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A physics curriculum for the modern world

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Increasingly, physics graduates take jobs outside academia. Active teaching approaches lead to deeper conceptual understanding and a more varied skill set and are therefore more likely to prepare students for successful careers.

The purpose of the study of physics has traditionally been to prepare future physicists for professional opportunities in the teaching and research sector. However, physics graduates' career paths have recently expanded into industry – into sectors such as energy, finance, meteorology or information technology – and into other scientific fields – for example, nanotechnology and biophysics. All these potential career paths require skills taught in traditional physics curricula, such as quantitative analysis and problem-solving[1]. However, there are many other skills that would benefit graduates seeking employment outside academia.

Two recent reports of the current state of physics education[2,3] indicate that many of these skills are neglected by physics programmes, under-preparing physics graduates for professional environments outside academia. Employers need physicists who are good at solving problems in different scientific fields. Although the ability to solve applied physics problems is one of the standard objectives of most current physics curricula, physics education research (PER) shows that this objective is not always achieved[2,4].

The prevailing teaching method is to get students to plug in the data into an ad hoc formula – an approach that has been shown to lead to superficial conceptual understanding[5]. Professional and governmental institutions would like the science (physics) curriculum to include real-world skills that focus on developing reasoning, critical thinking and in-depth understanding. These skills would help students to build expert-like knowledge structures and to get involved in relevant scientific research and problem-solving[3].

Physics students and recent graduates express satisfaction with their knowledge of physics and mathematics, problem-solving skills, and their research and programming experience[2,6]. However, they also seek additional skills not currently included in standard curricula, such as the ability to solve interdisciplinary problems, design and develop complex projects, work in and manage teams and analyse societal implications. The overall findings of these reports suggest that there is a need to review traditional physics curricula, add new content and change how existing content is taught.

Fostering innovation in the physics curriculum

The factors driving changes in physics curricula over the past two decades or so stem from the above-mentioned socio-cultural changes and from progress in PER. Systematic PER has demonstrated the need to include specific goals in the curriculum, such as knowing how to collect and interpret relevant data, how to convey ideas, and how to formulate

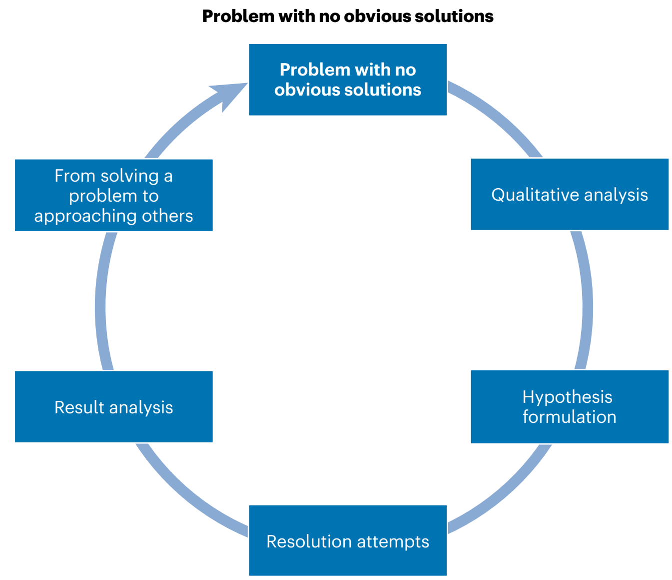

Fig. 1 | General characteristics of the active teaching approach. Qualitative analysis includes clarifying the research goal, simplifying the problem to make it amenable to quantitative analysis, outlining a theoretical reference framework, identifying variables and searching for data. Hypothesis formulation involves predicting how the system might change, establishing dependency relationships between variables and analysing borderline cases with physical relevance. Resolution attempts include identifying the fundamental principles or assessing possible alternative lines of inquiry. The analysis of the results requires checking the plausibility of dimensional consistency of the answer.

problems and solutions. PER also highlighted the importance of taking into consideration students' individual learning styles and attitudes towards the discipline.

Traditional teacher-focused lectures with passive students tend to be theoretical and abstract. Although instructors expect students to develop problem-solving skills and scientific reasoning using the problems they set, PER has repeatedly demonstrated that students rarely acquire these higher-level cognitive skills (Fig. 1). Examples of these skills include analysing situations, relating them to theory, formulating and testing hypotheses, proposing solution strategies and evaluating the consistency of results. Previous analyses show that students tend to see physics as a set of facts and believe that problem-solving consists of finding the correct formula[7]. These findings, combined with the need to train students who can tackle interdisciplinary projects, have led to innovative research-based, student-centred teaching approaches that mimic the characteristics of actual physics research[8,9].

A key aspect of problem-solving is making conjectures on dependencies between the variables in the system and generating hypotheses on how they might develop by means of creative speculation. Often, when solving a problem, multiple solving strategies are active at the same time, and come into conflict with one another, so that much of the challenge revolves around resolving this conflict and choosing just one strategy. At the analysis stage, it is crucial to discuss the meaning of the results obtained and their consistency in relation to the original problem-solving goals and initial hypotheses. The developed framework is then tested on more complex scenarios.

This process is not usually considered in traditional teaching and students tend to use a 'plug-and-chug' strategy based on the assumption that all the variables and data are well defined and that the solution is unique[10]. Active teaching approaches aim to address this gap by incorporating the aspects of research described above. A general framework with wide consensus in the PER community is shown in Fig. 1.

To solve problems following the PER strategy, students must first gain an understanding of physics concepts and laws that is deeper than what can be obtained from traditional teaching methods. PER groups have proposed active teaching approaches that involve students in activities designed to test their scientific knowledge in a collaborative environment and with feedback from peers and teachers[11,12]. Readers can refer to the Physport website for a broad selection of such activities along with suggestions on how to evaluate student learning outcomes. Here we briefly describe a few key points.

Various PER groups have demonstrated the importance of an intentional teaching approach in which students take part in activities that have learning goals related to each topic they study. These activities are designed to take into account various possible reasoning processes that the students might follow and any reasoning difficulties they might encounter[11]. An active learning setup is proposed as follows. (1) The students are organized into cooperative groups of three or four. (2) The activities are structured around several problems and solving these problems helps students to attain the desired learning objectives. (3) Each problem involves a series of activities that guide students as they solve the problem and give them the chance to make well argued decisions. (4) The teacher guides a discussion on all possible ways of solving the task, and a summary is written of the key ideas required to solve the problem[13].

Active teaching approaches range from proposals that are easily introduced in a large lecture hall to modifications that require changes involving a considerable redesign of the curriculum and support from the university's administrative structures. The results from most of these proposals indicate that students who receive active teaching have considerably better conceptual comprehension and problem-solving skills than students who are lecture-taught[4,14]. Active learning is correlated with greater student interest in their own learning, greater retention of the contents than students taught traditionally and greater awareness of inclusion issues in physics[15].

The physics community and society in general increasingly recognize the need to include diversity, equity, and inclusion (DEI) issues in the physics curriculum to help students take on their societal responsibilities in personal and professional situations. It is beneficial for students to reflect on the identity of a physicist, and discuss what it means to create, test and interpret scientific models and theories, in order to become aware of what diversity (race, gender, and so on) can bring to physics.

Diversity leads to better science, helps to dismantle prejudices and tackles the uneven distribution of influence[16]. It is possible to argue that although these topics are important, they do not belong to a physics class. However, reports from professional and academic institutions clearly show that discussing these matters is part of the professional practice of physics. Including units in the curriculum that work on DEI issues helps to promote an open perspective among physics students and encourages a sense of identity and belonging that, together with the right academic support, drives student success. These changes help to define broader curricular objectives that complement the deep-rooted idea in traditional teaching that physics is an intellectual achievement and a human skill, whose value is in itself sufficient to arouse interest in studying it.

The role of physics departments and governmental institutions

Although there is wide consensus among teachers, students, administrators and public institutions on the need to make changes to the curriculum along the lines mentioned above, teachers are still grappling with the question of which contents and skills should be prioritized and how they should be taught. Although there is no easy answer to this question, these difficulties should not be used as an excuse for the continued prevalence of traditional lectures in many physics courses[17], given the benefits of research-based, student-focused instruction strategies. Overhauling passive teaching is also increasingly important given the above-mentioned growing need for physicists in industry.

To make change possible, physics teachers and department boards must work with universities to promote the use of new strategies and methodologies in the classroom for student-focused learning. A teaching approach that directly links the theory taught in class to its application in daily life or in industry will probably motivate students and challenge the often-held view that physics is boring and abstract. It will also enhance students' abilities to solve problems that are part of complex interdisciplinary projects, which will make them more likely to be successful in a rapidly changing world.

We mention two examples, among others, of collaboration between university departments and governmental institutions. One example is the Science Education Initiative launched by Carl Wieman and colleagues at University of Colorado and University of British Columbia[18]. Another example is the physics group of the European Tuning Calohee project (https://www.calohee.eu/physics/), composed of 15 members representing different European countries. It aims to exchange ideas between different countries and institutions in order to identify what competence a student should achieve at the end of a physics degree, and to reflect on good teaching, learning and assessment practices to achieve the goal.

These benefits for physics graduates and for society point to the need for universities, physics departments, teachers and employers to cooperate and to commit to innovating physics curricula on the basis of PER findings.

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Competing interests
The authors declare no competing interests.