even 20 years ago, van Driel and colleagues (1998) stated that *"there is no universally accepted conceptualization of PCK"* (p. 677). Park and Oliver (2008) later extended the work of van Driel and colleagues by giving an extensive overview of different conceptualizations; they identified the following five distinctive dimensions in a working definition of PCK:

a) Orientation towards teaching science
b) Knowledge of curriculum
c) Knowledge of learners
d) Knowledge of instructional strategies
e) Knowledge of assessment

Orientation towards teaching science refers to teachers' knowledge and beliefs about the aims and goals of teaching science to a certain age level that guide their instructional decisions. Knowledge of curriculum refers to knowledge of mandated goals and objectives as well as of specific curricular programs and materials. Originally, Shulman and colleagues considered this to be a separate knowledge base (Wilson et al., 1988), but it was later included by Magnusson and colleagues in their conceptualization of PCK because this knowledge unambiguously distinguishes pedagogues from content specialists and thus acts as a defining feature of PCK (Magnusson et al., 1999). Knowledge of learners includes knowledge of students' conceptions and of areas in science that students find difficult. From a constructivist viewpoint, this knowledge base involves emphasizing the importance of the learner and acknowledging that students' preexisting cognitive structures actively influence their learning outcomes (Duit & Treagust, 2003). Knowledge of instructional strategies combines knowledge of broadly applicable subject-specific strategies and of much narrower topic-specific strategies. From a teacher's point of view, this knowledge includes representations, activities, and methods that work in a classroom. Knowledge of assessment refers to knowledge of important science domains to assess and knowledge of how to assess students.

PCK and professional development for teachers

Shulman's model of PCK is widely recognized, and, as mentioned above, there is widespread agreement among scholars about its applicability and importance for teachers. However, there is also considerable discussion of how teachers develop PCK (Wallace & Loughran, 2012). Grossman (1990) stated that *"teachers have a variety of sources from which to construct their knowledge of teaching a specific subject"* (p. 10). Among those sources, she identified the time spent as a student (apprenticeship of observation), subject matter preparation (disciplinary background), taking part in subject-specific methods courses (professional coursework), and actual classroom practice (learning from experience). The last source, learning from experience, is backed up by previous research suggesting that classroom practice plays a significant role in the development of PCK (Baxter & Lederman, 1999; Magnusson et al., 1999; van Driel et al., 2001). For instance, Hashweh (2005) argued that PCK can be seen as a repertoire of pedagogical tools that teachers acquire over time through repeatedly teaching a certain topic. From this repertoire, an "expert teacher" is able to choose the right instruction that is effective for any group of students on any given day.

However, the complex nature of PCK, considered by education researchers to be knowledge that is person-, topic-, and situation-specific (van Driel & Berry, 2012), leaves room for various interpretations regarding its development. For example, Bindernagel and Eilks (2009) chose a definition of PCK as a highly personal domain of knowledge and focused on the influence of recommendations from trusted colleagues. Their rationale was that PCK is built on beliefs that are difficult to capture but that can be isolated and examined when teachers share their experiences with colleagues by discussing teaching strategies. This approach is supported by the work of Schneider and Plasman (2011), who conducted a broad literature review of research articles on the development of PCK. They arrived at the same conclusion: it is necessary to provide teachers with clear opportunities to experience and reflect on how to think about each aspect of PCK. In addition, their findings indicated the relevance of curriculum materials that support teachers in developing their own teaching strategies.

While the different interpretations concerning the development of PCK provide a broad theoretical framework for conceptualizing it, the challenge remains of how best to implement such strategies in professional development programs for teachers. This is a prominent question because there is an increasing need for higher-quality and more effective professional development opportunities aimed at teachers' development of PCK (Borko et al., 2010). When considering PCK as the organizing force, professional development programs can no longer be limited to supplying teachers only with input, such as examples of expert teaching of subject matter. Instead, supported by specific input, teachers should be enabled to enact innovative instructional strategies through programs that are closely aligned with their professional practice (van Driel & Berry, 2012). Furthermore, research suggests that to be effective, such programs should focus on students' learning (Borko et al., 2010) and include opportunities for teachers to reflect, individually and collectively, on their experiences (Park & Oliver, 2008).

Rationale and research question

To contribute to the rich body of research on teachers' development of PCK, we present a study that examines an innovative form of professional development for teachers. The program is in the field of design-based research (Design-Based Research Collective, 2003) and follows the aforementioned suggestions from education research to involve teachers in the process and enable them to enact instructional strategies. Specifically, it relies on the technique of probing acceptance (Jung, 1992). The research method is aimed at investigating learning processes and identifying learners' resistances to elements of specific information with the ultimate goal of developing adequate teaching material. Traditionally, the technique of probing acceptance is used in one-on-one interview sessions that last 40–60 minutes and contain defined interview phases.

In previous studies, we used the technique of probing acceptance to develop a novel learning unit that introduces the subatomic structure of matter to 12-year-olds. The unit aims to introduce a modern atomic model, from electrons down to quarks, by considering students' documented conceptions. In total, we conducted 20 one-on-one interviews with grade-6 students during the iterative development phase of the unit, which led to the final version of the learning unit (Wiener et al., 2015). For the next step, we focused our research on the perspective of teachers to gain insight into their evaluation of the unit's adequacy and didactic feasibility. Therefore, a follow-up study with a total of 17 students was carried out to once again probe acceptance of the learning unit by grade-6 students. This time, however, the one-on-one interviews were led by instructed teachers instead of by education researchers, and their evaluation of the unit was documented during semistructured post-intervention interviews. To our satisfaction, the teachers' results validated our findings from the initial study and showed the final version of the learning unit to be adequate and well suited for a broad evaluation in the classroom (Wiener et al., 2017). Furthermore, all the teachers found their new role as education researchers during the one-on-one interviews to be highly interesting and informative. In particular, the opportunity to observe the learning processes of their respective students appealed greatly to the teachers and received entirely positive feedback.

Based on this interesting outcome of our previous study, we focused our research on the development and improvement of the technique of probing acceptance as a form of professional development for teachers. We consider the setting to be promising because it combines a teaching aspect and a research aspect that the teacher must incorporate by switching roles between presenting input and then conducting research on it. Our hypothesis is that the preparation and execution of one-on-one interviews in accordance with the technique of probing acceptance should have an impact on the development of teachers' PCK. Being asked to present novel information to a single student within a research environment should challenge teachers to revisit their subject matter knowledge and to deeply reflect on their instructional strategies. Conducting the different interview phases by helping the student to evaluate, paraphrase, and adapt the novel knowledge should further deepen their understanding of the topic discussed and enable them to observe the student's learning process. Embedding the intervention in a professional development program, with several teachers preparing together for their new role as education researchers and then conducting one-on-one interviews in parallel, should give them the opportunity to reflect, individually and collectively, on their experience. As the program can be implemented briefly and can be closely aligned with teachers' professional practice, we consider it to be an interesting and promising development opportunity for teachers, especially regarding the dissemination of innovative instructional strategies and novel teaching material. Hence, keeping in mind the aforementioned conceptualization of PCK by Park and Oliver (2008), this article addresses the topic through the following research question:

To what extent are the dimensions of teachers' PCK influenced by the preparation and execution of one-on-one interviews based on the technique of probing acceptance?

Methods

Study design

To investigate the research question, we designed a study based on our previous work (Wiener et al., 2015; 2017). Teachers were invited to take part in education research by conducting two one-on-one interviews with grade-6 students to evaluate the developed learning unit on the subatomic structure of matter. This time, however, the focus of our research was on the development of the teachers' PCK during the study. Their one-on-one interviews were videotaped, transcribed word for word, and evaluated based on the coding manual from our previous studies to ensure comparability. Additionally, semistructured interviews were conducted with each teacher immediately after the intervention to document the effect of the study on different dimensions of their PCK.

The study was implemented in a professional development program for teachers that contained two parts: a briefing session and the intervention (Figure 1). The aim of the briefing session, which occurred the day before the intervention and lasted about three hours, was to instruct the teachers about the novel learning unit and to help them prepare for the intervention. The first part of the briefing was a presentation on the novel learning unit that explained its development; gave an overview of students' documented conceptions of the structure of matter; and highlighted the unit's main concepts: conveying the central role of models in physics, focusing on linguistic accuracy, and using novel typographic illustrations. Furthermore, the key ideas of the unit (Table I), which act as elementary steps for the topic, were presented and discussed. Our previous publications provide a detailed description of the learning unit and its development process (Wiener et al., 2015; 2017). This presentation of the learning unit took one hour and was followed by the introduction of the research method.

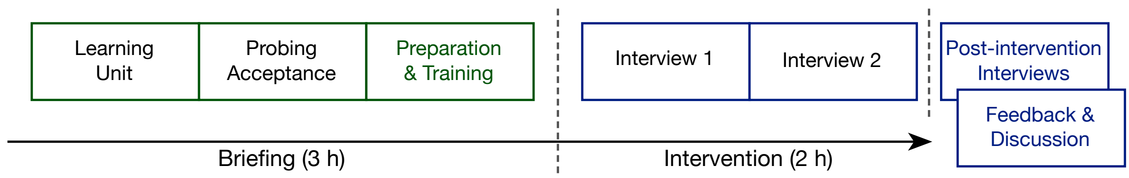


Figure 1. Design of the professional development program, with a briefing session followed by an intervention. During the intervention, each teacher conducted two one-on-one interviews. The intervention was concluded by post-intervention interviews, which were conducted individually with every teacher. In parallel, a feedback and discussion session enabled the teachers to collectively reflect on their experiences and discuss the main outcomes of their one-on-one interviews.

Table I. Key ideas of the learning unit on the subatomic structure of matter.

#	Key idea
I	Matter is everything that can be touched, practically or theoretically.
II	Reality is described through models. For example, the model of particle physics.
III	In this model, there are atoms, which may combine to form compounds.
IV	In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.
V	In the nucleus-space, protons and neutrons are located.
VI	Protons and neutrons are particle systems, which are made of quarks.
VII	Quarks are indivisible. In this model, these are called elementary particles.
VIII	In the orbital-space, it is possible to find electrons.
IX	Electrons are indivisible. In this model, these are called elementary particles.
X	In this model, apart from particles, there is only empty space.

During the next hour, the technique of probing acceptance was explained in detail by presenting representative examples from our previous study, which were then discussed among the teachers. Additionally, each teacher received his or her own research manual, which had been developed during our previous study to enable teachers to conduct the one-on-one interviews in accordance with the setting of the study and to ensure comparability. It contained a set of anchor phrases to facilitate conducting the interview (Table II), a list of the ten key ideas, and the general time frame of the interview. The research manual was discussed and worked through with the teachers to summarize the presentation of the technique of probing acceptance.

For the last hour of the briefing, it was the teachers' task to prepare themselves, individually and collectively, for the intervention by trying out the research manual and practicing specific parts of the one-on-one interviews with their colleagues. This part of the briefing session also included time to prepare the information input; the individual adaptation of the material provided was left to the discretion of each teacher. However, while the teachers were asked to prepare their own information input individually, based on the learning unit's key ideas, they were encouraged to discuss their ideas with colleagues. To ensure comparability among the teachers and with the setting of our previous study, a time constraint of 8-10 minutes was given for the duration of the information input, and teachers were required to mention every key idea at least once during their instruction.

Table II. Examples of anchor phrases in the research manual

Phase	Anchor phrases
Evaluation	• How does this sound to you? • Was the presented information easy to understand? • Can you recall any details that you could not understand at all? • What is your general impression of this information input?
Paraphrasing	• Can you tell me again – in your own words – everything you remember from what I have just presented to you? • How would you explain this to a friend?
Transfer example	• How does this example relate to what you just heard? • How do you picture this "in reality"? • Can you think of another, different way of explaining this?

The intervention occurred the next day and lasted about two hours. During the intervention, each teacher conducted two one-on-one interviews with two different grade-6 students. The rationale of this approach was to give the teachers the opportunity to learn from the experience gained during the first interview and thus to enable them to adapt their instructional strategies for the second interview. While the entire intervention was limited to a feasible duration, this setting allowed for a more detailed analysis of the applicability of the topic discussed. After the second one-on-one interview, we conducted a semistructured interview with each teacher. In parallel, the professional development program was concluded by a short feedback and discussion session that enabled all the teachers to collectively reflect on their experiences regarding the preparation and execution of their one-on-one interviews.

Setting of the one-on-one interview

Mirroring the setting of the original study and in line with the definition of the technique of probing acceptance (Jung, 1992), the one-on-one interviews were designed to comprise four interview phases with a maximum interview duration of 40 minutes (Figure 2). Depending on the definition of "acceptance", the name of the research method can be misleading. Our understanding of the research method is that it gives insight into the plausibility of an information input in terms of whether it makes sense to students. Probing *acceptance* thus means identifying elements of the instruction that students *accept* as useful and meaningful information and that they can successfully adapt during the one-on-one interview.

The teachers were guided through their one-on-one interviews by the research manual. The design of the manual was based on the list of ten key ideas, which the teachers had to work through. During each interview phase, each key idea was to be addressed and then checked off the list. Only after all the key ideas had been discussed could the next interview phase begin.

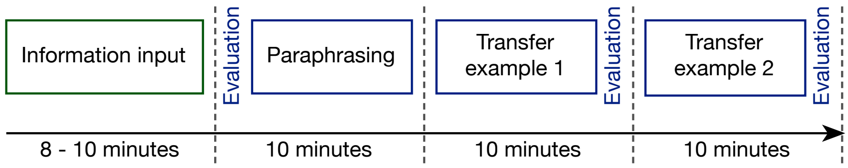


Figure 2. Setting and time frame of the one-on-one interview.

Each one-on-one interview started with the presentation of the information input, which was individually prepared by each teacher. This was followed by the student's first evaluation to document immediate feedback regarding the novel information. For example, the teacher asked, "What do you think about this topic?" and "Was there anything that you could not understand? Or anything that you really liked?" This evaluation marked the beginning of the second interview phase. The teacher was then prompted by the manual to ask the student to paraphrase the presented information "in their own words". The student was tasked with recalling as much of the initial information input as possible. The paraphrasing concluded the second interview phase.

Next, as a first transfer example, it was the teacher's task to sprinkle some grains of salt across the table and ask the student to apply the new knowledge to this concrete example by solving the problem of whether salt can be identified as matter and to explain what salt is made of. The student was expected to argue from an atomistic point of view, starting with atoms as the building blocks of matter and then moving on to the subatomic structure of matter. This transfer example was followed by the student's second evaluation of the information input, which concluded the third interview phase.

For the fourth and final phase of the one-on-one interview, it was the teacher's task to guide the student through the second transfer example. Instead of grains of salt, the teacher scattered some droplets of water on the table. The student was then expected to explain whether water qualifies as matter and to further give a description of what it is made of. While both transfer examples focused on the same question, the rationale of the approach was to document the students' reasoning about the subatomic structure of matter for two different aggregate states, solid (salt) and liquid (water). For the final task, each student was asked to give a third evaluation of the information input, which concluded the fourth interview phase and marked the end of the one-on-one interview.

Data collection and analysis

The study occurred at an Austrian high school, or *Gymnasium* (age group 10-18 years), with four teachers voluntarily taking part in the professional development program. Each teacher carried out two one-on-one interviews in German, the native language of all the participants. Eight grade-6 students were randomly selected by the teachers, with the only limitation being that the students should be interested in trying out new teaching material. To avoid conflicts of interest, each teacher conducted his or her one-on-one interviews with students who were taught and chosen by another teacher. All students as well as their parents gave their informed consent in writing.

The group of teachers can be seen as a typical sample of Austrian high school teachers. All four teachers had received their academic degree from a university, with physics as one of their two teaching subjects. The individual teaching experience of the teachers varied from 2 to 25 years (Table III). Not only did the teachers volunteer to take part in the professional development program, but they also received support from their principal, who permitted them to clear their schedules for four consecutive hours. This allowed for continuous and harmonic data collection.

Table III. Overview of the four teachers taking part in the professional development program.

#	Gender	Age	Teaching experience
Teacher 1	Female	26	2 years
Teacher 2	Male	34	4 years
Teacher 3	Male	41	9 years
Teacher 4	Male	50	25 years

As described above, during the intervention, each teacher conducted one-on-one interviews with two different grade-6 students. After their second one-on-one interview, we enabled the teachers to collectively reflect on their research experience. In parallel, we conducted an individual semistructured interview with each teacher to document the potential influences on various dimensions of their PCK. These post-intervention interviews lasted approximately 15 minutes and started with a request that the teacher characterize both students to facilitate the interpretation of the recorded data of each one-on-one interview. The post-intervention interviews then followed a guide consisting of the following open questions:

- How was your experience as an education researcher?
- Were the briefing and the material provided sufficient to prepare for today's intervention?
- Did you encounter differences between the two one-on-one interviews? If so, please specify.
- Did you notice any specific key ideas that were easy/difficult to explain? If so, please specify.
- Have you used any of the contents discussed in your classes before? If so, please specify.
- During this program, has your attitude towards particle physics changed? If so, please specify.
- To what extent did the professional development program influence your
  - content knowledge of particle physics?
  - pedagogical content knowledge of particle physics?
  - knowledge of the physics curriculum regarding particle physics?
  - knowledge of students' conceptions regarding particle physics?
  - knowledge of instructional strategies regarding particle physics?
  - knowledge of how to assess students?

We used GoPro© cameras to videotape both the one-on-one interviews and the post-intervention interviews, and all recordings were transcribed verbatim. Based on the conceptualization of PCK by Park and Oliver (2008), we applied a qualitative content analysis (Mayring, 2010) to all transcripts of the post-intervention interviews. To ensure a transparent and traceable process, the analytic procedure followed the full cycle of phases for analyzing qualitative data (Yin, 2011). The cycle included frequent disassembly and reassembly of the recorded data driven by the defined categories of the five dimensions of PCK. The analysis was peer-validated among the research team and by other researchers in physics education.

Results

The following report focuses on our findings, which we documented during the briefing session and especially during the post-intervention interviews, to describe the potential influence of the professional development program on the PCK of the four teachers. We distinguish among the five dimensions of teachers' PCK based on the conceptualization by Park and Oliver (2008). As the content of the professional development program was directed at the subatomic structure of matter and how to introduce it to 12-year-olds, we mostly recorded topic-specific statements by the four teachers. Hence, we want to stress the fact that we limit our analysis of the dimensions of PCK to the field of particle physics before drawing general conclusions in the Discussion section. In the following sections, we summarize the documented findings and give a detailed overview of our analysis for all five dimensions of PCK.

Orientation towards teaching science

This dimension of PCK refers to teachers' knowledge and beliefs about the aims and goals of teaching science to a certain age level that guide their instructional decisions. The analysis of this dimension was strongly influenced by the fact that the learning unit aims to introduce the topic of the subatomic structure of matter to 12-year-olds. All the teachers strongly acknowledged the importance of particle physics and stated that they already had experience in teaching it. When asked about the adequate age level for learning the subject, all four teachers stated that although the particle model is used at an earlier stage in the curriculum, particle physics is typically covered in their grade-11 and grade-12 classes. For example, teacher 2 explained, *"[Particle physics] is a big topic in grade 12. This is something I really enjoy, and I try to cover as much as possible. Even particle accelerators or cosmic particles, because these are a good link when introducing Einstein's theory of relativity."* Similarly, teacher 3 mentioned, *"To me, particle physics is one of the most important topics in the whole curriculum. Because the feedback from the students, well, from the grade-12 students at least, is very positive. And as a teacher, it is always rewarding when students let you know that something that you consider to be important is interesting for them as well."*

Given that all four teachers already showed a profound orientation towards teaching particle physics, we noted only few statements regarding the possible influences on this dimension of PCK. These statements primarily concerned the possibility of introducing particle physics at an earlier stage in the curriculum, as proposed by the learning unit discussed. All the teachers stated that they were critical of the idea at first, but all four evaluated the age level as adequate after having discussed the learning unit with the 12-year-olds during the one-on-one interviews. For instance, teacher 4 explained, *"Well, in general, I am a fan of introducing modern physics at an early stage in the curriculum. Because otherwise, you just teach normal physics, and suddenly, when they [students] are 17 or 18 years old, you confront them with modern physics. But I must admit, I was critical of whether it makes sense to start with 12-year-olds. This was very interesting for me, because it showed me that, well, in principle, it works. This was very rewarding to see, and I will take this back to my classroom."* Teacher 1, who started teaching only two years ago, stated, *"Well, I clearly need more experience, but what I can already see is that it makes sense to use basic concepts of the learning unit, for example, the orbital-space and the nucleus-space, from the very beginning. Because then the students already get used to these terms, and I as the teacher can avoid problematic phrasings that do not necessarily convey an adequate model."*

We noted more statements regarding the teachers' orientation towards particle physics and especially regarding the suitable age level for an introduction to particle physics. However, as these were merged with statements about other dimensions of PCK, we categorized them accordingly. Such statements overlapped mostly with statements concerning knowledge about the contents of the physics curriculum, which we present next.

Knowledge of curriculum

This dimension of PCK refers to knowledge of mandated goals and objectives as well as of specific curricular programs and materials. Both during the briefing and especially during the post-intervention interviews, all four teachers displayed an extensive knowledge of the relevant physics curriculum and referred to many available educational resources. This did not come as a surprise, as teacher education in Austria is closely aligned with the physics curriculum for middle and high schools. Furthermore, the physics curriculum acts merely as a guideline and is loosely formulated regarding which basic concepts students should be able to demonstrate at certain stages rather than which topic should be introduced in which grade. Hence, when the teachers were prompted to link the topic of the learning unit to the physics curriculum, we documented almost identical statements from all four of them, which were in line with the curriculum. For example, teacher 3 explained, *"Linking this topic [of the structure of matter] to the* *curriculum is easy because the curriculum starts with the concept of particles and the atomic model in grade 6. So, introducing the basic concepts of the unit is essentially already in there."* Similarly, teacher 4 stated, *"Sure, this is easy; it is already in the curriculum for grade 6. You have the particle model and the atomic model in there, so this is where the learning unit fits best."* In addition, we noted several statements through which the teachers tried to link the learning unit not only to the physics curriculum but also to the chemistry curriculum. For instance, teacher 1 mentioned, *"I think it is quite easy to introduce this topic already to grade 6 students. I mean, the notion of particles is already in the curriculum, so using at least the basic concepts of the unit makes a lot of sense. But, I could also picture introducing it in grade 7 because this is when the students start with their chemistry classes, and then one could coordinate with the chemistry teacher to build a consistent atomic model together. So, to have it right from the start both from a physics and a chemistry point of view."*

As the post-intervention interviews progressed, the teachers started to increasingly mention specific topics of the physics curriculum that they deemed suitable for the learning unit. For instance, the answer from teacher 2 regarding the possible links to the physics curriculum was similar to those of his colleagues: *"Hm, well, I am not sure if all concepts of the learning unit are applicable in the classroom. I mean, yes, of course, in grade 6, when we start with the atomic model, it makes sense to use it. And, at least from what I saw in my two [one-on-one] interviews, the learning unit is adequate to be used already at this early stage. Hm, but right now, I cannot think of any other connections to the physics curriculum."* However, in his later post-intervention interview, he paused for a few moments and then gave the following overview of possible links to the curriculum: *"Hm, I think there is more to the concepts of the learning unit than I initially thought. I mean, to some extent, you can also link it to thermodynamics, and if you introduce fundamental interactions and forces, there is a link to mechanics. So, it would make sense to use it in both grade 6 and grade 7. Well, and electricity, obviously; I mean, this is closely linked to the atomic model as well – or at least the notion of a model; I mean, this plays a big role for all these topics. Hm, radioactivity in grade 8 [laughs]; looks like there are way more links to the curriculum than I thought."* Although this teacher was prompted to revisit his knowledge about the physics curriculum only during the post-intervention interview, we also noted statements from the other teachers indicating that this process had occurred during the briefing session. For instance, teacher 3 stated, *"Yesterday, during the briefing, my colleagues and I* *already briefly discussed the possibility of using this learning unit at the beginning of grade 6 and then use the notion of models and particles for all the other topics to follow. And today, I even asked one of my two students at the end of the [one-on-one] interview what she thinks about it, because she was very interested during the interview. And her feedback was very positive as well. So, I think, if it is possible to link the model of particles to other topics in the curriculum, such as electricity and radioactivity, this would be very ambitious but also very rewarding."* The ideas mentioned in this comment, which was similar to one from teacher 4, can be traced back to the last part of the briefing session, during which the teachers discussed the content of the learning unit and collectively prepared for the intervention.

Overall, our analysis of this dimension of PCK revealed that the four teachers already possessed a profound knowledge of the physics curriculum. When it came to possible links among different topics of the curriculum, however, we also documented several statements indicating that the knowledge of the teachers was influenced and enhanced by the professional development program.

Knowledge of learners

This dimension of PCK includes knowledge of students' conceptions and of areas in science that students find difficult. As mentioned before, this aspect played a large role in the development process of the learning unit and especially in the professional development program. Indeed, during the briefing session, students' relevant documented conceptions were presented to and discussed with the teachers to sensitize them to the importance of considering their students' prior knowledge.

At the beginning of every post-intervention interview, all four teachers acknowledged the importance of students' conceptions for their everyday work in the classroom. However, they all also stated that it is challenging to always adhere to those conceptions. For example, teacher 2 mentioned, *"I am fully aware that it is important to take students' conceptions into account. But sometimes, I mean, from time to time, when you want to cover everything in detail, I mean, you have to find a compromise. And sometimes I get sloppy, and I just accept that my teaching is not 100% precise."* When we asked specifically about the overview of students' documented conceptions of the structure of matter that was presented during the briefing session, we noted similar statements from teachers 2, 3, and 4, who acknowledged that most of the presented conceptions were new to them. On the other hand, teacher 1, who had only recently finished her academic studies, stated that only a few of the conceptions were new to her: *"Well, it was great going through all the students' conceptions because I knew most of them already, which showed me that my knowledge is up-to-date."* Nonetheless, all four teachers agreed that the overview was a helpful reminder for both the intervention and their daily teaching, as was elegantly expressed by teacher 4: *"After the briefing session, I was looking forward to the intervention, and I was especially curious to see whether my students would show similar conceptions during the interviews. But from a more general point of view, this was a very helpful reminder that students have their own ideas about physics, not just particle physics. This is something that every teacher should be aware of."*

When looking at topic-specific statements that could hint at further influences on the teachers' knowledge about students' conceptions, our analysis revealed that the rather young age group of the students also played an important role in the teachers' evaluation of the professional development program. Specifically, the fact that the 12-year-olds could be considered novices regarding particle physics, which was the case in our previous studies (Wiener et al., 2015; 2017), appealed greatly to all four teachers. For instance, teacher 3 reported, *"For me, it was very interesting to see that both of my students had no prior knowledge about atoms. I mean, they had heard the name before, but aside from this, I did not encounter any prior knowledge or even misconceptions. This was very rewarding to see because it showed me that it can make sense to introduce elementary particles even to very young students."* We noted a similar statement from teacher 4, who also highlighted this aspect as one of his main outcomes of the study: *"I am not sure how representative my students were, but at least with those two, there were no problems with potential misconceptions at all. This is already very good to know, because this motivates me in my daily teaching to try out more advanced topics at an earlier stage in the curriculum."*

Overall, our findings show that both the presentation of students' documented conceptions during the briefing session and the intervention itself had a substantial impact on the teachers' knowledge of learners. Specifically, the three teachers who had shown only a little knowledge of the relevant students' conceptions prior to the professional development program mentioned a specific knowledge gain regarding students' conceptions of particles. Furthermore, when asked about these conceptions, which were new to them, all the teachers tried to explain how best to address them. For instance, teacher 2 stated, *"I have to admit, I never thought about the difficulties students might have in imagining particles. And I never really questioned the illustration of particles. I always kind of accepted that they are shown as spheres. But now that I have seen how easy it is to avoid any questions about the 'inside' of elementary particles, I am aware that it absolutely makes sense to use letters as symbols."* Teacher 3 said, *"I really like the idea of emphasizing the model character of physics. Maybe this is really a way to avoid misconceptions. To some extent, the model aspect made it even easier to explain elementary particles to the students, because there are many facts that we just do not know. For example, what particles look like. This was no discussion during my sessions, because it was clear that this is just a model. This is something that I will try out in my classroom right away."* We consider these findings to be very promising, as they show that the teachers not only accepted the learning unit's key ideas but also started to reflect on their new knowledge and were already trying to integrate it into their pedagogical content knowledge during the intervention.

Knowledge of instructional strategies

This dimension of PCK combines the knowledge of broadly applicable subject-specific strategies and of much narrower topic-specific strategies. We believe it is safe to say that this dimension is the core of our research, as the professional development program is essentially tailored around our novel learning unit on the subatomic structure of matter. Specifically, the fact that the teachers were invited to evaluate and further develop the learning unit through the professional development program had a major impact on their feedback.

As mentioned before, all the teachers had received physics degrees at the university level. Hence, every teacher was familiar with the topic covered by the learning unit, and during the briefing session, all the teachers mentioned that they had experience teaching the subatomic structure of matter at the high school level. Furthermore, at the end of the briefing, individual strategies and best-practice examples of how to introduce the atomic model and elementary particles to students were discussed among the group of teachers. Here, we noted that teachers 2, 3, and 4 possessed a richer and more diverse knowledge of instructional strategies than their less experienced colleague regarding the introduction of the atomic model. When looking at the teachers' knowledge about how to introduce elementary particles, however, we documented that all the teachers showed a similar basic knowledge of instructional strategies. These two findings were confirmed by the teachers during the post-intervention interviews when they were asked to comment on their respective experiences of introducing the subatomic structure of matter in the classroom. For instance, teacher 4, who was the most experienced teacher of the group, answered, *“Well, regarding the content [of the learning unit], there was nothing new to me. I mean, the atomic model is in the curriculum, and I have been teaching this to students of all age groups for more than 20 years. The same goes for elementary particles, but I must say, I never really thought about a different way of presenting them to students. I always kind of followed the textbook approach.”* In comparison, when asked about the content of the professional development program, teacher 1, who was only in her second year of teaching, stated, *“I think I had heard everything already. But it was a good repetition. After all, this is why I like to attend teacher trainings because it is always good to see that your knowledge is up-to-date. Until now, I only used the standard atomic model with shells, but I think that it is a good idea to avoid the notion of shells completely and introduce orbitals instead, simply to avoid misconceptions and because we use orbitals later on anyway. But here, I have not had any experience in the classroom yet.”*

After the general discussion of instructional strategies regarding the subatomic structure of matter, the focus was shifted towards the learning unit. This shift occurred naturally, as, together with students’ conceptions, the key ideas and main concepts of the unit had a great impact on the teachers’ statements during the post-intervention interviews. This fact enabled us to distinguish between the teachers’ existing knowledge of instructional strategies and any potential influences that had occurred during the professional development program. For instance, regarding the constant focus of the unit on the model aspect of physics, teacher 3 stated, *“I, myself, noticed that models do not play such a big role in my teaching as they probably should. This became very clear to me, since I saw that it makes sense to focus on the model aspect of physics already at the grade-6 level.”* Similarly, teacher 2 said, *“I think, over the coming days, I need to reflect deeply on my teaching practice. Specifically, how to incorporate the notion of models in my physics lessons. I think introducing models early on makes a lot of sense, but I will need to spend more time thinking about how best to adopt this methodology.”*

In addition to comments regarding the model aspect of physics, which the learning unit aims to convey, we noted several statements concerning the second main concept of the unit: focusing on linguistic accuracy by using key terms and phrasings. Namely, the distinction between particles (leptons and quarks) and particle systems (mesons and hadrons) appealed greatly to all four teachers and was mentioned frequently. For instance, teacher 4 stated, *"I mean, you know, I am a big fan of linguistic accuracy in the classroom, and I always try to give all key terms meaning. Sometimes, I even enjoy introducing details early on, although I know that the students will probably see the deeper meaning behind it only a couple of years later. But this is very important to me. So, I was very excited about the idea of distinguishing between elementary particles and particle systems. This makes a lot of sense to me."* Similarly, teacher 2 said, *"It became clear to me again how important it is to think about the words we use in the classroom. This is so important and so difficult, because if you do not take care from the very beginning, this will trigger nasty questions, which are even more difficult to answer. So, for me, focusing on linguistic accuracy, not just in particle physics but in every topic, is one of the takeaway messages of today."* The difficulty of using the correct terms in the classroom was also discussed by teacher 1, who stated, *"Sometimes it is just so tempting to use colorful phrasings and explain something through a funny story, which is only barely correct but keeps the students interested. But I think that students who already have trouble following my lessons might have serious problems distinguishing between my colorful language and the facts. So for me, this was yet another reminder that I have to work on being more precise in the classroom and that I have to try to avoid using too many loosely worded explanations."*

The third main concept of the unit, using typographic illustrations to represent particles and the atomic model, also led to many statements regarding instructional strategies. While most of the learning unit design is clearly novel – perhaps even radical, to some extent – the graphic representations are clearly an outstanding feature. Hence, all the teachers evaluated them as intriguing and interesting, as elegantly expressed by teacher 3: *"Well, of course, the content of the unit was clear to me, and I also know that I have to be careful with which words to use when, but the one thing that was really new to me were the typographic illustrations. Using letters to represent particles is so smart and can be done so easily even on the blackboard. So, this is something I will definitely incorporate into my teaching practice."* Additionally, teacher 2 said, *"Already during the briefing [session], I started to plan ahead how best to use the typographic illustrations in my teaching. This was a completely new aspect, and I gladly added it to my collection of teaching strategies."*

Overall, we noted several statements from all four teachers regarding instructional strategies, which enabled us to analyze the potential influences on this dimension of the teachers' PCK. In addition, the young age group of the students was again mentioned frequently by all the teachers, who were intrigued by the specific setting of the one-on-one interviews. For instance, teacher 4 mentioned, *"Well, I am now aware that there are 12-year-olds who can easily understand and make use of elementary particles. This is already good to know. Because if it does not work during these one-on-one interviews, it will definitely not work in the classroom. Now it is our job how best to transform the learning unit for our daily job."*

We noted more statements regarding the age of the students, but like the statement above, these were mostly merged with statements concerning the knowledge of assessment, which we present in the following section.

Knowledge of assessment

This dimension of PCK contains knowledge of important science domains to assess and knowledge of how to assess students. Since our research was implemented as a professional development program, in which teachers were prepared and enabled to actively take part in education research by assessing students in one-on-one interviews, the study design played an essential role in our analysis. Hence, while being limited to the topic of the professional development program, the setting itself enabled us to document the influences on the teachers' knowledge of assessment in detail.

Based on our analysis of the teachers' knowledge of curriculum, learners, and instructional strategies, we noted that every teacher had a profound knowledge of the science domains to assess during the one-on-one interviews. These consisted of the key ideas of the learning unit, which every teacher used successfully at the beginning of each one-on-one interview for his or her presentation of the information input. In addition, we noted several statements over the course of the professional development program that went far beyond the scope of the unit. For example, the careful use of red, blue, and green as the colors of quarks to set up the notion of color charge appealed greatly to all the teachers. During the briefing session, this concept led to a longer dialogue between the presenting researcher and teacher 4 about the concept of fundamental charges. This dialogue was mentioned by teacher 1 during the post-intervention interviews: *"Hm, so, about the colors. After you and [teacher 4] discussed it* *yesterday, I went home and read up on it. OK, I mean, yes, I knew about it, but I wanted to make sure that I know the background of the learning unit – just to feel prepared in case of any questions."* Teacher 2 also stated during the post-intervention interview, *"Within the learning unit, there was nothing new to me. But, yesterday's discussion about the concept of charge was very interesting to me. It just helped me to see the bigger picture."* Therefore, regarding the subatomic structure of matter, we believe it is safe to say that prior to our study, every teacher already possessed sufficient knowledge of important science domains to assess. Furthermore, our analysis showed that during the professional development program, all the teachers revisited this specific knowledge, which led to a deeper perceived understanding of science domains beyond the scope of the learning unit.

Furthermore, when analyzing teachers' knowledge of how to assess students, we noted that at first, their statements were influenced mainly by the setting of the one-on-one interviews, the young age of the students, and especially the technique of probing acceptance itself. For instance, teacher 3 stated, *"Well, in a way, this was quite extreme. I mean, elementary particles for 12-year-olds is already quite radical, but then these different tasks during the [one-on-one] interview… this was a very special way of assessing students. I think we got the clearest picture possible of their thoughts and conceptions. Because you can really see which key idea works immediately and which one takes longer for them to understand."* Teacher 4 explained his take on the benefits of the one-on-one interviews as follows: *"I have to say, this technique of probing acceptance is really well designed and simple. First, you give them something new, and then you just watch them, step by step, how they start making use of it. Specifically, when you arrive at those transfer examples, and the student really needs to apply the new knowledge to something practical. This was so rewarding to see, because, even after only two sessions, I already have a good feeling of which concepts really work always and which can be tricky."*

Later, during the post-intervention interviews, the focus of the teachers' feedback shifted towards their everyday jobs, and the teachers started to compare the unusual one-on-one situation to their classroom settings. This enabled us to gather information about their knowledge of how to assess students and to document the potential influences on this dimension of their PCK. For example, teacher 2 mentioned, *"Usually, you do not get this kind of feedback. Discussing something with only one student is* *completely different from a class full of students. So, this feedback was very useful for me."* Teacher 1 stated, *"I think, for us teachers, discussing topics with one or two students… maybe just in an informal way… is very important. Because in the classroom, you will never really know whether all students can follow. So, this kind of special feedback can help to make sure that my teaching is meaningful."* Consequently, this comparison led to the question of whether the technique of probing acceptance could be used as a technique to assess students on a general basis. Here, we noted several statements from all the teachers. For instance, teacher 4 stated, *"I think this could be very rewarding. You select a small group of students and discuss with them a topic before you introduce it in the classroom. Maybe even just one student and then following the whole setting of the one-on-one interview. Yes, I think this could be really interesting." Teacher 3 stated, "In my advanced physics course, I have only a small group of five or six students. And sometimes only one or two of them show up. So, this would be a perfect setting to use the technique of probing acceptance to try out new ideas, which I can then modify and use in the classroom."* In addition, teacher 2 came up with an even more creative use of the technique of probing acceptance, which he explained as follows: *"I have one class with very diverse students, some who are really, really excellent and some who struggle a lot already with the basics. Maybe I could use the technique of probing acceptance as kind of an expert interview, where the brilliant students conduct these one-on-one interviews with other students. Not like a study, but still with the different interview phases… more like a game. I think this could be an interesting approach, which should be helpful for both students. And at the same time, I would also see which aspects appeal to the students."*

Overall, we noted that all four teachers showed great interest in using the technique of probing acceptance in their classrooms. However, they also acknowledged the preparation time required to adequately conduct the one-on-one interviews. For instance, teacher 1 mentioned, *"I probably enjoyed the briefing session more than the [one-on-one] interviews. The questions how do I present this information to the student, which aspects do I need to focus on, and how will the whole concept work were exciting to me, and I learned a lot just by preparing myself for the intervention." Teacher 2 stated, "Well, it does not work without preparation, this is clear. I mean, the briefing session was really well organized and nicely structured. So if I want to use it on my own, I would need to properly prepare myself for it. Otherwise, it would just not make any sense."*

We also noted that teachers 1, 2, and 3 were more self-critical about their one-on-one interviews than their more experienced colleague. This difference is striking, since our analysis of all eight one-on-one interviews led to similar results regarding the students' acceptance of the key ideas of the learning unit. For example, teacher 3 stated his doubts as follows: *"I am afraid I lost my concentration during the second [one-on-one] interview. I was so excited and focused during the first one, but then this worked really well, so I was more relaxed during the second one and probably lost the tension a bit."* In contrast, teacher 1 stated, *"I was too stressed during the first [one-on-one] interview. It felt like I rushed through the first interview phase because I was afraid to run too long. During the second [one-on-one] interview, however, I was more relaxed and found it easier to conduct the individual interview phases."* Teacher 2 mentioned, *"I do not think that both my [one-on-one] interviews were perfect. It did not feel like I managed to follow the golden thread of the manual. I mean, it was OK, but it could have been way better."* Teacher 4, however, had no major criticisms of his one-on-one interviews. Instead, he stated, *"I did not make any changes between the two [one-on-one] interviews. The first one worked very well, and so I just replicated everything in the second interview again. Well, instead of a toy train, I used a globe to explain the concept of models to the second student. But aside from this, everything was the same. It was fun."*

Discussion and conclusions

This study investigated the potential for the technique of probing acceptance to be used as a tool in teachers' professional development. Specifically, the study was driven by the research question of whether the preparation and execution of one-on-one interviews based on this research method would have an impact on five dimensions of teachers' PCK. The results indicate that this is indeed the case. Not only were we able to document various statements by all the teachers hinting at the influences on all dimensions of their PCK, but we also received promising feedback from the teachers about the design of our professional development program. Indeed, our results show that all four teachers revisited their existing knowledge about the subatomic structure of matter and left with updated pedagogical content knowledge, especially regarding their knowledge of learners and knowledge of instructional strategies. Indeed, our findings show that all four teachers already possessed knowledge of topic-specific instructional strategies regarding the subatomic structure of matter. However, as shown above, our analysis strongly indicates that the teachers were challenged by the professional development program to revisit their existing knowledge of instructional strategies. Specifically, discussing students' documented conceptions about particles and reflecting on the design of the novel learning unit seemed to have a great impact on the teachers' knowledge. Hence, given the short-term nature of the professional development program, we consider the outcome of our study to be successful and very promising for future applications.

The quasi-experimental design of our study also bears limitations that must be discussed before drawing general conclusions from our results. First, choosing to focus on a small sample of four teachers enabled us to document the potential influences on the dimensions of their PCK in detail. While this approach served the purpose of this exploratory study, it limited the possibilities of conducting an additional in-depth analysis of our results. For instance, when comparing statements from teacher 4, who was the most experienced teacher of the group, and teacher 1, who started her teaching career only two years ago, our analysis hints at major differences in the extent to which the different dimensions of their PCK were influenced. Here, a more detailed analysis would be fruitful, since education research has shown that professional development programs usually have the same effect on early-career teachers and experienced teachers (Schneider & Plasman, 2011). Such an analysis, however, would require significantly more data collection with more teachers at different levels of teaching experience through further iterations of the professional development program, which will be the focus of our future research.

Second, the students who participated in the study were selected by the teachers and were highly motivated to participate in the one-on-one interviews; thus, their selection can be considered an additional limitation for the interpretation of our findings. As mentioned above, we tried to minimize the potential bias by mixing every pairing to ensure that teachers conducted their one-on-one interviews with students whom they did not teach on a daily basis. Nonetheless, this does not overcome the fact that the students were selected by the teachers based on their motivation and interest in participating in the study. Indeed, since the one-on-one interviews are designed to be highly interactive and contain several student-centered activities, we consider such willingness to be necessary for the successful implementation of the technique of probing acceptance. However, especially regarding the teachers' evaluation of their experiences during the one-on-one interviews, the student sample limits our ability to generalize from the results presented.

Third, the selection of the subatomic structure of matter as the topic of the learning unit on which the professional development program was based is ideal for the purpose of our study. It not only represents a prominent and current topic of the physics curriculum for middle and high school but is also considered a fundamental topic in science (Vikström, 2014). Furthermore, education research has shown that middle and high school students have significant difficulties integrating the concept of particles into their conceptions of everyday life (Adbo & Taber, 2009). The importance of the topic, together with the radical approach of the learning unit for introducing it to 12-year-olds, made it a prime candidate for motivating teachers to actively participate in the professional development program. Indeed, we noted several statements by all four teachers highlighting the topic of the learning unit as the main motivation to participate in our study. Therefore, we believe it is safe to conclude that the learning unit itself influenced the teachers' perceived knowledge gain to some extent and thus limits the generalizability of the study. Hence, for future iterations of the professional development program, it remains to be seen whether similar results can be achieved if the focus is placed on less appealing topics of the physics curriculum.

Fourth, when looking at the five dimensions of PCK that emerge from the conceptualization of Park and Oliver (2008), our analysis shows differences in the extent to which they were influenced during the professional development program. We found that all four teachers made considerably more statements hinting at the influence on their knowledge of learners and their knowledge of instructional strategies than on the three remaining dimensions. This did not come as a surprise, as the professional development program was aimed at updating the teachers' knowledge about students' documented conceptions and focused especially on conveying the instructional strategy of the novel learning unit. Therefore, we are tempted to attribute this imbalance entirely to the design of our exploratory study. However, since these two dimensions are considered Shulman's key elements of PCK (van Driel et al., 1998), we add the cautionary note that due to the small sample size, we are limited in excluding all potential sources for the imbalance. For instance, a possible explanation could also lie within the teachers' personal orientation towards teaching science, which may have been already well established, in which case the potential influences on this dimension of PCK would have been negligible. We expect a more detailed answer to this question when more data are collected through future iterations of the professional development program.

Implications of the study

Overall, our results show that the technique of probing acceptance is well suited for teachers' professional development, and we strongly believe that the program that emerged from this exploratory study merits further exploration. We identified three aspects of the professional development program that we consider very promising for future research. First, the program's short-term character is probably its greatest asset for fruitful applications. Indeed, the approach of involving teachers in design research projects with the overarching aim of developing their knowledge has already been established in the field of education research (Bannan-Ritland, 2008). However, this involvement is usually based on teachers' participation in long-term research cycles, which require them to commit to the research project in full. While such an endeavor can clearly promote teachers' learning of content and certainly prompts them to rethink their beliefs and practices, it does not come without cost, commitment, and effort. These aspects can make it difficult to persuade teachers to participate in the research process. In this sense, our approach of using the technique of probing acceptance during a short-term professional development program proves to be very promising. Provided that the content of the program is confined, its implementation is feasible in a very time-effective manner, and as demonstrated in our study, the intervention can be closely aligned with the teachers' professional practice.

Second, we want to highlight the setting of the one-on-one interviews, which we consider to be especially interesting for teachers' professional development. As described above, it combines a teaching part, when the teachers present their information input to the student, with a research part, when the teachers use the technique of probing acceptance during the different interview phases. Hence, it enables teachers to receive firsthand insight into the feasibility of the material that is being probed during the one-on-one interview. Furthermore, due to the different tasks set by the technique of probing acceptance, teachers can observe a student's learning process in detail. This is a unique opportunity for teachers, which education research suggests can help them understand the principles by which their actions shape student learning (Nuthall, 2004).

This suggestion leads to the third aspect, which speaks loudly for using the technique of probing acceptance with teachers during professional development programs because of its implications for education research. This approach can have added value for both the teachers who take part in the program and the researchers who conduct it. Indeed, this was true during the course of this study. We documented the influences on the teachers' dimensions of PCK during the professional development program and managed to disseminate our previously developed learning unit. Furthermore, by preparing the teachers to replicate our previous research during the one-on-one interviews, the key ideas of the unit and the accompanying illustrations were not just distributed but thoroughly discussed in a meaningful way. We consider this in-depth discussion of the material to be a very promising detail of our study design, since education research suggests that teachers need support when using provided teaching material (Bismack et al., 2014). In addition, based on the teachers' evaluation and through several iterations of the professional development program, we were able to further develop and improve the material discussed. Indeed, our study design enabled us to analyze both the teachers' knowledge and the feasibility of the learning unit. Given the timing and planning challenges that every design-based research project faces, this is another intriguing aspect that cannot be omitted from a research perspective. Hence, we conclude by emphasizing the promising implications of using the technique of probing acceptance with teachers, which we suggest merits further exploration in education research.

References

Abell, S. K. (**2007**). Research on science teacher knowledge. In S. K. Abell, & N. G. Lederman (eds.), Handbook of research on science education. Mahwah: Lawrence Erlbaum Associates, 1105–1149.

Adbo, K., & Taber, K. S., (**2009**). Learners' mental models of the particle nature of matter: a study of 16-year-old Swedish science students. *International Journal of Science Education*, 31(6), 757–786.

Bannan-Ritland, B. (**2008**). Teacher design research: an emerging paradigm for teachers professional development. In A. E. Kelly, R. A. Lesh, & J. Baek (eds.), Handbook of design research methods in education: innovations in science, technology, engineering, and mathematics learning and teaching. Routledge: Taylor & Francis, 246–262.

Baxter, J. A., & Lederman, N. G., (**1999**). Assessment and measurement of pedagogical content knowledge. In J. Gess-Newsome & N. G. Lederman (eds.), Examining pedagogical content knowledge: the construct and its implications for science education. Boston: Kluwer, 147–161.

Bindernagel, J. A., & Eilks, I. (**2009**). Evaluating roadmaps to portray and develop chemistry teachers' PCK about curricular structures concerning sub-microscopic models. *Chemistry Education Research and Practice*, 10, 77–85.

Bismack, A. S., Arias, A. M., Davis, E. A. & Palincsar, A. S. (**2014**). Connecting curriculum materials and teachers: elementary science teachers' enactment of a reform-based curricular unit. *Journal of Science Teacher Education*, 25, 489–512.

Borko, H., Jacobs, J., & Koellner, K. (**2010**). Contemporary approaches to teacher professional development. In P. L. Peterson, E. Baker, & B. McGaw (eds.), International encyclopedia of education (Vol. 7). Amsterdam: Elsevier, 548–556.

Bruce, L. R. (**1971**). A study of the relationship between the SCIS teachers' attitude toward the teacher-student relationship and question types. *Journal of Research in Science Teaching*, 8(2), 157–164.

Cochran, K. F., DeRuiter, J. A., & King, R. A. (**1993**). Pedagogical content knowing: an integrative model for teacher preparation. *Journal of Teacher Education*, 44(4), 263–272.

Design-Based Research Collective (**2003**). Design-based research: an emerging paradigm for educational inquiry. *Educational Researcher*, 32, 5–8.

Duit, R., & Treagust, D. F. (**2003**). Conceptual change: a powerful framework for improving science teaching and learning. *International Journal of Science Education*, 25(6), 671–688.

van Driel, J. H., Beijaard, D., & Verloop, N. (**2001**). Professional development and reform in science education: the role of teachers' practical knowledge. *Journal of Research in Science Teaching*, 38(2), 137–158.

van Driel, J. H., & Berry, A. (**2012**). Teacher professional development focusing on pedagogical content knowledge. *Educational Researcher*, 41(1), 26–28.

van Driel, J. H., Verloop, N., & de Vos, W. (**1998**). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching*, 35(6), 673–695.

Grossman, P. L. (**1990**). The making of a teacher: teacher knowledge and teacher education. New York: Teachers College Press.

Hashweh, M. Z. (**2005**). Teacher pedagogical constructions: a reconfiguration of pedagogical content knowledge. *Teachers and Teaching: theory and practice*, 11(3), 273–292.

Jung, W. (**1992**). Probing acceptance, a technique for investigating learning difficulties. In R. Duit, F. Goldberg, & H. Niedderer (eds.), Research in physics learning: theoretical issues and empirical studies. Kiel: IPN, 278–295.

Loughran, J., Berry, A., & Mulhall, P. (**2006**). Understanding and developing science teachers' pedagogical content knowledge. Rotterdam: Sense Publishers.

Magnusson, S., Krajcik, J., & Borko, H. (**1999**). Nature, sources and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Lederman (eds.), Examining pedagogical content knowledge: the construct and its implications for science education. Boston: Kluwer, 95–132.

Mayring, P. (**2010**). Qualitative Inhaltsanalyse. In G. Key & K. Mruck (eds.), Handbuch Qualitativer Forschung in der Psychologie. Wiesbaden: Springer, 601–613.

Northfield, J. R., & Fraser, B. J. (**1977**). Teacher characteristics and pupil outcomes in secondary science classrooms. *Research in Science Education*, 7, 113–121.

Nuthall, G. (**2004**). Relating classroom teaching to student learning: a critical analysis of why research has failed to bridge the theory-practice gap. *Harvard Educational Review*, 74(3), 273–306.

Park, S., & Oliver, J. S. (**2008**). Revisiting the conceptualisation of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education*, 38, 261–284.

Rothman, A. I., Welch, W. W., & Walberg, H. J. (**1969**). Physics teacher characteristics and student learning. *Journal of Research in Science Teaching*, 6(1), 59–63.

Schneider, R. M., & Plasman, K. (**2011**). Science teacher learning progressions: a review of science teachers' pedagogical content knowledge development. *Review of Educational Research*, 81(4), 530–565.

Shulman, L. S. (**1986**). Those who understand: knowledge growth in teaching. *Educational Researcher*, 15(2), 4–14.

Shulman, L. S. (**1987**). Knowledge and teaching: foundations of the new reform. *Harvard Educational Review*, 57(1), 1–22.

Smith, D. M., & Cooper, B. (**1967**). A study of various techniques in teaching science in the elementary school. *School Science and Mathematics*, 67(6), 559–566.

Tamir, P. (**1988**). Subject matter and related pedagogical knowledge in teacher education. *Teaching and Teacher Education*, 4(2), 99–110.

Vikström, A. (**2014**). What makes the difference? Teachers explore what must be taught and what must be learned in order to understand the particulate character of matter. *Journal of Science Teacher Education*, 25, 709–727.

Wallace, J., & Loughran, J. (**2012**). Science teacher learning. In B. J. Fraser, K. G. Tobin, & C. J. McRobbie (eds.), Second international handbook of science education. Dordrecht: Springer, 295–306.

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**2015**). Can Grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education*, 3(4), 313-322.

Wiener, G. J., Schmeling, S. M., & Hopf, M. (**2017**). Why not start with quarks? Teachers investigate a learning unit on the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education* (submitted).

Wilson, S. M., Shulman, L. S., & Richert, A. E. (**1987**). “150 different ways of knowing: representations of knowledge in teaching.” In J. Calderhead (ed.), Exploring teachers’ thinking. Sussex: Holt, Rinehart, & Winston.

Yin, R. K. (**2011**). Qualitative research from start to finish. New York: The Guilford Press.

5. Discussion

Overall, the doctoral research project led to very promising results and thus was concluded successfully. Indeed, as presented in articles A to F, a substantial contribution to the field of physics education research was made by investigating how to best introduce elementary particle physics early in the classroom. First, during the initial phase of the doctoral research project, the learning unit on the subatomic structure of matter was developed through a design-based research project with iterative retesting and redesign phases. Here, the final version of the learning unit led to great acceptance by the grade-6 students, who took part in the studies. In addition, various aspects of elementary particle physics were identified, which can be introduced in the classroom in an appropriate and meaningful way. Furthermore, the evaluation of the learning unit also showed that by taking the unit's main concepts into account, common misconceptions about the nature of particles can be avoided (Wiener et al., 2015).

Next, the initial study was replicated, but this time the research was conducted by professionally developed teachers, instead of by education researchers. Indeed, this follow-up study was facilitated by establishing a new professional development programme, which introduces teachers to novel teaching material and enables them to evaluate it by using the technique of probing acceptance. Again, the findings from this follow-up study showed the unit's key ideas and main concepts to be adequate and well-suited for a broad evaluation in the classroom (Wiener et al., submitted1).

Hence, the successful development of the learning unit with both high school students and teachers gave way to the second phase of the doctoral research project, which was directed at exploring the potential benefits of transforming the technique of probing acceptance into a tool for teacher training. Therefore, an exploratory study was designed to investigate the impact of the previously established professional development programme on teachers' pedagogical content knowledge (PCK). In doing so, the timeframe of the professional development programme was slightly modified and the research focus was shifted towards documenting and analysing the teachers' statements made during the semi-structured post-intervention interviews. Indeed, in accordance with the rationale of the study, findings indicated that the preparation and execution of one-on-one interviews based on the technique of probing acceptance had an influence on dimensions of teachers' PCK, especially with regard to their knowledge of learners and knowledge of instructional strategies (Wiener et al., submitted3).

In conclusion, successful and promising findings were obtained during the doctoral research project, which can be divided into two parts: the development of the learning unit on the subatomic structure of matter through the technique of probing acceptance, and, second, the examination of the technique of probing acceptance as a tool for teacher training. Hence, this final discussion of the dissertation is also split into two parts, to adequately summarise and discuss both aspects of the doctoral research project, before drawing general conclusions from the findings presented in the individual publications of the dissertation.

A. The learning unit and its development

The most important outcome of the development of the learning unit are its key ideas (Table I) and main concepts, which turned out to be very promising for use in the classroom. Namely, focusing on linguistic accuracy and the use of novel typographic illustrations (Figure 1) can be considered as the unit's most prominent features. Indeed, findings showed that taking both aspects into account facilitates an early introduction of elementary particles and supports the unit's aim of strongly conveying the model aspect of physics. Moreover, since these features were developed with grade-6 students, who possessed no prior knowledge about elementary particles and atoms, the unit's evaluation also highlighted its potential to be used with older students at a later stage in the physics curriculum. This is also supported by students' documented avoidance of misconceptions about the "appearance" of particles, which was traced back to the use of typographic illustrations.

In each iteration of the initial study's design-based research approach, several terms and phrasings were found to be problematic for use with 12-year-olds and required educational reconstruction. Here, the challenge consisted in maintaining a balance between physical accuracy and educational adequacy in the formulations of each key idea. For instance, during the first iteration of the learning unit, students' feedback strongly suggested the use of "model of particle physics" as a simplified and more meaningful version of the commonly used “Standard Model of particle physics”. Hence, this key term was adapted accordingly, leading to it being more broadly accepted during further iterations of the one-on-one interviews. This example illustrates the difficulty of introducing established terms, that students might find difficult to understand. However, by comparison, developing appropriate educational reconstructions of explanations about the nature of elementary particles turned out to be even more challenging. For example, when it came to the introduction of electrons and the theory of orbitals, it was difficult finding the right words for an adequate formulation, which describes the idea of orbitals without triggering misconceptions of electrons fizzing around on defined orbits. Here, several phrasings, such as “electrons are located…” or “electrons exist…”, were used during the development of the learning unit, until the current description of the orbital-space as the location, where “it is likely to find electrons”, was identified to be the most understandable explanation for grade-6 students. Nonetheless, both from a scientific and an educational point of view, this phrasing still has limitations, as it bears the risk of introducing the misconception that one can define the precise location of an electron within the orbital-space. However, it is worthwhile noting that the learning unit was entirely developed in German, the native language of the students, who volunteered to evaluate its content. Here, the original phrasing “Im Orbital-Bereich kann man irgendwo Elektronen finden” conveys a more probabilistic meaning than its English translation, and thus illustrates the challenge of using teaching material in different languages.

Table I. Key ideas of the learning unit on the subatomic structure of matter.

#	Key idea
I	Matter is everything that can be touched, practically or theoretically.
II	Reality is described through models. For example the model of particle physics.
III	In the model of particle physics, there are atoms, which may combine to form compounds.
IV	In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.
V	In the nucleus-space, protons and neutrons are located.
VI	Protons and neutrons are particle systems, which are made of quarks.
VII	Quarks are indivisible. In this model, these are called elementary particles.
VIII	In the orbital-space, it is possible to find electrons.
IX	Electrons are indivisible. In this model, these are called elementary particles.
X	In this model, apart from particles, there is only empty space.

Figure 1. Typographic illustrations of a) the atomic model, which highlights the distinction between the nucleus-space and the orbital-space, b) a proton and a neutron, as used at the beginning of the learning unit, and c) a proton and an antineutron, as used at the end of the learning unit.

When considering the technique of probing acceptance, which was used to develop the learning unit, the successful implementation of the study design shows this specific research method to be well-suited for the design-based approach of the doctoral research project. In particular, the high degree of interactivity during the one-on-one interviews and the student-centred focus of the individual interview phases led to a rich and diverse set of qualitative data to be documented, which allowed for a detailed evaluation of the various adaptations of the learning unit. Furthermore, the possibility of using the technique of probing acceptance with instructed teachers gave way to an additional facet of evaluating the learning unit from the teachers' perspective, and ultimately led to the exploratory study, which investigated potential influences on dimensions of teachers' PCK during their one-on-one interview sessions.

However, aside from the ambiguous name of the technique of probing acceptance – as already mentioned, the overall analysis of the studies suggests "probing plausibility" or "checking feasibility" as better-suited descriptions of this technique – the selection of participating students for the one-on-one interviews is crucial for a successful implementation of the research method and thus deserves some comment. Indeed, not only must the students' prior knowledge and interest regarding the topic discussed be taken into account, but their personal orientation towards the individual tasks during the one-on-one interview plays an even more important role. Specifically, due to their being so strongly student-centred, one-on-one interviews with students who feel comfortable discussing and evaluating new material yield a considerable amount of data for analysis. Hence, such a positive selection of the student sample is preferred to ensure the successful implementation of the research method. At the same time, however, this limits the extent to which conclusions drawn from the analysis of the one-on-one interviews can be generalised, and care must be taken when transferring findings from the quasi-experimental setting into the classroom.

Based on the successful development of the learning unit on the subatomic structure of matter, several research goals can be outlined for future research. First, the follow-up unit, which builds on the atomic model by introducing fundamental interactions and their associated bosons, still awaits research-driven formulation. This would lead to the development and evaluation of adequate learning material about fundamental interactions between elementary particles. Investigating such a unit‘s potential by means of a design-based research project using the technique of probing acceptance appears to be logical. However, the question arises, how to best implement such a study in a timely manner, since both learning units ought to be investigated simultaneously. Moreover, such an evaluation should also focus on exploring whether and how the two units support each other, which adds another layer to the research question. Here, it might be useful and interesting to slightly shift the age-group towards grade-8 students, who already have knowledge about the atomic model, to also document the feasibility of using the main concepts of the learning material at a later stage in the curriculum.

Second, to facilitate the learning unit's international transfer in physics classrooms, the successful evaluation of the learning unit's original German version could be replicated in the English language. Specifically, investigating students' understanding of the unit's key ideas, when they are translated into a different language, could reveal elements of the information input, that work independently of the respective language. In addition, evaluating a different language version of the unit should also give insight into language-specific students' conceptions about the subatomic structure of matter, which occur due to the respective phrasings of the unit's key ideas. Ultimately, by implementing yet another scheme of iterative retesting and redesign phases, such evaluation should lead to the development of an adequate English version of the learning unit to be used in the classroom.

Third, to further facilitate the learning unit's transfer into the classroom, educational perspectives on relevant topics from the physics curriculum could be reconstructed by incorporating the learning unit's key ideas and main concepts. For example, the topic of radioactivity is a prime candidate to further discuss the subatomic structure of matter. Hence, by focusing on examples and processes of natural radiation, the previously established notion of elementary particles and fundamental interactions could be implemented in a meaningful way. Furthermore, reconstructing the prominent topics of optics and electricity from a particle point of view could also lead to the development of adequate learning and teaching material, which would support teachers in their endeavour of introducing particle physics in the classroom.

B. The technique of probing acceptance for teachers' professional development

The most important outcome of the second part of this doctoral research project is the successful transformation of the research method itself into an effective tool for teacher training. Indeed, enabling teachers to use the technique of probing acceptance during one-on-one interview sessions led to a shift in the research focus, and instead of solely investigating the students' understanding and teachers' evaluation of the unit's key ideas, an additional exploration of influences on the teachers' PCK was carried out. Here, initial findings strongly suggest that having teachers prepare for and execute one-on-one interviews based on the technique of probing acceptance has a positive impact on the development of their PCK about the topic discussed. Hence, the research method itself proved to be very promising for further exploration in future adaptions of the professional development programme. Furthermore, aside from its potential to train teachers, this approach also bears promising implications for education research. Specifically, since it enables researchers to develop and evaluate new learning material, while at the same time instructing teachers about its contents and rationale to document their evaluation, this setting gives way to multi-layered analyses of the material in question. In addition, another strong asset of this approach is the fact that the professional development programme can be implemented in close alignment with teachers' classroom practice in a timely manner, which highlights the programme's potential to be investigated in a professional context.

However, enabling teachers to conduct one-on-one interviews based on the technique of probing acceptance comes at a cost. Indeed, a lot of effort is required to prepare the material in question and to implement it within the professional development programme. Specifically, careful design of the briefing session for teachers is key to a successful execution of the interview sessions later on. First, this briefing needs to convince teachers of the effectiveness and usefulness of the material to be tested. Here, the presentation of documented students' conceptions and how they are addressed within the learning unit turned out to be very helpful for motivating teachers to actively work through the unit's key ideas. Next, the technique of probing acceptance needs to be thoroughly discussed with the teachers. This crucial part of the briefing can be supported by showcasing the research manual, which simultaneously serves as a guide for teachers during their one-on-one interviews. Here, the use of a check-list format proved to be beneficial, since it led teachers from step to step and ultimately ensured a complete data collection (The complete research manual can be found in the appendix to this thesis). The handling of this research manual, however, requires practise, which needs to be addressed and accounted for during the briefing session. Indeed, looking at the design of the exploratory study shows that the short-term character of the professional development programme is only an asset if it is based on long-term preparation.

Bearing in mind the promising results of the exploratory study, one can identify several research aspects which merit further investigation to fully develop the professional development programme. Specifically, future adaptions of the professional development programme should focus on different topics of the physics curriculum, to better investigate its general applicability. Indeed, the initial findings from the exploratory study do not give full insight to what extent the rather prominent topic of elementary particles influenced the teachers' perception of the professional development programme, which limits the generalisability of the results. Hence, it would be very interesting to see replications of the professional development programme which focus on learning material discussing more commonly used topics, such as, for example, mechanics, optics, or electricity. Furthermore, since in the programme's current form the teachers are only introduced to previously evaluated learning material, another intriguing approach could be to implement the professional development programme at an earlier stage in the design and development process of learning material. This would strengthen the design-based research aspect of the programme and lead to an increased involvement of the teachers. The potential benefits of such an approach for the development of teachers' pedagogical content knowledge, however, remain to be investigated through further iterations of the professional development programme.

C. General conclusions

Overall, the successful results of the doctoral research project have implications for both physics education and physics education research. Indeed, by developing and examining the learning unit on the subatomic structure of matter, substantial contributions have been made regarding the teaching of elementary particle physics in early physics education. Specifically, the unit's key ideas proved themselves to be understandable and meaningful for 12-year-olds, which showed them to be well-suited for evaluation in the physics classroom. In addition, two of the three unit's main concepts, namely linguistic accuracy and typographic illustrations, were identified as key sources for the reduction of documented students' misconceptions, which also strongly support the unit's third main concept – conveying the model aspect of physics. Most of all, however, the successful development of the learning unit highlights the important role of design-based and theory-driven education research as the foundation of today's physics education. This is especially true for the transformation of the technique of probing acceptance into an effective method for teachers' professional development, which strongly benefited from the design-based approach of the exploratory study. Indeed, both research aspects of the doctoral research project heavily relied on iterative testing and designing, which led to the successful development of the learning unit and the promising exploration of the research method.

For future steps, the results of the doctoral research project can act as a starting point to facilitate the transfer of elementary particle physics into the classroom and to fully investigate the potential of the technique of probing acceptance. Indeed, this dissertation gives way to several research questions, which merit exploration through further research. Specifically, a broad evaluation of the learning unit on the subatomic structure of matter at different grade levels would be intriguing. Such an investigation would also benefit from the additional development of learning and teaching material, which builds on the learning unit's key ideas and main concepts. Furthermore, the exploration of the technique of probing acceptance as a tool for teachers' professional development deserves further research as well. Here, the focus should be placed on examining its general applicability by conducting further editions of the professional development programme with different topics of the physics curriculum. In addition, implementing editions of the professional development at varying stages of the development of the learning material in question could give further insight into the programme's potential and open the door to the development of a more research-oriented teacher training.

Overall, the topic of elementary particle physics is a prime candidate for the introduction of modern physics in the classroom. Satisfyingly, the results and findings of this doctoral research project support the ongoing integration of elementary particles and fundamental interactions into modern curricula.

6. References

Aydm, S., Demirdögen, B., Muslu, N. & Hanuscin, D. L. (**2013**). Professional journals as a source of PCK for teaching nature of science: an examination of articles published in the science teacher (TST) (an NSTA journal), 1995–2010. *Journal of Science Teacher Education*, 24, 977–997.

Boz, Y. (**2006**). Turkish pupils' conceptions of the particulate nature of matter. *Journal of Science Education and Technology*, 15, 203–213.

Bransford, J. D., Brown, A. L. & Cocking, R. C. (**2000**). How people learn: brain, mind, experience, and school. Washington, D.C.: National Academy Press.

Cochran, K. F., DeRuiter, J. A. & King, R. A. (**1993**). Pedagogical content knowing: an integrative model for teacher preparation. *Journal of Teacher Education*, 44(4), 263–272.

Design-Based Research Collective (**2003**). Design-based research: an emerging paradigm for educational inquiry. *Educational Researcher*, 32, 5–8.

Duit, R. (**1996**). The constructivist view in science education – what it has to offer and what should not be expected from it. *Investigações em Ensino de Ciências*, 1, 40–75.

Duit, R. & Treagust, D. F. (**2003**). Conceptual change: a powerful framework for improving science teaching and learning. *International Journal of Science Education*, 25(6), 671–688.

Duit, R., Treagust, D. & Widodo, A. (**2008**). Teaching science for conceptual change: theory and practice. In S. Vosniadou (ed.), International Handbook of Research on Conceptual Change. New York: Routledge, 629–646.

Fortus, D. & Krajcik, J. (**2012**). Curriculum coherence and learning progressions. In B. J. Fraser et. al. (eds.), Second International Handbook of Science Education. Dordrecht: Springer, 783–798.

Grossman, P. L. (**1990**). The making of a teacher: teacher knowledge and teacher education. New York: Teachers College Press.

Harrison, A. G. & Treagust, D. F. (**1996**). Secondary students' mental models of atoms and molecules: implications for teaching chemistry. *Science Education*, 80, 509–534.

Harrison, A. G. & Treagust, D. F. (**2000**). Learning about atoms, molecules, and chemical bonds: a case study of multiple-model use in grade 11 chemistry. *Science Education*, 84, 352–381.

Jung, W. (**1992**). Probing acceptance, a technique for investigating learning difficulties. In R. Duit, F. Goldberg & H. Niedderer (eds.), Research in Physics Learning: Theoretical Issues and Empirical Studies. Kiel: IPN, 278–295.

Kattmann, U., Duit, R., Gropengießer, H. & Komorek, M. (**1995**). Educational reconstruction – bringing together issues of scientific clarification and students' conceptions. Paper presented at the annual meeting of the National Association of Research in Science Teaching, St Louis, MO.

Kattmann, U., Duit, R., Gropengießer, H. & Komorek, M. (**1997**). Das Modell der Didaktischen Rekonstruktion – Ein Rahmen für naturwissenschaftsdidaktische Forschung und Entwicklung. *Zeitschrift für Didaktik der Naturwissenschaften*, 3, 3–18.

Koponen, I. T. & Pehkonen, M. (**2010**). Coherent knowledge structures of physics represented as concept networks in teacher education. *Science & Education*, 19, 259–282.

Kosso, P. (**2009**). The large-scale structure of scientific method. *Science & Education*, 18, 33–42.

Loughran, J., Berry, A. & Mulhall, P. (**2006**). Understanding and developing science teachers' pedagogical content knowledge. Rotterdam: Sense Publishers.

Magnusson, S., Krajcik, J. & Borko, H. (**1999**). Nature, sources and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Lederman (eds.), Examining Pedagogical Content Knowledge: The Construct and its Implications for Science Education. Boston: Kluwer, 95–132.

Mayring, P. (**2010**). Qualitative Inhaltsanalyse. In G. Key & K. Mruck (eds.), Handbuch Qualitativer Forschung in der Psychologie. Wiesbaden: Springer, 601–613.

McComas, W. F., Almazroa, H. & Clough, M. P. (**1998**). The nature of science in science education: an introduction. *Science & Education*, 7, 511–532.

Mestre, J. P. (**2001**). Implications of research on learning for the education of prospective science and physics teachers. *Physics Education*, 36(1), 44–51.

Mestre, J. P. & Cocking, R. R. (**2002**). Applying the science of learning to the education of prospective science teachers. In R. W. Bybee (ed.), Learning Science and the Science of Learning. Arlington, Virginia: NSTA, 13–22.

Ministry of Education and Training of the State of North Rhine-Westphalia (**2014**). Secondary Education Physics Curriculum. http://www.schulentwicklung.nrw.de/lehrplaene/upload/klp_SII/ph/KLP_GOSt_Physik.pdf (accessed: 28 February 2017).

Mullis, I., Martin, M., Minnich, C., Stanco, G., Arora, A., Centurino, V. & Castle, C. (**2012**). TIMSS 2011 Encyclopedia: Education Policy and Curriculum in Mathematics and Science, Volumes 1 and 2. Chestnut Hill, MA: TIMSS & PIRLS International Study Center, Boston College.

Nousiainen, M. & Koponen, I. T. (**2010**). Concept maps representing knowledge of physics: connecting structure and content in the context of electricity and magnetism. *Nordic Studies in Science Education*, 6(2), 155–172.

Novick, S. & Nussbaum, J. (**1981**). Pupils' understanding of the particulate nature of matter: a cross-age study. *Science Education*, 65, 187–196.

Park, S. & Oliver, J. S. (**2008**). Revisiting the conceptualisation of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education*, 38, 261–284.

Pfundt, H. (**1981**). Das Atom – Letztes Teilungsstück oder erster Aufbaustein? Zu den Vorstellungen, die sich Schüler vom Aufbau der Stoffe machen. *chimica didactica*, 7, 75–94.

Shulman, L. S. (**1986**). Those who understand: knowledge growth in teaching. *Educational Researcher*, 15(2), 4–14.

Shulman, L. S. (**1987**). Knowledge and teaching: foundations of the new reform. *Harvard Educational Review*, 57(1), 1–22.

Snir, J., Smith, C. L. & Raz, G. (**2003**). Linking phenomena with competing underlying models: a software tool for introducing students to the particulate model of matter. *Science Education*, 87, 794–830.

Snyder, J. L. (**2000**). An investigation of the knowledge structures of experts, intermediates and novices in physics. *International Journal of Science Education*, 22, 979–992.

Stavy, R. (**1991**). Children's ideas about matter. *School Science and Mathematics*, 91(6), 240–244.

Tamir, P. (**1988**). Subject matter and related pedagogical knowledge in teacher education. *Teaching and Teacher Education*, 4(2), 99–110.

Treagust, D. F., Chandrasegaran, A. L., Crowley, J., Yung, B. H. W., Cheong, I. P.-A. & Othman, J. (**2010**). Evaluating students' understanding of kinetic particle theory concepts relating to the states of matter, changes of state and diffusion: a cross-national study. *International Journal of Science and Mathematics Education*, 8, 141–164.

Vikström, A. (**2014**). What makes the difference? Teachers explore what must be taught and what must be learned in order to understand the particulate character of matter. *Journal of Science Teacher Education*, 25, 709–727.

Vosniadou, S., Vamvakoussi, X. & Skopeliti, I. (**2008**). The framework theory approach to the problem of conceptual change. In S. Vosniadou (ed.), International Handbook of Research on Conceptual Change. New York: Routledge, 3–34.

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**2015**). Can Grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education*, 3(4), 313-322.

Wiener, G. J., Woithe, J., Brown, A. & Jende, K. (**2016**). Introducing the LHC in the classroom: an overview of education resources available. *Physics Education*, 51(3), 1-7.

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**accepted**). An alternative proposal for the graphical representation of anticolor charge. *The Physics Teacher*.

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted1**). Why not start with quarks? Teachers investigate a learning unit on the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education*.

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted2**). Introducing 12-year-olds to elementary particles. *Physics Education*.

Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted3**). The technique of probing acceptance as a tool for teachers' professional development: a PCK study. *Journal of Research in Science Teaching*.

Yin, R. K. (**2011**). Qualitative research from start to finish. New York: The Guilford Press.

van Zele, E., Lenaerts, J. & Wieme, W. (**2004**). Improving the usefulness of concept maps as a research tool for science education. *International Journal of Science Education*, 26, 1043–1064.

7. Appendix

A. Research Manual

Probing acceptance of the subatomic structure of matter with 12-year-olds: from a teacher's perspective

CERN 2015 | jeff.wiener@cern.ch

1. Questions about the person

1.1 Gender

☐ female
☐ male

1.2 Age

_____ years

1.3 Teaching experience

_____ years

1.4 Teaching subjects

____

2. Questions about particle physics

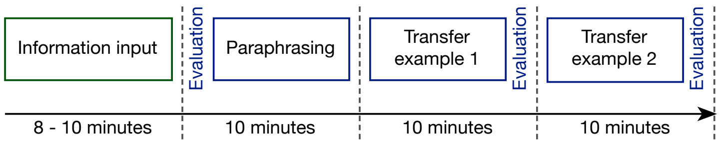
	I consider particle physics to be	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
2.1	…exciting	☐	☐	☐	☐	☐
2.2	…picturesque	☐	☐	☐	☐	☐
2.3	…easy to understand	☐	☐	☐	☐	☐
2.4	…meaningless	☐	☐	☐	☐	☐
2.5	…useless	☐	☐	☐	☐	☐
2.6	…monotonous	☐	☐	☐	☐	☐

3. Questions about the learning unit

	I consider an early introduction of basic concepts of particle physics to be	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
3.1	…adequate	☐	☐	☐	☐	☐
3.2	…feasible	☐	☐	☐	☐	☐
3.3	…complicated	☐	☐	☐	☐	☐
3.4	…useful	☐	☐	☐	☐	☐

Probing acceptance of the subatomic structure of matter with 12-year-olds: from a teacher's perspective
CERN 2015 | jeff.wiener@cern.ch

Setting and timeframe of the one-on-one interview



Key words and how they are used in phrasings

Key word	Example
Description	Reality is described through models. For example, the model of particle physics.
Particle	In the model of particle physics, electrons and quarks are elementary particles.
Particle system	Protons and neutrons are particle systems, which are made of quarks.
Nucleus-space	Protons and neutrons are located in the nucleus-space.
Orbital-space	In the orbital-space, it is possible to find electrons.

Useful anchor phrases

Phase	Anchor phrases
Evaluation	• How does this sound to you? • Was the presented information easy to understand? • Can you recall any details that you could not understand at all? • What is your general impression of this information input?
Paraphrasing	• Can you tell me again – in your own words – everything you remember from what I have just presented to you? • How would you explain this to a friend?
Transfer example	• How does this example relate to what you just heard? • How do you picture this 'in reality'? • Can you think of another, different way of explaining this?

Probing acceptance of the subatomic structure of matter with 12-year-olds: from a teacher's perspective
CERN 2015 | jeff.wiener@cern.ch

10 Minuten | 20 Minuten | 30 Minuten | 40 Minuten

Key Ideas	**Paraphrasing** "in own words"	**Transfer example 1** Grains of salt	**Transfer example 2** Droplets of water
1. Matter is everything that can be **touched**, practically or theoretically.	☐	☐	☐
2. Reality is **described** through models. For example the model of particle physics.	☐	☐	☐
3. In this **model**, there are atoms, which may combine to form compounds.	☐	☐	☐
4. In this model, atoms are divided into two **areas**: the nucleus-space and the orbital-space.	☐	☐	☐
5. In the **nucleus-space**, protons and neutrons are located.	☐	☐	☐
6. Protons and neutrons are particle systems, which are **made of quarks**.	☐	☐	☐
7. Quarks are indivisible. In this **model**, these are called elementary particles.	☐	☐	☐
8. In the **orbital-space**, it is possible to find electrons.	☐	☐	☐
9. Electrons are indivisible. In this **model**, these are called elementary particles.	☐	☐	☐
10. In this **model**, apart from particles, there is only empty space.	☐	☐	☐

☐ Evaluation ☐ Evaluation ☐ Evaluation

B. Supervisor's confirmation regarding the doctoral candidate's contribution to the publications

universität
wien

Austrian Educational
Competence Centre Physics

Univ.-Prof. Dr. Martin Hopf
Porzellangasse 4
A-1090 Vienna

T +43-1-4277-60330
martin.hopf@univie.ac.at
http://www.univie.ac.at/aeccp/

Vienna, February 28th 2017

Dissertation Mag. Wiener

I hereby confirm that Mag. Wiener was by far the principal contributor to the publications printed in this dissertation.

M. Hopf

Martin Hopf

Acknowledgements

With these lines I close my dissertation and conclude my doctoral research project. I look back at an incredibly educational chapter of my professional life, which was driven by eye-opening research studies, lengthy phases of both dreadful and joyful peer-review, enlightening encounters with students and teachers, but most of all by the collaborative spirit at CERN in which I was fortunate to take part.

From the very beginning, I was expertly supported by my university advisor, Prof. Dr. Martin Hopf, who not only showed me the importance and elegance of design-based research, but also guided me throughout my doctoral research project with his deep and broad knowledge. Indeed, his highly accurate yet realistic approach to physics education research is a prime example of how I aspire to continue in my own research career. Thank you, Martin!

I also want to thank my CERN supervisor, Dr. Sascha Schmeling, for his continuous support and friendship. When I started my first contract at CERN five years ago, I could never have dreamed of all the amazing opportunities that he would present me with. I am extremely grateful for these, and I am looking forward to our future collaboration.

My first days at CERN were greatly influenced by my encounter with Konrad Jende and Martin Hawner, who welcomed me into their office with open arms. It is impossible to find better colleagues and friends, and I nostalgically look back at the good old triumvirate days.

I am eternally indebted to Alex Brown for his careful proof-reading, helpful suggestions, and valuable linguistic explanations regarding the many drafts of my papers. My scientific work was also fuelled by many fruitful discussions with Mathias Tomandl, Michael Kobel, Rodney Jory, and many others. Furthermore, I want to thank all the students and teachers who devoted their time to participate in my studies.

Last, I want to express my gratitude to Julia for all her patience and encouragement, and I want to thank my entire family – especially my parents, Ingeborg and Wolfgang Wiener – for their life-long support and backing.

Curriculum Vitae

Mag. Gerfried Wiener

Date of birth: 13.11.1985

Place of birth: St.Veit/Glan, Austria

Education and Work Experience

since 2016
PostDoc Research Fellow and CERN Teacher Programme Manager

2013 – 2017
PhD studies, physics education research, University of Vienna & CERN

2012 – 2013
CERN Project Associate, Netzwerk Teilchenwelt, Technical University of Dresden

2011 – 2012
Voluntary teaching position, ACODO orphanage, Siem Reap, Cambodia

2009 – 2011
Teaching position at GRG 21 “Bertha von Suttner – Schulschiff”, Vienna

2008 – 2010
Tutor, physics didactics and e-learning, University of Vienna

2004 – 2010
Studies of physics, psychology and philosophy, University of Vienna

Educational Outreach

since 2012
Official CERN conférencier and guide (CERN visits service & travelling exhibitions)

2013 - 2014
Design, project management, and development of CERN’s S’Cool LAB

Talks and Posters

2015
International Conference on Physics Education, Beijing, China
Probing acceptance of the subatomic structure of matter with 12-year-olds (T)

2015
GDCP Annual meeting, Berlin, Germany
Akzeptanzbefragungen als LehrerInnenfortbildung (P)

2015
DPG Spring meeting on physics didactics, Wuppertal, Germany
Alternativvorschlag zur graphischen Darstellung von Anti-Farbladungen (T)

2014
GDCP Annual meeting, Bremen, Germany
Akzeptanzbefragung mit 12-Jährigen zum subatomaren Aufbau der Materie (P)

2014
AECC Summer School, Spital am Pyhrn, Austria
Entwicklung eines Unterrichtsmodells zu den Grundlagen der Teilchenphysik (T)

Publications

1. Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted**). The technique of probing acceptance as a tool for teachers' professional development: a PCK study. *Journal of Research in Science Teaching*
2. Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted**). Introducing 12-year-olds to elementary particles. *Physics Education*
3. Wiener, G. J., Schmeling, S. M. & Hopf, M. (**submitted**). Why not start with quarks? Teachers introduce grade-6 students to quarks. *European Journal of Science and Mathematics Education*
4. Wiener, G. J., Schmeling, S. M. & Hopf, M. (**accepted**). An alternative proposal for the graphical representation of anticolor charge. *The Physics Teacher*
5. Woithe, J., Wiener, G. J. & Van der Veken, F. (**accepted**). Let's have a coffee with the Standard Model of particle physics! *Physics Education*

6. Wiener, G. (**2017**). Wie kommt man am besten zum CERN? *Praxis der Naturwissenschaften - Physik in der Schule*, 66(1), 36-39

7. Feistmantl, A., Woithe, J., Wiener, G. & Hopf, M. (**2017**). Verschiedene Detektoren für den Unterricht - ein Überblick. *Praxis der Naturwissenschaften - Physik in der Schule*, 66(1), 33-35

8. Wiener, G., Schmeling, S. & Hopf, M. (**2017**). Elementarteilchenphysik im Anfangsunterricht. *Praxis der Naturwissenschaften - Physik in der Schule*, 66(1), 15-21

9. Woithe, J. & Wiener, G. (**2017**). Der Lagrangian entmystifiziert - Kaffeeklatsch mit dem Standardmodell der Teilchenphysik. *Praxis der Naturwissenschaften - Physik in der Schule*, 66(1), 9-14

10. Wiener, G., Woithe, J., Brown, A. & Jende, K. (**2017**). Wie passt der LHC in den Physikunterricht? *Praxis der Naturwissenschaften - Physik in der Schule*, 66(1), 5-8

11. Wiener, G., Schmeling, S. & Hopf, M. (**2016**). Akzeptanzbefragungen als LehrerInnenfortbildung. In: C. Maurer (Hrsg.), Authentizität und Lernen – das Fach in der Fachdidaktik. Gesellschaft für Didaktik der Chemie und Physik, Jahrestagung in Berlin 2015 (S. 536-538). Universität Regensburg

12. Wiener, G. J., Woithe, J., Brown, A. & Jende, K. (**2016**). Introducing the LHC in the classroom: an overview of education resources available. *Physics Education*, 51(3), 1-7

13. Wiener, G. J., Schmeling, S. M. & Hopf, M. (**2016**). Probing acceptance of the subatomic structure of matter with 12-year-olds. Proceedings of the International Conference on Physics Education (Beijing)

14. Wiener, G., Schmeling, S. & Hopf, M. (**2015**). Alternativvorschlag zur graphischen Darstellung von Anti-Farbladungen. PhyDid B - Didaktik der Physik - Beiträge zur DPG-Frühjahrstagung 2015: Wuppertal

15. Wiener, G. J., Schmeling, S. M. & Hopf, M. (**2015**). Can grade-6 students understand quarks? Probing acceptance of the subatomic structure of matter with 12-year-olds. *European Journal of Science and Mathematics Education*, 3(4), 313-322

16. Wiener, G., Schmeling, S. & Hopf, M. (**2015**). Akzeptanzbefragung mit 12-Jährigen zum subatomaren Aufbau der Materie. In: S. Bernholt (Hrsg.), Heterogenität und Diversität - Vielfalt der Voraussetzungen im naturwissenschaftlichen Unterricht. Gesellschaft für Didaktik der Chemie und Physik, Jahrestagung in Bremen 2014 (S. 450-452). Kiel: IPN

17. Wiener, G. (**2011**). Welle? Teilchen! Wittgensteins sprachphilosophischer Grenzbegriff im Kontext Heisenbergs moderner Physik als Stütze einer zeitgemäßen Physikdidaktik. VDM Verlag Dr. Müller