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Designing inquiry-based learning environments for quantum physics education in secondary schools

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Abstract
This paper describes the design process for a digital instructional sequence on introductory quantum physics for upper secondary education. Based on a collaboration between teachers and physics education researchers, this sequence incorporates relevant theoretical foundations from the field of science teaching to promote meaningful and conceptual learning of quantum physics. The sequence is composed of units, which are being developed using the Go-Lab ecosystem (www.golabz.eu), a free online platform for teachers to create digital inquiry-based lessons. So far, the sequence covers the photoelectric effect, wave-particle duality, and tunnelling phenomena. This paper focuses on the sequence’s first unit, addressing the photoelectric effect. The unit is used in this paper to exemplify the incorporation of the sequence’s theoretical foundations: digital inquiry-based learning with simulations, collaborative learning, and conceptual change. The unit was pilot-tested with 114 students in four Dutch high schools. Answers to multiple-choice and open-ended questions were collected through
1. Introduction

Introductory quantum physics (QP) has been included in secondary school curricula worldwide throughout the past two decades [1]. Research [2–4] has reported that students often distort the non-deterministic character of QP in an attempt to relate this novel content to their previous knowledge of classical, deterministic physics [5].

The increased understanding of student difficulties in introductory QP has served as a starting point for the design of educational interventions. These interventions (see [5] for an overview) show the potential of various pedagogical approaches, such as the use of active learning strategies [6, 7]. One way to have students learn QP in an active way is to use digital simulations that allow students to visualise representations of quantum phenomena and experiment with them. The Relevant project [8], which features collaborative learning with simulations and animations, is an example of intervention that realises this approach.

In the current research, we build on these interventions and develop an instructional sequence for introductory QP that uses modern technology for inquiry-based learning: a process in which students learn through investigation. When well supported, inquiry learning can be an effective form of science instruction and can be combined with other types of active learning such as collaborative learning [9].

In this paper, we describe the design process of combining inquiry learning, collaborative learning, computer simulations, and conceptual change principles into a sequence of digital learning units covering introductory QP topics. We start with a structural overview of the sequence’s first learning unit in section 2. Section 3 describes an initial needs assessment and how the pedagogical principles that guided the design of this learning unit were incorporated. Finally, in section 4, we report the main findings of pilot tests of the first learning unit in Dutch high schools and in section 5 we draw conclusions for our future work.

2. Description of learning unit

Our learning sequence was designed for Dutch upper secondary schools. The sequence thus far is comprised of four digital units, which were designed using the Go-Lab ecosystem (www.golabz.eu). Each unit within the sequence is expected to take up two 50-minute lessons.

Our first unit covers the photoelectric effect. This unit was designed so that, by the end, students would grasp: Einstein’s law of the photoelectric effect; the fundamentals of the particle model of light; and why the latter explains the occurrence of the photoelectric effect. Figure 1 depicts the overall structure of this unit, and figure 2 shows a screenshot of the digital environment through which students access the unit.

3. Analysis and design

3.1. Quantum physics education in the Netherlands

This section reports the main findings from a needs assessment done to identify the requirements and constraints of the Dutch educational context. This assessment was carried out through an analysis of the Dutch curriculum and of results of QP questions from the Dutch national exams, and focus groups with Dutch high school physics teachers.

3.1.1. Dutch curriculum and exams. In the Netherlands, QP is taught to upper secondary school students who choose physics as part of their curriculum. At this level, the QP topics covered are: the photoelectric effect, the double
Designing inquiry-based learning environments for quantum physics education in secondary schools

Figure 1. Structure of the first unit in our learning sequence.

Figure 2. User interface for the photoelectric effect unit, using the Go-Lab ecosystem. The different phases of the lessons can be accessed in the left-hand column.

The slit experiment, de Broglie wavelength, probability distribution, tunnelling, Heisenberg’s uncertainty principle, 1D potential wells, and atomic physics [1]. These topics are divided between two sub-domains: ‘quantum world’ and ‘radiation and matter’. Results from the national physics exams show that between 2016 (year in which the ‘quantum world’ sub-domain was added to the national exam) and 2019, the average p value of ‘quantum world’ questions was 47%. For ‘radiation and matter’ questions, the p value was 55%. This is low compared to other physics.
sub-domains, which have average $p$ values ranging between 61% and 65%.

3.1.2. Focus groups. The role of focus groups with Dutch teachers in our needs assessment was twofold. First, they allowed us to identify which QP topics would be appropriate to cover in our learning sequence, based on the difficulties teachers see their students experiencing. As a result, the chosen topics covered so far by our sequence are the photoelectric effect, the double slit experiment, de Broglie wavelength, probability distributions, and tunnelling. Second, the focus groups were used to learn about student difficulties. For instance, participating teachers reported that their students struggled with understanding why the photoelectric effect is an example of light’s particle behaviour. Teachers reported that the number of different variables at stake in the photoelectric effect and how each variable influences it potentialize this struggle. In our photoelectric effect unit, this input from teachers was used to implement a step-wise approach to the different variables (discussed in more detail in section 3.2) and led us to leave the voltage variable out of the unit.

3.2. Theoretical foundations and pedagogical approaches

Our design was based on the principles of inquiry and collaborative learning. The following sections describe how these approaches were incorporated in the photoelectric effect unit.

3.2.1. Guided inquiry-based learning. In inquiry-based learning, students follow a series of phases based on the scientific method. An example of an inquiry cycle is the orientation, conceptualisation, investigation, conclusion, and discussion cycle presented by Pedaste et al [10], which was the framework used to structure our unit.

In our design, we chose to build digital lessons, because of advantages such as the possibility of offering instant feedback and embedding multimedia resources [11]. Moreover, a digital environment allows the use of simulations and tools that help to guide the inquiry process. There are various documented types of guidance in digital environments [12], and their appropriate use depends on factors such as the complexity of the topic addressed by the lesson.

Our unit uses three main types of guidance [13]:

(a) **Process constraints**: With process constraints, students are restricted from performing certain actions. Constraints are applied so that students cannot, for example, explore different variables at the same time and not learn their isolated roles. This is how process constraints are applied in our unit, meaning that students are instructed to explore the role of the independent variables in the photoelectric effect one at a time.

(b) **Prompts**: Prompts are hints that elicit an overlooked process. They are used throughout our unit as instructions on when to make a prediction (with examples of what a prediction is) or as an instruction to return to the simulation if a wrong conclusion was drawn; and in the form of investigation assignments: tasks instructing students to investigate a relation between two or more variables. As an example, students in our unit are asked to create and interpret two separate graphs (number of freed electrons versus intensity and kinetic energy of freed electrons versus frequency).

(c) **Direct presentation of information**: Once students have drawn conclusions about the role of the intensity and frequency of light in the photoelectric effect, they are introduced to Einstein’s theory of quanta and how it explains the occurrence of the effect. We chose to introduce this latter content through direct presentation of information using text, images, and video, because of the content’s novel and unexpected character. Thereafter, students complete exercises and activities to make sense of the data obtained in the simulation, using the theory of light quanta.

3.2.2. Collaborative learning. Following upon the work of Mazur [14] on the peer instruction method, further research has shown the value of student dialogues in physics education. For example, more recently Deslauriers et al [15]...
and Bungum et al. [16] used student dialogues for teaching introductory QP at the secondary and undergraduate levels, highlighting their benefit for learner engagement and externalisation of ideas. The proven value of student dialogue for (quantum) physics learning led us to design our lessons to be done in pairs.

To ensure effective collaboration between students (e.g. so that one student does not dominate the collaborative process), our lessons are scripted. Our scripts are based on two characteristics of known effective collaborative scripts: sequencing and role assignment [17]. Sequencing helps students take a step-by-step approach to a task by assigning sub-tasks to them. Role assignment allows students to approach a topic or process from different perspectives, according to the assigned role. In practice, our units offer the option of two scientist personas. Student pairs are instructed to choose which scientist each student would like to be. In the photoelectric effect unit, the scientists are Schrödinger and Heisenberg, whose names are used to guide the students’ collaboration throughout the lesson. For example, during the phase ‘get to know the simulation’, the instructions are: ‘Heisenberg: take 5 minutes to explore the simulation, varying its parameters as you wish. Schrödinger: take notes about what you observe while Heisenberg explores the simulation.’ In the next phase, the roles are reversed.

Similar to the peer instruction method, our unit includes a teacher-led lecture and whole-class discussion at its end. The importance of a balance between student and teacher-led discourse in science teaching was emphasised by Scott et al. [18], who indicated that these opposed approaches to communication support each other. In a study evaluating peer instruction and just-in-time teaching in a quantum mechanics course, Sayer et al. [19] implemented lectures following out-of-class activities. The latter made use of student discourse and were intended to prime students to learn from subsequent lectures. They based their intervention on the work of Schwartz et al. [20] and Kapur [21], who proposed that students who reflectively engage in pre-lecture activities are more likely to learn from lectures. Despite Sayer et al.’s [19] unfavourable results, which suggested their participants were not primed by their activities, we argue that the approach of implementing a lecture and teacher-led discussion at the end of our unit can be advantageous. Our claim is based on the likelihood that our pre-lecture activity (i.e. engaging in the inquiry cycle) will allow students to achieve both a reflective engagement level, proposed by Schwartz et al. [20] and a productive failure cycle, recommended by Kapur [21].

3.2.3. Support for conceptual change. QP challenges the deterministic character of classical physics and can be characterised as counterintuitive. The theory of conceptual change in science learning proposes that, to correctly comprehend such counterintuitive information, students must undergo the process of conceptual change: a gradual process that requires revisions and restructuring of one’s understanding [22]. Given the complexity of such process, students require support to go through it.

Recommendations by Vosniadou et al. [22] and Duit et al. [23] on how to support conceptual change are implemented in our photoelectric effect unit, as explained below.

(a) Facilitation of metaconceptual awareness: Students are often unaware of their own understanding of a subject and how such understanding influences knowledge acquisition. Therefore, learning environments should facilitate the process of metaconceptual awareness (i.e. becoming aware of one’s understanding and the limitations it imposes on knowledge acquisition). Thus, students should be given opportunities to express their ideas and compare them with those of peers. Besides encouraging discussion between students in pairs, our learning environment provides discussion topics formulated specifically to trigger prior knowledge known to cause misconceptions related to QP. Consequently, learners are prompted to become aware of this knowledge by articulating and evaluating it. For instance, in the introduction and conclusion phases of the photoelectric effect unit, students are exposed to three wrong explanations of the effect’s cause (see figure 3). The explanations cover: the belief that only intense light causes the effect; the
idea that light collides with electrons deterministically; and the assumption that the wave behaviour of light ejects electrons. Students are encouraged to discuss why these explanations are wrong and to provide their own explanation of how the effect occurs.

(b) **Cognitive conflict:** Promoting cognitive conflict means exposing students to educational experiences designed to confront their misconceptions, so that students can experience a conflict between their misconceptions and the scientific explanation. In our learning sequence, the exploration phases address the production of such conflict: students observe a phenomenon that their conceptions of light cannot explain. The phases after the exploration are used to resolve this conflict and to present the concept of quanta. However, we point out that our process of cognitive conflict is based not only on student misconceptions about light, but also on the fact that the wave model of light does not explain the photoelectric effect.

(c) **Motivation for conceptual change:** According to Vosniadou *et al.* [22], ‘students often do not see the reason to change their presuppositions because they provide good explanations of everyday experiences’ (p 393). To motivate students to go through the process of conceptual change, a learning environment should provide meaningful learning experiences and relate its topic to sociocultural contexts. Therefore, our learning environment makes use of videos depicting the results of real-life experiments and of the historical background behind the phenomenon being studied.

4. **Pilot testing**

Our first unit underwent pilot testing with 114 students from four Dutch high schools. At each school, the pilot involved two 50-minute lessons during which the photoelectric effect unit was tried out. The data were collected through the digital environment in which the unit is embedded and consisted of students’ answers to multiple-choice and open-ended questions posed throughout the unit. The main results are outlined below.

4.1. **Identified misconceptions**

Misconceptions about the photoelectric effect identified by Krijtenburg-Lewerissa *et al.* [5] were also present in the results of our pilot testing. For instance, when asked in the Introduction phase to...
make a prediction about what causes the photoelectric effect, four out of 41 pairs answered ionisation, another four answered that photons and electrons collide, and three said that the effect requires voltage.

As reported in section 3, we attempted to address some misconceptions through an exercise presenting three wrong explanations of the effect. To assess how students made sense of these explanations after having gone through the inquiry process, the explanations were revisited at the end of the lesson and students were asked why the explanations are incorrect. Out of the 22 pairs who answered this question:

- Nine were able to explain why all three explanations were wrong. An example of a pair’s answer is: ‘Explanation 1 is wrong because intensity does not affect the kinetic energy of electrons. 2 is wrong because electrons are freed only above a certain value of frequency. 3 is wrong because the emission of electrons is independent of the intensity.’
- Eight could correctly argue about one or two explanations, but their answer was incomplete or partly incorrect. Example: ‘Frequency and wavelength influence the kinetic energy of electrons. There is a minimal frequency value for the effect to happen. Electrons are fixed in one layer and therefore do not vibrate.’
- Five focused on providing mechanical explanations for the statements. Example: ‘The emission of electrons is not related to the electron. The electrons receive more energy from light and that is why they are emitted. It does not have to do with warmth, wavelength or vibration.’

Out of those 13 pairs who provided an incomplete answer or focused on mechanical aspects, seven manifested clear misconceptions in their answers. Examples of these misconceptions were: ‘emission of electrons depends on high intensity and frequency’ and ‘higher intensity releases electrons faster.’

4.2. Learning outcomes

Multiple-choice and open-ended question responses were analysed to determine the learning outcomes for the tested unit. At the end of the inquiry learning cycle, the majority of students understood the roles of the frequency and intensity of light in the phenomenon studied. Specifically, 82% of the pairs (40 out of 49) concluded that there is a cut-off frequency under which the photoelectric effect does not happen; 80% concluded that the frequency influences the kinetic energy of freed electrons; 62% concluded that, as long as the frequency is above its cut-off, electrons are freed for any value of intensity above 0%; and 92% concluded that the intensity influences the number of freed electrons.

Regarding student understanding of the particle model of light and how it applies to the photoelectric effect, 59% of the pairs (26 out of 44) interpreted Einstein’s law of the photoelectric effect correctly in a multiple-choice question. Despite this positive result, students’ answers to the open-ended question ‘Why does the particle model of light explain the photoelectric effect?’ were not as successful. Examples of answers to this open-ended question were: ‘If photons are particles, they can release electrons from the plate’ or ‘Light has different properties than waves’. Nevertheless, in later discussions with teachers involved in the pilot testing, they reported that during the lecture and teacher-led discussion students grasped the concept of light quantisation and its influence on the photoelectric effect with ease. This observation from teachers supports our claim that the inquiry cycle as a pre-lecture activity could succeed in priming students to learn more from the teachers’ explanations.

5. Conclusion

This article described the theoretical framework incorporated in the design of a digital, inquiry-based learning unit about the photoelectric effect. The results of testing this unit in four high schools showed that students could explain most aspects of the photoelectric effect after their inquiry activities. However, the particle nature of light was still not fully understood, as many student explanations built on classical physics concepts. Our results also suggest that our 100 minute unit can promote effective reasoning about the role of the intensity and frequency variables in the photoelectric effect, in particular when the unit is
complemented with a targeted lecture and teacher-led discussion. With these results, we aim to improve the current unit by providing greater focus on the wave-particle nature of light and by creating supportive materials for teacher-led discussions. Ultimately, we hope to develop and improve more units about other QP topics and thereby to offer physics teachers free and effective resources for QP teaching at the secondary level.

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Ethical statement

This research was carried out in accordance with the IOP’s ethical policy and was approved by the ethics committee of the Behavioural, Management, and Social Sciences faculty of the University of Twente (project ID: 191 241).

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References

[1] Stadermann H K E, van den Berg E and Goedhart M J 2019 Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic Phys. Rev. Phys. Educ. Res. 15 010130

[2] Mannila K, Koponen I T and Niskanen J A 2002 Building a picture of students’ conceptions of wave-and particle-like properties of quantum entities Eur. J. Phys. 23 45–53

[3] Greca I M and Freire Jr O 2003 Does an emphasis on the concept of quantum states enhance students’ understanding of quantum mechanics? Sci. Educ. 12 541–57

[4] Ayene M, Krick J and Damitie B A 2018 holistic picture of physics student conceptions of energy quantization, the photon concept and light quanta interference Int. J. Sci. Mathematics Education 17 1049–70

[5] Krijtenburg-Lewerissa K, Pol H J, Brinkman A and Van Joolingen W R 2017 Insights into teaching quantum mechanics in secondary and lower undergraduate education Phys. Rev. Phys. Educ. Res. 13 010109

[6] Müller R and Wiesner H 2002 Teaching quantum mechanics on an introductory level Am. J. Phys. 70 200

[7] McKagan S B, Handley W, Perkins K K and Wieman C E 2012 A research-based curriculum for teaching the photoelectric effect A research-based curriculum for teaching the photoelectric effect 87 87–94

[8] Bungum B, Henriksen E K, Angell C, Tellefsen C and Be M V 2015 Relequant – improving teaching and learning in quantum physics through educational design research Nordina: Nordic Studi. Sci. Education 11 153–68

[9] de Jong T 2019 Moving towards engaged learning in STEM domains; there is no simple answer, but clearly a road ahead J. Comput. Assist. Learn. 35 153–67

[10] Pedaste M, Mäeots M, Siiman L A, de Jong T, van Riesen S A, Kamp E T, Manoli C C, Zacharia Z C and Tsourilidakis E 2015 Phases of inquiry-based learning: Definitions and the inquiry cycle Edu. Res. Rev. 14 47–61

[11] D’Angelo C, Rustein D, Harris C, Bernard R, Borokhovski E and Haertel G 2014 Simulations for Stem Learning: Systematic Review and Meta-Analysis (Menlo Park, CA: SRI International)

[12] Zacharia Z, C et al 2015 Identifying potential types of guidance for supporting student inquiry when using virtual and remote labs in science: a literature review Educational Technol. Res. Development 63 257–302

[13] de Jong T and Lazonder A W 2014 The Guided Discovery Learning Principle in Multimedia Learning 2nd edn (Cambridge: Cambridge University Press) pp 371–90

[14] Mazur E 1997 Peer Instruction: A User’s Manual Series in Educational Innovation (Hoboken, NJ: Prentice Hall)

[15] Deslauriers L and Wieman C 2011 Learning and retention of quantum concepts with different teaching methods Phys. Rev. Phys. Educ. Res. 7 010101

[16] Bungum B, Be M V and Henriksen E K 2018 Quantum talk: how small-group discussions may enhance students’ understanding in quantum physics Sci. Educ. 102 856–77
Designing inquiry-based learning environments for quantum physics education in secondary schools

[17] Ertl B and Mandl H 2008 *Scripts for Facilitating Computer Supported Collaborative Learning* 1st edn (Pennsylvania, PA: IGI Global) pp 745–50

[18] Scott P, Mortimer E and Aguiar O 2006 The tension between authoritative and dialogic discourse: A fundamental characteristic of meaning making interactions in high school science lessons Sci. Educ. 90 605–31

[19] Sayer R, Marshman E and Singh C 2016 Case study evaluating Just-In-Time Teaching and Peer Instruction using clickers in a quantum mechanics course Phys. Rev. Phys. Educ. Res. 12 020133

[20] Schwarz D L and Martin T 2004 Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction Cognition Instruction 22 129–84

[21] Kapur M 2008 Productive failure Cognition Instruction 26 379–424

[22] Vosniadou S, Ioannides C, Dimitrakopoulou A and Papademetriou E 2001 Designing learning environments to promote conceptual change in science Learning Instruction 11 381–419

[23] Duit R and Treagust D F 2003 Conceptual change: A powerful framework for improving science teaching and learning Int. J. Sci. Educ. 25 671–88

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