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Toward a more coherent and profession-related physics teacher education: Linking subject-specific and physics education content in the study entry phase

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The introductory phase of the physics teacher education program at the Friedrich–Alexander University Erlangen–Nuremberg (FAU), Germany, was redesigned to improve the coherence of the program and reduce the high dropout rates in the introductory phase of the physics teacher education program by making the courses more relevant and appealing to the students' future professional roles. The new organization combines subject-specific lectures on experimental physics with a simultaneous presentation of the corresponding perspectives of physics education through a new course called "Focus Class: physics education and school-related topics." This new course is directly linked to the subject-specific content of the lecture and focuses on the conceptual hurdles that school students may encounter when confronted with the subject matter being taught in lectures and emphasizes active learning strategies. In this paper, we describe the course design and report on student experiences from an evaluation of the course. https://doi.org/10.1119/5.0223735

I. INTRODUCTION

Like elsewhere in the world,[1] Germany is currently experiencing a shortage of teachers,[2,3] especially regarding secondary school physics teachers,[4] with an insufficient number of students enrolling in physics teacher training programs. In particular, over 40% of those who enroll drop out during their studies (across all subjects).[5]

In certain subjects, including physics, the number of first-year students is insufficient to meet the projected demand for teachers over the next decade, even in the absence of dropouts.[5] In the German state of North Rhine-Westphalia, for instance, only 16.8% of vacancies for physics teachers can be filled with new teachers by 2030/31.[6]

An analysis of the dropout rates in Germany reveals that studies leading to degrees in natural sciences or mathematics have the highest dropout rates, at around 50%.[7] Almost half of these students at universities terminate their studies within the first year of their Bachelor studies.[8] The majority of students who withdraw from physics teaching degree programs do so within the first few semesters.[9]

The most prevalent causes of attrition from university are academic difficulties and a lack of motivation.[8] In particular, pre-service physics teachers have expressed concerns about the lack of relevance of the degree program to their future careers and the excessive workload.[9] A recent study also shows raised stress-levels in first year physics students.[10]

German pre-service physics teachers primarily express discontent with the excessive depth of their subject-specific training, yet lament the limited focus on pedagogy and physics education within their studies.[9] As demonstrated by Doil and Pietzner,[11] countries that perform well on the Programme for International Student Assessment (PISA) examination often demonstrate a strong connection between laboratory practices, physics lectures, and physics education in their teacher education.

Our primary goal is to create a more engaging and profession-related physics curriculum that not only improves student retention but also better prepares future teachers for the realities of the classroom by linking subject-specific knowledge with pedagogical perspectives. By focusing on practical applications of physics in education, we hope to reduce the dropout rate and, in turn, increase the overall number of qualified physics teachers.

At the FAU, Germany, in the study entry phase, physics teacher candidates take the introductory experimental physics courses, covering mechanics and thermodynamics (first semester) and optics and electricity (second semester), separate from the training of regular physics students. These courses for pre-service teachers include four weekly lecture periods and two weekly exercise sessions; both lectures and exercises are 45 min long. There are no laboratory periods; these start in the second year.

Building upon the insights of our Finnish colleagues[12] and in alignment with the recommendations put forth by Doil and Pietzner,[11] we have redesigned a course on experimental physics as a part of the introductory phase of the physics teacher education program at FAU. In this course, we emphasize conceptual aspects of the subject-specific content, identifying potential misconceptions, and elucidate the relevance of the subject content for the teaching and learning of physics at schools through a Focus Class entitled "Focus Class: physics education and school-related topics." The Focus Class is implemented as a flipped classroom format, guided by Kim *et al.*'s design principles,[13] that replaces one of the four lecture periods.

The course redesign did not modify the exercise session, in which students solve problems, mainly with mathematical methods.

It is evident that the incorporation of additional content into the curriculum must be accompanied by the necessary adaptations to the existing curriculum framework: Therefore, the traditional curriculum was reviewed and revised to meet the students' needs. As resources for the revision, we made use of the following:

(a) standards for physics teacher education in Germany,[14]
(b) the content covered in the state examination at the end of studies as identified through a qualitative content analysis of the exam tasks over the last decade,[50] and
(c) the German secondary school physics curricula.

II. DESIGN AND IMPLEMENTATION OF FOCUS CLASS: PHYSICS EDUCATION AND SCHOOL-RELATED TOPICS

A. Design of Focus Class: Physics education and school-related topics

The worksheet is a fundamental element of the Focus Class, providing a structured framework for the class's activities. Figure 1 illustrates an example of a typical worksheet.

The material for each Focus Class is typically comprised of a worksheet and a reading text. The reading texts, typically two pages long, are adapted from a physics education textbook or research article and provide students with relevant information for the worksheet. The corresponding reading text for the Focus Class in Fig. 1 is an excerpt from a textbook on mechanics written for the specific purpose of providing an introduction to the subject matter for pre-service teachers.[15] It also explicitly addresses the distinction between Newton's third axiom and the equilibrium of forces, which is essential for the completion of the tasks assigned in this Focus Class.

The following gives an overview of the topics covered in the Focus Classes of the introductory experimental physics courses as a part of the introductory phase of the physics teacher education program at FAU:

- Mechanics: Teaching concept: two-dimensional dynamics,[16] Equilibrium of forces vs. Newton's third law,[17] Differentiation between energy, momentum, and force,[18] and The harmonic oscillator in different contexts.[19]
- Thermodynamics: Intensive and extensive quantities,[20] Teaching concept: The Karlsruhe physics course,[21] Kinetic gas theory,[22] and Thermodynamic cycles in childrens' toys.[23]
- Electricity: Batteries and accumulators: Electrochemistry,[24] Teaching concept: Teaching electricity using the electron gas model,[25] Learning difficulties related to Kirchhoff's laws,[26] and Teaching electricity in different contexts.[27]
- Optics: Color,[28] Ray model of light,[29] Teaching concept: phenomenological optics,[30] and Interference phenomena: thin-film interference.[31]

The worksheets make use of items from concept inventories[51] to deepen the respective subject content or address the learning difficulties that many secondary school students have been found to face.[32] They also initiate discussions about research-based teaching concepts on core topics covered in the experimental physics courses, thereby reflecting on models typically used in the different areas of physics or expert terminology and its effect on secondary school student learning.

The tasks are typically structured in a manner that requires students to engage in discussions and collaborative problem-solving.

Concept test items[33–38] are used in two different scenarios during the Focus Classes: pre-service teachers are guided through a think-pair-share process to identify the correct answer option of the concept item, encouraging them to develop convincing explanations, or pre-service teachers are asked to identify learning difficulties that might be encountered by secondary school students who choose one of the incorrect answers and to discuss possible implications for classroom practice (see exercises 1 and 3 in Fig. 1).

Additionally, in the sense of the model of educational reconstruction,[39] the subject-specific perspective (lecture content) and the learner perspective (discussion of items from concept tests and learning difficulties) are brought together through the discussion of research-based teaching concepts, which the students get to know via the reading texts: Such teaching concepts are based on research in physics education, e.g., on learning difficulties encountered by students, and aim at supporting students' conceptual development.[40]

After having been introduced to at least one research-based teaching concept, the pre-service teachers are also guided from time to time to reflect on given classroom scenarios dealing with students who express learning difficulties. The pre-service teachers then apply both their subject-specific knowledge and their pedagogical content knowledge to work out practical implications in the classroom. An example of such an assignment is exercise 3 of the worksheet shown in Fig. 1.

Not all of the elements presented here are included on all worksheets, as this would not be feasible in just 45 min. We do not attempt to replace the content that will be taught in future physics education courses; rather, the aim is to familiarize the students with their future profession and to introduce them to the pedagogical lens through which they will view it. Additional sample worksheets on topics related to thermodynamics, electricity, and optics are provided in the supplementary files.

B. Contextualization within evidence-based practices

In this section we will situate the tasks on the provided worksheet (Fig. 1) in the context of evidence-based practices.

We elected to address the doorbell paradox in the Focus Class because we discovered that pre-service teachers were unable to resolve it even in their third, fourth, or fifth year. This indicates that they may be confusing the balance of forces with Newton's third axiom in this context, despite being able to verbalize and explain the two concepts independently. In light of these observations, we proposed that the paradox be addressed when Newton's axioms are introduced for the first time at the university level. The rationale behind the associated exercises is explained in detail below.

In Exercise 1, students are instructed to solve the conceptual doorbell paradox using the think-pair-share method. The students are initially prompted to engage in independent reflection, articulating their understanding of the paradox (think) and subsequently engaging in a collaborative exchange of ideas with their fellow student (pair). The students are required to verbalize and explain their thoughts, thereby potentially identifying and addressing any underlying misconceptions. The objective of the joint discussion is to identify a solution to the paradox that is mutually acceptable and, as a result, more accurate than an individual

Focus class:
physics education and school-related topics

FAU

Class 4: Equilibrium of forces vs. Newton's third law

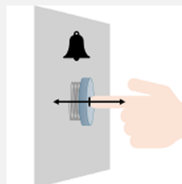
Exercise sheet

Homework: Reading assignment

Read the corresponding reading text for this focus class.

The doorbell paradox [1]

Paul claims: "When I press a doorbell button, I exert a force on it. However, due to Newton's third law, there is an equal but opposite counterforce that the bell exerts on the finger. If I press harder, the counterforce also increases. Since the two forces are equal, they cancel each other out and I cannot move the bell button."



Exercise 1: Solve the paradox

Discuss the paradox and solve it for Paul with Think-Pair-Share. Then vote for the correct answer by raising your hand.

Exercise 2: The Difference

Define the term equilibrium of forces and formulate Newton's third law. Then compare the concepts.

Exercise 3: Misconception

Some students think that "force and counterforce act on the same body." [2]. Discuss possible teaching activities to deal with or prevent this idea.

The pictograms were created by IDP-Münster.

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Fig. 1. Sample worksheet guiding one of the Focus Class sessions.

solution.[41] Subsequently, the solutions proposed by the pairs are discussed by the entire class (share).

Given that our course has an enrollment of approximately ten students, and that Peer Instruction, as developed by Eric Mazur,[42,43] is designed for large lectures, we have adapted the think-pair-share method,[41] which was also developed for school classes and is therefore more suited to our enrollment size, to the context of peer instruction. The think-pair-share method is employed exclusively for conceptual questions; individual responses are not collected, as is customary in peer instruction. In terms of structure, the two concepts are otherwise comparable due to the process (individual solution → peer solution → group solution) and the role of the lecturer as moderator. It is of great importance to develop a compelling solution or explanation of the conceptual problem, as this has professional implications for the students' future teaching careers.

In the second task, students are required to demonstrate their understanding of the technical distinction between the equilibrium of forces and Newton's third law. Wöllermann *et al.*[17] introduced this distinction in class before addressing the doorbell paradox. The task is designed to help students structure and differentiate between these two concepts, emphasizing that the point of application of the forces is key to distinguishing between force equilibrium and Newton's third law. This serves as essential technical preparation for the next task, where students will apply this distinction in the context of teaching activities. Additionally, the distinction helps to address the misconception underlying the doorbell paradox, namely, the false belief that the action and reaction forces in Newton's third law act at the same point of application.[32]

The third and final task in this Focus Class is specifically designed to address the above-mentioned misconception. The students are required to engage in a discussion regarding teaching strategies that support learners' conceptual development. It is expected that students develop ideas that explicitly address the point of attack of the force and engage in a critical analysis of the advantages and disadvantages associated with these approaches. The context of the teaching activities is not explicitly provided; it can be either the development of an introductory class to differentiate between the two concepts or the situation in which individual students encounter difficulties with this learning objective and the teacher provides assistance to help them overcome it. The overarching objective is to facilitate the development of pedagogical approaches rooted in students' content knowledge. This endeavor aims to equip students with the ability to address learning difficulties and to discuss the suitability of these approaches in diverse contexts. This task is therefore explicitly designed to prepare students for a future career in teaching and is the only one that explicitly addresses pedagogical content knowledge.

The discussion of misconceptions can also include the acknowledgment that they often contain a kernel of truth. Additionally, the source of the misconception should be identified, which may include drawings, language, teaching methods, or everyday experiences. In this case, however, we are dealing with a misconception that has been induced by teaching, which is why only the discussion of the cause would be relevant in this case. As this misconception has its roots in the classroom, we inquire of our students as to how they might prevent its development.

In conclusion, the students address the paradox from three distinct perspectives: initially from an individual standpoint, utilizing the insights acquired from the reading text and lecture; subsequently, from a professional standpoint; and finally, from an educational standpoint.

In all Focus Classes, the various perspectives presented in the course of the worksheet are contextualized with respect to one another, in a manner analogous to the approach taken in tutorials with regard to conceptual understanding. In contrast to the approach taken in tutorials, where the focus is on explicitly addressing and overcoming misconceptions, the tasks in Focus Classes are designed to guide students through educational concepts in a structured manner, while also repeatedly incorporating specialist science as a basis. On occasion, however, the Focus Classes also facilitate the exploration of school-relevant topics in greater depth.

III. CLASSROOM EXPERIENCES

The course was implemented as a whole for the first time in the 2023/2024 academic year. A more thorough evaluation study will be conducted for future implementations; however, feedback has already been collected via a questionnaire from 12 participating students to gain insights into how to refine the Focus Classes before the next implementation.

The students particularly value the profession-related content of the Focus Class, noting that it provides an invaluable opportunity to examine the subject matter in relation to the school physics and their future students. They see this as a useful exercise that allows them to identify potential areas of difficulty and focus on those aspects that require special attention when it comes to teaching and learning physics. Furthermore, the students emphasize that they want to become physics teachers, not physicists, and therefore appreciate the existence of the Focus Class. The students also felt that the Focus Class was a better preparation for real classroom situations than "pure theoretical knowledge."

In addition, students view the Focus Class as a crucial component of their physics studies, as indicated by their statements: "From a student's point of view, the Focus Class is of great value because it encourages a deeper, reflective, and critical examination of the theory learned." One of the participants states: "I have never learned as much physics as I have in the Focus Class." Additionally, the students regard the think-pair-share method as a highly valuable tool for conceptual tasks. It enables them to engage in constructive problem-solving and address their own learning difficulties in a productive manner.

Finally, the students indicate that the approach entangling subject-specific and physics education perspectives is of significant importance to them. This is evidenced by the following quote: "In my opinion, it does not make much sense to start with this [physics education/communication of subject content to students] in later terms."

IV. FUTURE DEVELOPMENTS

Another hurdle in the entry phase of physics teacher education programs, which has not been addressed in this article, relates to the mathematical skills of pre-service physics teachers. Undergraduate mathematical skills have been found to correlate with student performance in physics programs.[44–47] However, the mathematical requirements pose a conspicuous obstacle for physics students in the entry phase, especially for pre-service teachers who do not study mathematics as a second subject. However, only about half of the students in a physics teaching degree study program also study mathematics as their second subject.[9] Therefore, students need to be supported in acquiring a solid mathematical foundation in order to be able to solve physics problems. Due to time constraints, it is not possible to introduce mathematical methods in a comprehensive and practical way within the regular introductory physics courses. Instead, we are planning to focus on self-study periods to enable students to develop the necessary skills.[48]

Therefore, in the future, we will extend the curriculum presented in this article through an online instructional program that provides individual practice opportunities of essential mathematical methods. One solution we are implementing is based on the STACK plug-in available for learning management systems.[49] STACK uses a computer algebra system to create problems that involve randomized variables or functions, enabling unlimited practice (see Fig. 2).[49] In addition, STACK is able to compare algebraically equivalent solutions to the model solution and evaluate them accordingly. After completing the online tasks, students receive

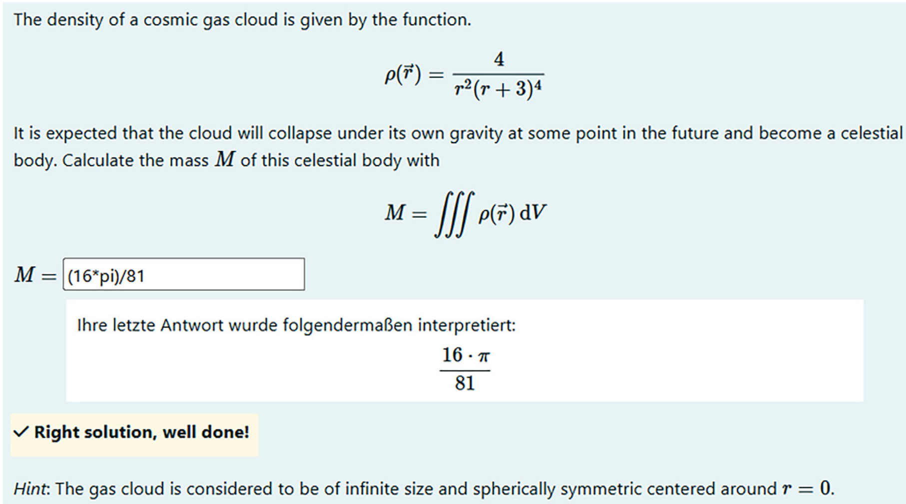

Fig. 2. Example of a STACK problem for volume integrals in spherical coordinates with the solution already entered by a student. Students are given (a) an interpretation of their input so that they can check it and (b) feedback on their result.

individualized feedback, which can include typical errors or the evaluation of subsequent errors.

In previous work, we have already demonstrated a first test-implementation of STACK exercises and have assessed the effectiveness in equipping students with necessary mathematical competences during the self-study phase.[48] As a next step, we plan to design a coherent course program that combines subject-oriented lectures and group exercises with both the "Focus Class: physics education and school-related topics" and the self-study STACK support for physics teacher students with a comprehensive just-in-time approach implemented during the freshman year.

V. CONCLUSION AND OUTLOOK

The favorable feedback from students illustrates the potential of the presented approach. It is our hope that other locations will be encouraged to implement similar approaches. Furthermore, we encourage fellow teacher educators to adapt our worksheets as well as create their own for their specific pedagogical purpose.

SUPPLEMENTARY MATERIAL

See the supplementary material for details, in which we provide some exercise sheets for the Focus Classes in English and German.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

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[50]Physics teacher training in Germany ends either with a master's degree or with a state examination, depending on the state. In Bavaria, the state of Germany in which the Friedrich–Alexander University Erlangen–Nuremberg is located, physics teacher education at the university level ends with a state examination in which prospective teachers must pass examinations in physics (and their second subject), physics education, and educational science.
[51]Concept inventories can be found via PhysPort (https://www.physport.org).