Practitioners’ views on new teaching material for introducing quantum optics in secondary schools

Philipp Bitzenbauer

Friedrich-Alexander-Universität Erlangen-Nürnberg, Department Physik, Didaktik der Physik, Staudstraße 7, D-91058 Erlangen, Germany
E-mail: philipp.bitzenbauer@fau.de

Abstract
In an earlier contribution in Physics Education (Bitzenbauer and Meyn 2020 Phys. Educ. 55 055031), we presented a new teaching sequence on quantum optics on the secondary school level, and we reported on promising results of a first pilot study concerning its learning effectiveness. In the sense of design-based research, the developed teaching material is now being revised in several iteration steps and optimised through feedback from teachers from the field in order to favour the implementation of the new teaching approach to quantum physics in secondary schools. We present the design principles from the literature that our teaching material’s development is based on and report on a survey of physics teachers’ practical experiences with our teaching material.

Keywords: quantum physics, teaching material, secondary schools, teacher survey

1. Teachers’ usage of innovative teaching material
A central goal of physics education research is to improve the quality of physics teaching. Therefore, innovative teaching concepts and related materials are developed and evaluated [1]. However, studies on the implementation of developed teaching concepts and teaching materials in classroom practice show that these are often only poorly established in schools. Instead, it is observed that teachers use materials provided very heterogeneously [2, 3] and often differently than intended by the material developers [4, 5]. This is not surprising, since teachers’ goals with the teaching materials, e.g. supporting learning objectives [6], may differ from those of the material developers [5, 7].
Physics teachers’ use of teaching materials is centrally dependent on material-specific properties and external factors [8]. A reciprocal influence between teacher and teaching material is described in Remillard’s model [9]: this model outlines the interplay between material characteristics (e.g. design, goals of the material, structuring) and teacher characteristics, e.g. the teachers’ beliefs about learning and teaching [10] or the teachers’ abilities [11], when planning and performing classroom lessons. Thus, teachers’ characteristics influence the teachers’ usage of teaching material [9]. These teachers’ characteristics are also taken account in Gregoire’s cognitive-affective model of conceptual change [12]. In this model, various teachers’ characteristics influencing the use of new pedagogical ideas in classroom practice are related to each other in order to describe the process of implementing these new pedagogical ideas in the classroom from the perspective of teachers (cf. figure 1). Breuer et al. [13] argue that this model can also be applied to teachers’ use of innovative teaching material and state that teachers make anchor decisions when assessing new teaching concepts or materials, which ultimately influence the teachers’ use of the material. For example, by answering questions such as ‘Does the new material implicate me, is it important to me?’ (cf. figure 1).

Based on Gregoire’s model [1] visualised in figure 1 the following key aspect becomes clear: the necessary prerequisite for the teachers’ use of innovative teaching materials in the classroom is the extent to which teachers require these new materials. Thus, in order for innovative teaching materials to become established in classroom practice, their development must be oriented to the teachers’ needs.

One area where teachers have a particular need for new teaching materials for their classes is quantum physics. In the next section, we present the results of a recently published Delphi study on teachers’ needs for new teaching materials on quantum physics (section 2). We then show how we have taken these teachers’ requirements into account to develop teaching materials for a new teaching concept on quantum optics in schools according to design principles from the literature (section 3). In section 4, we report teacher survey results on practical experiences with our teaching material in the classroom. In order to clarify the following research question: How do teachers evaluate the new teaching materials for introducing quantum optics in secondary schools that have been developed on the basis of needs analysis results and according to design principles from the literature?

2. What requirements do teachers have for teaching materials on quantum physics?

The results of a Delphi study [14] provide an insight into the needs of teachers concerning teaching quantum physics. First of all, it is striking that the teaching concepts on quantum physics from physics education research are predominantly unknown to the teachers [14, p 181]. This is consistent with the findings presented in section 1. One of the exceptions are Küblbeck and Müller’s reasoning tools [15]. In order to emphasise the distinction between classical physics and quantum physics with conceptual clarity and to demystify quantum physics, Küblbeck and Müller have originally elaborated the reasoning tools in [15]. They are described as follows:

(a) Statistical behavior: ‘Single events are not predictable, they are random. Only statistical predictions (for many repetitions) are possible in quantum physics’ [16, p 3].

(b) Interference of single quantum objects: ‘Interference occurs if there are two or more ‘paths’ leading to the same experimental result. Even if these alternatives are mutually exclusive in classical physics, none of them will be ‘realized’ in a classical sense’ [16, p 3].

(c) Unique measurement results: ‘Even if quantum objects in a superposition state need not have a fixed value of the measured quantity, one always finds a unique result upon measurement’ [16, p 4].

(d) Complementarity: ‘Exemplary formulations are: ‘Which-path information and interference pattern are mutually exclusive’ or ‘Quantum objects cannot be prepared for position and momentum simultaneously’’ [16, p 4].
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Figure 1. Visualisation of the cognitive-affective model of conceptual change according to [12] and applied to teachers’ use of new teaching materials according to [13]. The material’s importance for the teacher, the motivation or beliefs of the teacher, and the teachers’ skills are seen as the central factors influencing teachers’ engagement with the teaching material provided.
For more than half of the teachers surveyed, the reasoning tools serve as a framework for their lessons on quantum mechanics [14, p 182].

A large proportion of the physics teachers surveyed expressed a need for simulations or real experiments for quantum physics lessons: in particular, 65% of the teachers surveyed would like to see real experiments to teach quantum physics’ basic concepts on the secondary school level [14, p 184] or simulations to illustrate them. Teachers attach great importance to the practicality of the material provided. Finally, the authors of the Delphi study [14] observe a great interest among the teachers surveyed in topics from research on quantum physics, such as quantum computers or quantum cryptography [14, p 186]. This is an interesting observation which supports the work from physics education research because there are several proposals to integrate current quantum technologies [17] into the teaching of quantum physics [18–22].

With our Erlangen teaching concept for quantum physics, we address these teachers’ requirements for quantum physics teaching (cf table 1): we provide teachers with a hands-on approach to quantum physics for classroom practice. Using interactive screen experiments with single photons [26], learners can experience the basic concepts of quantum physics in the sense of Küblbeck’s and Müller’s reasoning tools [15, 16]. To enable easy implementation of our teaching concept in the classroom, we provide different teaching materials (worksheets, explanatory video, interactive screen experiments). Besides, we provide a teacher’s guide that offers insights into the technical background and didactic considerations for teachers.

In the next section, we first outline the key ideas of our teaching concept. In addition, we present design principles for developing teaching materials from the literature that we have considered in creating our materials.

### 3. Teaching material on the Erlangen teaching concept for quantum physics

#### 3.1. A brief outline of the concepts’ key ideas

We presented our teaching concept in detail in an earlier contribution [25] and only outline the core ideas of the concept here. Our secondary school concept (11th/12th grade, 17–18 year old students) is structured in two main parts (four lessons in total, 90 min each). The focus of our concept is on coincidence and correlation experiments with single photons (cf figure 2).

To introduce the teaching concept, a self-developed explanatory video is shown. It motivates the students to deal with quantum objects and phenomena by means of the topic \textit{data security}: The importance of data security is briefly discussed with the young people beforehand on the basis of two newspaper articles and the influence of quantum physics on data security is taken up in the explanatory video. During the
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Figure 2. Contents of the Erlanger teaching concept on quantum optics for secondary schools as described in detail in [25]. All the experiments conducted during our teaching concept are shown in the figure’s headline. We provide interactive screen experiments developed by [26] for all these experiments. The experiment by Grangier et al. [28] is used to demonstrate the indivisibility of photons and single-photon interference in one experiment in the end of the teaching sequence.

In lessons three and four, the experimental results from single-photon experiments can be interpreted. Therefore, we use interactive screen experiments developed by Bronner et al. [26]. The focus of these experiments is on the behaviour of classical or quantum light at optical interfaces. The students are introduced to the theory of optical coherence [27] through elementary stochastic considerations: we discuss the anti-correlation of photons at the optical beam splitter [28], which leads to the indivisibility of the photon. Finally, we investigate single-photon interference using a Michelson interferometer in an interactive screen experiment. For a detailed description of the individual lessons, see our earlier contribution [25].

To guide students along a common thread through the concept, worksheets are provided for all lessons. These contain problem or discussion tasks and serve to reinforce the content covered. To enable teachers to implement the concept in their own lessons, we provide a detailed instructional manual that offers teachers more detailed insights into the didactic key ideas of the concept, that explains terms from a specialist perspective, and that summarizes solutions to the teaching materials. The Erlanger concept’s teaching material can be requested from the author in either German or English by e-mail to philipp.bitzenbauer@fau.de.
Table 2. Design principles for teaching material and explanations provided by [29]. In their article, Singer et al argue why ‘using these principles can promote understanding of scientific concepts and inquiry strategies and address the needs of diverse students’ [29, p 167].

| Design principle | Explanation |
|------------------|-------------|
| Context          | Anchoring events / contexts focus students on relations between newly constructed concepts and ideas |
| Standard based   | Provide framework for the specific strategies for training |
| Inquiry          | Extended inquiry engages students directly with phenomena and supports the learning of key scientific concepts |
| Collaboration    | Interaction among members of a community to share information and reach consensus decisions |
| Learning tools    | Tools used mirror the tools utilized by members of scientific community and engage learners in intellectually challenging tasks |
| Artifacts        | Fostering discourse within classroom |
| Scaffolds        | Learner-centered / use of subquestions allows key concepts and processes to be made explicit |

3.2. Design principles for material development

Various contributions have proposed design principles for the development of new, innovative teaching materials [29, 30] in order to ‘engage students in inquiry, make use of new learning technologies, and promote student learning’ [29, p 165]. Here, we follow the curriculum design principles according to [29], because in addition to their design principles, the authors also provide concrete suggestions for the implementation of these design principles (cf table 2):

In the next section 3.3, we present the new teaching materials in detail and justify step by step how these design principles were taken into account in their development. We understand our teaching material on quantum physics as a mediator between the three stakeholders, teachers, students and researchers (cf figure 3): According to this, researchers find themselves in a field of tension between the teachers’ needs on the one hand and the students’ needs on the other hand when developing innovative teaching materials. The students’ perspective is inevitably considered in empirical studies on new teaching materials, mostly in terms of students’ prior knowledge [31, 32], in order to ensure that new materials support the students’ learning process.

Less attention is paid to the teachers’ perspective: in section 1, we have used Remillard’s model [9] to show that different teachers’ characteristics influence whether teachers use innovative teaching materials. How these teachers’ characteristics then affect the implementation of innovative teaching materials in classroom practice is described in Gregoire’s model [12], cf figure 1. From that, we derived the following key point: only if teachers’ needs are taken into account in the development of new teaching materials, there is a chance that these new materials will become established in classroom practice. We have already collected the student perspective in a formative evaluation during the development of our new teaching concept and discussed it in detail in our earlier article [25]. Consequently, this paper is dedicated to the teachers’ perspective on the new teaching material on quantum physics. We present the results of a survey on teachers’ practical experiences with the new material in section 4.

3.3. Teaching material

To implement the Erlangen teaching concept [25] in the classroom, we provide working materials in the form of an explanatory video, interactive screen experiments and worksheets. The design principles from the literature (cf table 2) were used as a basis for the development of our teaching material. In the following, we briefly explain how we have taken them into account in the development of our working materials.
3.3.1. **Context.** The starting point of the concept is a discussion about secure communication and data security. Students are aware of the importance of this topic [34]. In an explanation video, this topic is addressed, and students learn that secure communication is of central interest in the context of emerging quantum technologies [17]. Our explanation video raises the question of which fundamental principles need to take hold in quantum physics in order for it to contribute to issues such as secure communication, thus providing an entry point into teaching quantum physics. Our explanation video was developed against the background of the cognitive load theory from learning psychology [35–37] and its development is presented in detail in [38].

3.3.2. **Standard based.** The concept of Kübler and Müller on the reasoning tools of quantum physics [15, 16] serves as a framework for our teaching material (cf. section 2). We mainly deal with the statistical behaviour of quantum objects and the ability to interfere. The behaviour of single photons at the semi-transparent mirror allows for a simple experimental access to the concept of superposition and thus to the probabilistic nature of quantum physics [39]. Single quantum objects’ ability to interfere is discussed using the example of the Michelson interferometer with single photons.

We lay great importance on the discussion that classically well-defined dynamic properties such as position cannot generally be attributed to quantum objects. For example, we do not talk about photons’ position between source and detector but emphasize the detection process itself. Regarding interpretations of quantum physics, this approach is based on the ensemble interpretation of quantum mechanics [40, 41]. We agree with the arguments provided by Müller indicating that ‘this interpretation provides a clear and comprehensible way of talking about quantum phenomena’ [42, p 202]. The ensemble interpretation of quantum mechanics thus serves as our standard.

3.3.3. **Inquiry.** On the worksheets provided, students are encouraged to independently discuss how to set up and conduct experiments with
single photons. At the beginning of the lesson, the teacher tells the students how photon pairs are generated in the laboratory using non-linear crystals and parametric down-conversion. With this knowledge, students then develop possible experimental set-ups to prepare single photons, initially guided by appropriate tasks, alone, with partners or in groups: In a class discussion, inspired by these work assignments, arguments for and against the individual student proposals are exchanged. In this way, the pupils independently work out the coincidence method. In another assignment, the students work out their suggestions for extending the coincidence experiment to investigate single-photon states’ behaviour at the beam splitter cube (cf figure 4). The screen experiments provided (cf section 3.3.5) enable the students to check their experimental ideas independently.

3.3.4. Collaboration. Worksheets encourage interaction between learners at various points. For example, when discussing the significance of measurement results for our interpretation of quantum physics, the learners discuss conceivable ideas about indivisible photons capable of interference. In the process, central aspects of the nature of science are conveyed; for example, that scientific knowledge is naturally shaped by subjective views and social negotiation processes [43], cf figure 5.

3.3.5. Learning tools. To make it possible to deal with real quantum optical experiments outside the laboratory (and in the classroom), interactive screen experiments developed by Bronner et al [26] are available for the experiments within the framework of the teaching concept: students can work on all the worksheets’ tasks using the screen experiments on their own devices or student PCs.

For the interactive screen experiments, original measurement data from a quantum laboratory are implemented, so no programmed data is used [26]. In the interactive screen experiments, the pupils can take different perspectives on the laboratory table because numerous photographs of the original experiments have been embedded. The students can also perform various actions on the experiment, e.g. they can switch devices on...
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Interpretation of the experimental results
One of the basic tasks of a scientist is to interpret data, and to formulate well-founded conclusions. Note down all your observations from the experiment single-photon states at the beam splitter and provide your individual conclusion from your own observation. Then, discuss with your neighbour and try to find a consensus, if possible. Lastly we discuss our observations in class.

| Personal observation | Consensus with neighbour | Consensus with class or course |
|----------------------|--------------------------|-------------------------------|

Figure 5. Excerpt from a worksheet on the interpretation of an experiment with single photon states at the beam splitter cube: the pupils first note down their own observations, compare them with those of their partners and then bring these different observations and interpretations to a consensus in the whole class. In this way, they experience how scientific knowledge acquisition processes can function.

Figure 6. Example of one of the interactive screen experiments developed by [26], here: investigating the properties of single photon detectors, an experiment conducted at the beginning of our teaching sequence. Depending on the learners’ needs, more or less help can be blended in. This allows for individual learning with the interactive screen experiments.

4. Teachers’ practical experiences with the teaching material

4.1. Setting of the survey

For the further development of the teaching material, the involvement of teachers from the field is necessary. We think, that only in this way the material can be optimized for the teachers’ and their students’ requirements in the sense of design-based research [44]. In our survey, ten teachers who had between 4 and 17 years of teaching experience reported on their experiences with our teaching material on quantum optics.

To get first insights into the teachers’ view on our teaching material, a questionnaire was developed that is partly based on the one used in [46]. The teachers were asked about their experiences with the teaching material using open-ended as well as closed questions. With the open-ended questions, the teachers could articulate the strengths and weaknesses of the concept. Based on the teachers’ answers, categories were formed to derive the teaching material’s primary strengths and weaknesses. In this way, targeted further development of the materials is aimed at. The closed questions provided statements about the teaching concept, which the teachers were asked to rate on a five-point Likert scale (1 = disagree, ..., 5 = agree). In terms of content, the closed questions referred to the following aspects [46, p 276]:
Figure 7. Teachers’ feedback concerning the concept in general on a five point Likert-scale (1 = disagree, ..., 5 = agree).

(a) didactic assessment of the teaching concept, (b) the assessment of the practicality and quality of the teaching material provided, and (c) the teachers’ use of the concept in the future.

As recommended in [47], Diverging Stacked Bar Charts were used to visualize the data from the closed questions with rating scale. Here, a bar corresponding to 100% of the ratings is aligned relative to the scale’s centre (0%). Thus, participants’ agreement corresponds to a swing of the bar to the right and disagreement corresponds to the bar’s swing to the left. To quantify the ratings, the mean value $m$ and the standard deviation $\sigma$ are also given in the form $m \pm \sigma$.

4.2. Results

4.2.1. Didactic assessment of the teaching concept. According to the teachers, the students mostly accept the Erlangen teaching concept (4.3 ± 0.6). They also believe that central quantum physics aspects are conveyed clearly and understandably with the help of the Erlangen teaching concept (4.3 ± 0.6). According to the teachers, the interactive screen experiments contribute to this in particular (cf figure 7).

The teachers’ high level of agreement with the following statements is striking:

- ‘The teaching concept conveys adequate ideas about modern natural sciences to pupils’ with a mean rating of 4.8 ± 0.4 and
- ‘The teaching concept achieves a good understanding of scientific measurement and working methods among pupils’ with a mean rating of 4.4 ± 0.7.

One teacher supports this finding with a comment on the open question about the strengths of the concept like this: ‘From concrete, scientific work to concrete results that are all comprehensible. University work becomes clear here, better than any day of physics [...]’

Remarks of this or similar kind occur more frequently (cf figure 8): six of the ten teachers describe the high reference to research as a great strength of the teaching material. Four out of ten emphasize the orientation to experiments and another four of ten indicate the clarity of quantum optics concepts’ presentation as a strength connected to the provided interactive screen experiments. At least two of the ten teachers emphasize the possible insights into scientific work and scientific knowledge acquisition. The strengths emphasized reflect our consideration of teachers’ needs for their quantum physics lessons when developing our teaching materials (cf table 1).

The main criticisms of the concept, according to the teachers, are the following:

(a) Lack of curriculum reference: two of the ten teachers interviewed express concerns about embedding the whole concept in their teaching. One teacher writes: ‘Scope too large for the time possibilities in secondary school. It cannot be directly integrated into current textbook / curriculum.’
(b) The second main criticism concerns the extensive time requirement (three out of ten respondents); this cannot be considered
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![Chart](attachment:image.png)

Figure 8. Strengths (relative frequencies) that teachers attribute to the teaching material related to the Erlangen teaching concept on quantum optics.

Table 3. Descriptive statistics on the items of the scale *practicality and quality of the worksheets* (1 = disagree, ..., 5 = agree).

| Item                                                                 | Mean value $m$ | Standard deviation $\sigma$ |
|----------------------------------------------------------------------|----------------|-----------------------------|
| The worksheets are well structured.                                  | 4.50           | 0.71                        |
| The worksheets are attractively designed.                            | 4.00           | 1.05                        |
| The worksheets guide meaningfully through the contents of the concept.| 4.40           | 0.52                        |
| The tasks of the worksheets are formulated in a clearly understandable way. | 4.40           | 0.84                        |
| The worksheets encourage meaningful teaching phases in which the pupils can work independently. | 4.20           | 0.79                        |
| The worksheets provide sufficient backup for the content of the lessons. | 4.00           | 0.82                        |

entirely separately from main criticism 1, e.g. ‘If you want to implement this concept, it costs a lot of time. This is mostly not available due to the abundance of topics.’

(c) Five of the ten teachers surveyed expressed concerns about the derivation of the anti-correlation factor $g^2(0)$ which we discuss together with students (cf our earlier contribution [25]). Some teachers felt that the statistical evaluation of the quantum optics experiments was too demanding or that the corresponding worksheets’ instructions were too sparse. In the opinion of one respondent, this is ‘well suited for high-achieving students’. For example, one teacher writes in more detail: ‘Mathematical derivation of anti-correlation factor, theory of a test — too demanding. [...] Better to explain only qualitatively!’

4.2.2. Assessment of the teaching material.

The practicality of the worksheets was assessed using a scale consisting of six items. The Cronbach’s alpha coefficient as an estimator for the internal consistency of the scale was found to be 0.83.

It is evident that the teaching materials provided are perceived as comprehensive and of high quality (cf table 3, figure 9). Only in the
statement about the worksheets’ design there is an adverse judgement. There was a particularly helpful teacher’s comment according to which it could be useful to include a ‘small conclusion at the end of each worksheet’. In this way, the status within the investigation of individual quantum objects can be recorded. Learners could follow the teaching sequence more easily: ‘What exactly has already been clarified? What still needs to be clarified?’

4.2.3. Use of the concept in future lessons. The participating teachers seem to judge the teaching material on the Erlangen teaching concept as suitable for practical use in the classroom (cf figure 10) because all of the teachers surveyed rated the statement ‘In the future, I will teach (part of) my quantum physics lessons with the concept’ with rather agree or agree (4.4 ± 0.5). Nine out of ten respondents state that they would recommend the concept to their colleagues.

5. Discussion and conclusion
The establishment of new teaching materials in classroom practice necessarily presupposes a need of teachers for these materials as we have seen from Gregoire’s model [12] in section 1. Taking into account the results of a Delphi study [14] on teachers’ needs for quantum physics teaching (cf section 2), we present the development of teaching material for an introductory course on quantum optics for secondary schools based on design principles from the literature (cf section 3). The results of a teacher survey presented in section 4 can be used to approach a clarification of our research question. The research question was the following: How do teachers evaluate the new teaching materials for introducing quantum optics in
secondary schools that have been developed on the basis of needs analysis results and according to design principles from the literature? The teachers predominantly assess the materials as positive (cf figure 9) and emphasise, for example, the close reference to current research or the orientation of the concept to experiments (cf figure 8). Reflecting back on the results of the Delphi study results [14] presented in section 2, these were precisely the demands expressed by teachers for new teaching materials on quantum physics. Of course, the teachers surveyed were a positive selection because they voluntarily expressed a willingness to engage with the new teaching material but still the teacher survey results suggest that the material development was successful in the first step.

However, in the sense of design-based research, we are now using this survey’s results for further improvements of our teaching material. We follow individual teachers’ advice that the more in-depth statistical evaluation of the experiment on anti-correlation of single-photon states at the semi-transparent mirror was too demanding for many students. We are moving this part to an optional course section. In addition, the feedback was that working through the entire concept in class takes too much time, which is why we are dividing the course into a basic and an advanced course for the further development of our concept so that teachers can more easily teach only individual parts of the sequence and still have a well-rounded introductory course to modern quantum physics available.

For easy accessibility of the materials and to enable teachers to use the materials even more individually, the teaching concept is to be made publicly available on a homepage that meets today’s requirements for web offerings. It is also planned to create further explanatory videos in the context of our teaching sequence so that our quantum optics concept can also be taught in a flipped classroom format.

Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

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Ethical statement
Authors acknowledge that the research was conducted anonymously, that consent was obtained from all identifiable participants, and that all identifiable participants are informed about the publication of the results of this study.

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ORCID iD
Philipp Bitzenbauer © https://orcid.org/0000-0001-5493-291X

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Philipp Bitzenbauer holds a PhD in Physics Education from the University of Erlangen. His research interests include classroom experimentation, the empirical investigation of learning processes in quantum physics and teaching quantum technologies for future workforce. In addition to his research activities, he works as a secondary school teacher.