PHYSICS BACHELOR’S STUDIES IN EUROPE

A position paper and programme specification by the European Physical Society (EPS)

EPS Publications

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CONTENTS

EXECUTIVE SUMMARY

Purpose and scope

1. The present document presents an update of the first edition to reflect the current conditions and perspectives for physics bachelor's degree programmes (PBPs). New evidence, developments, and opportunities have emerged, such as sustainable development, data science and digital technologies, and artificial intelligence, as well as new workplace realities and employer expectations that need to be considered. Another important aspect considered are the benefits physics can offer to address current challenges in a range of key domains (energy, health, sustainability, and others). Moreover, many physics departments face problems including low enrolment, gender inequity, or high dropout rates.

2. Today, a wealth of evidence-based teaching and learning approaches for physics bachelor's studies is available. Drawing on these established resources can meaningfully support efforts to assure and improve the quality of the offered programmes. For that purpose, good practice and best evidence approaches, as well as recommendations, are included for many topics.

Educational aspects

3. Core physics topics (mechanics, electromagnetism, thermodynamics/statistical physics, waves/optics, properties of matter, quantum physics) are central for PBPs, while introductory exposure to more advanced areas (micro- and macrocosm, complex systems) should also be provided to motivate students and orient specialisation choices.

4. Disciplinary competences emphasise mastery of fundamental knowledge, experimental and modelling skills, and mathematical fluency; these should be complemented by generic competences (problem solving, ethical/scientific integrity, etc.).

5. Educational approaches deserve strong attention and effort, regarding teaching for active and meaningful learning and assessment beyond mere calculation problems. Teaching and assessment form a natural unity and should be seen in very close alignment. Relying on traditional teaching methods solely because they require less effort and time should be avoided, and available good practice examples and empirical research should be consulted to guide the selection and integration of promising teaching practices.

6. Integrating computation and digital technologies in physics studies is necessary to equip students for data-rich environments across academia, industry, and public sectors. They should be structurally embedded in PBPs, with sustained support for curricular innovation, infrastructure, and instructor training.

7. Interdisciplinary components (*e.g.* biophysics, computing, materials, *etc.*) and links to Sustainable Development Goals provide authentic contexts that increase relevance, student motivation, and applicability to societal challenges.

8. Evaluation is often limited to traditional end-of-term student questionnaires, which have well-known limitations and are frequently considered by faculty merely as a tedious duty. However, many good practice and best evidence approaches, as well as useful tools, are available, and a well-thought-out strategy can make evaluation a powerful lever for enhancing teaching quality, supporting faculty development, and advancing student learning and success.

Framework

9. The report documents the importance of interfaces and transitions in PBPs with secondary* education, master's and doctoral studies, and the workplace, and provides a range of good practice and best evidence approaches conducive to the programme goals and purposes.

10. The report acknowledges PBPs' already tight study programmes and increasing budgetary and other constraints. To facilitate stepwise improvement, emphasis is given to easy, actionable first steps with a low entry barrier, existing good practice and best evidence approaches, and useful implementation resources.

PREFACE TO THE PRESENT EDITION

This document presents a Europe-wide view of the competences and achievements that graduates of physics bachelor's degree programmes (PBPs) should have attained through their studies and education.

The first edition of this document in 2009 was mainly concerned to facilitate the Bologna process within the European physics community, by providing a common curricular basis to foster mobility and to facilitate mutual recognition of studies as an essential prerequisite of mobility. Specifically, it was conceived to serve the following objectives:

– as a source of reference for higher education institutions (HEIs) when new programmes are being designed and developed, providing general guidance for articulating the learning outcomes associated with the programme, and not meant as detailed descriptions of a core or model curriculum;
– as a means to support to institutions for internal development and quality assurance, enabling the learning outcomes of PBPs to be reviewed and evaluated against agreed general expectations;
– as a source of reference that may be used for the purposes of external review and accreditation.

In 2026 the Bologna process is well established, and in a stage of continuous adjustment rather than initial implementation. National statements and guidelines have been established in most countries.

The present edition subscribes to the above objectives and presents an update to reflect the current conditions and perspectives. The previous edition of this document contained a European Benchmark which has served for the accreditation of PBPs in several countries. To retain this use also in the present edition, the core elements which can be used in accreditation procedures are listed in Annex A1.

Beyond the document's initial scope, new developments—specifically in sustainable development, data science, digital technologies, and artificial intelligence—along with evolving workplace realities and employer expectations, need to be taken into account. Another important aspect to be considered is the benefit physics can offer to help resolve current challenges in a range of key domains (energy, health, sustainability, and others).

Today, a wealth of evidence-based teaching and learning approaches for physics bachelor's studies is available. Drawing on these established resources can meaningfully support efforts to assure and improve the quality of the offered programmes. For that purpose, good practice and best evidence approaches, as well as recommendations, are included for many topics.

The present document thus serves a double purpose: a position paper on new challenges and opportunities, and a programme specification as described above.

As in the first edition, we emphasise that the suggestions of this document should not be used as a rote checklist for accreditation but rather it should be employed alongside careful consideration of the relevant programme descriptions and purposes, the institutions' own objectives, and internal evaluation documentation, in order to arrive at a conscientious judgment based on a broad basis of deliberation and evidence.

A Glossary of key terms in higher education can be found in [COE++] &[VGP07], and of some further terms (indicated in the text by *) relevant to the present document in Annex A2 .

Editorial note: For several topics, good practice examples (and in one case the rationale) are provided in separate text boxes; relevant literature is also given within each box to facilitate independent use.

PREFACE TO THE EDITION FROM 2009

The European Physical Society (EPS) is a European-wide professional association with 41[1] national member societies. The EPS supports the Bologna Process and provides with a series of specifications a means to describe the characteristics of the physics study programmes in a European dimension. This series covers (a) the bachelor's or first-cycle or EQF level 6, (b) master's or second-cycle or EQF level 7 and (c) doctorate or third-cycle level or EQF level 8, which together constitute one of the three priorities of the Bologna Process [EC09]. The specifications also describe general expectations about the standards for the award of qualifications at the given level and articulate the attributes and capabilities -i.e., the learning outcomes -that those possessing such qualifications should be able to demonstrate. These qualifications agree with the European Qualifications Framework (EQF) [EQF++]. National statements and guidelines [MEN04, KFP05, IME07, LME07 and QAA08] have already been established in some countries and have been very influential in designing these specifications. The European bachelor's level or EQF level 6 corresponds to the UNESCO level ISCED6 [UNESCO11]. The present EPS specification refers to the physics bachelor's degree in a European perspective. Specifications are used for a variety of purposes. Primarily, they are an important external source of reference for higher education institutions (HEIs) when new programmes are being designed and developed. They provide general guidance for articulating the learning outcomes associated with the programme but are not detailed descriptions of a core or model curriculum. Specifications provide for variety and flexibility in the design of programmes and encourage innovation within an agreed overall national, regional or institutional framework. They also provide support to institutions in pursuit of internal quality assurance. They enable the learning outcomes specified for a particular programme to be reviewed and evaluated against agreed general expectations.

Finally, specifications are among a variety of external reference points that may be drawn upon for the purpose of external review. Reviewers should not use specifications as a crude checklist for these purposes, however. Rather, they should consider them in conjunction with the relevant programme descriptions, the institutions' own internal evaluation documentation, to arrive at a rounded judgment based on a broad range of evidence.

This present physics bachelor specification has been undertaken by a European group of physics higher education specialists. The group's work has been funded with support from the European Commission [EC07] and was facilitated by the European Physical Society, which publishes and distributes these documents. The present document went through a full consultation and validation process with the wider European academic community and the stakeholder groups.

In due course the specification will be revised to reflect developments in physics (and astronomy) and the experiences of institutions and others who are working with it. The EPS will initiate revision and will make arrangements for any necessary modifications to the document in collaboration with the European physics community.

In the Annex, a common European Benchmark framework for bachelor's degrees in physics is added. It was kindly provided by the Working Group 1 in the STEPS (Stakeholders Tune European Physics Studies) TWO network. It is aimed at the level of an indicative listing, which broadly specifies the common programme which can be found in most physics degrees across Europe. Also, this document went through a full consultation and validation process with the wider European academic community and the stakeholder groups.

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[1] 42 in 2025

PHYSICS BACHELOR’S STUDIES

1 Introduction

1.1 The present position paper and specification for physics bachelor’s degree programmes (PBP) characterises a European-wide view of the competences and achievements that graduates of physics bachelor’s degrees should have acquired/attained through their studies and training. There exists a wide range of programmes delivering such degrees reflecting the varying aspects of physics and different national perspectives, traditions and educational policy imperatives. However, there is wide agreement across Europe of what constitutes the basics of physics and the essentials of what should be included in a first degree in physics. This paper relates to programmes where physics (including astronomy) and mathematics represents a significant proportion -at least 70%- of the programme (note, however, that many aspects discussed below also apply to other physics-related programmes, *e.g.* bi-disciplinary programmes).

A description of physics as a discipline is given in Box 1. It serves to ensure a shared understanding for different interested parties; in particular, such a description is a necessary element of accreditation procedures.

1.2 Physics is a major discipline in the European Higher Education Area (EHEA) with well over 100.000 students registered on undergraduate HE programmes [OECD25]. Physics graduates play a major role in the EU economy [EPS25]. However, physics is not only essential for scientific and technical professionals, it is also fundamental to our understanding of the natural world and the principles governing the universe. As such it has wide and deep cultural dimensions, and its study is of universal value. Physics is also foundational to the other natural sciences and to new advances in technology. It thus constitutes an essential factor in the development and economy of modern societies, and in addressing their challenges in a variety of important fields (communication, energy, health, security, sustainability). **1.3** Physics is a maturing and demanding discipline. An understanding of the frontiers of physics often requires *advanced knowledge*, which cannot necessarily be acquired during a bachelor’s degree programme. The present specification has taken this into account in interpreting the generic competences of the qualification framework for bachelor’s or first-cycle level physics degree programmes.

1.4 Physics degrees will continue to evolve in response to developments in the discipline and in the educational system (*e.g.* changes in the secondary school curriculum). Hence, this document concentrates on general conditions for successful PBPs and on how current key factors can be implemented in the current educational landscape. This serves as a source of concrete examples for future implementations as the landscape evolves.

1.5 The present document contains several elements that may be considered not (yet) standard parts of PBPs (such as interdisciplinarity, links with the workplace, emphasis on educational approaches, *etc*.). A main objection against the integration of such elements concerns how to incorporate them within already tight study programmes and increasing budgetary and other constraints. However, these are evidence-based approaches to counter issues faced by physics departments as mentioned above (low interest in physics studies, gender inequity, high dropout). If these issues are taken seriously and there is a will for improvement, it would be unwise to ignore existing evidence and best practice when enhancing study programmes. Box 1: **PHYSICS AS A DISCIPLINE**

This description serves as a foundation for diverse audiences (curriculum developers, students, quality reviewers, external examiners, accreditation bodies, and employers), in order to ensure a shared understanding of the discipline that underpins the standards and recommendations that follow. In particular, two purposes are central:

- a position paper about physics bachelor's degree programmes should contain a description of the discipline informative and helpful for bachelor' students;
- such a description is a necessary component in reports to accreditation agencies.

The following description of the essential features of physics and its approaches as scientific discipline is strongly based on QAA25. An in-depth description of the self-understanding of physics as a discipline by the EPS under the perspective Physics for Society in the Horizon 2050 is provided by [Hid24].

1. Physics is concerned with the quantitative observation, understanding and prediction of natural phenomena and the behaviour of human-made systems. It deals with profound questions about the nature of matter and the universe (such as quantum entanglement, particle physics, and cosmology) and with some of the most important practical, environmental and technological issues of our time (such as energy, climate and sustainability). Its scope is broad and involves mathematics and theory, measurement, *i.e.* quantitative experimentation and observations, computing, technology, materials and information theory. Concepts and techniques from physics also drive developments in related disciplines, including chemistry, computing, engineering, materials science, mathematics, medicine, biology and the life sciences, earth and atmospheric sciences, meteorology, environmental science, statistics, as well as in applications linked to the humanities such as archaeology and the investigation and preservation of cultural heritage [EPN25b].
2. Physics is both experimental and theoretical, and it evolves continuously. Its foundation lies in the assumption that even complex systems can be understood through a small set of key quantities (such as energy and momentum), and the universal governing principles (such as symmetry). A major strength of physics is the limited number of such principles, extending beyond physics to other sciences. Both aspects are well illustrated by Newton's laws of mechanics: derived from planetary motion, they apply equally to everyday phenomena and to the dynamics of stars and galaxies; today, however, they cannot, e.g., correctly define GPS timing, which requires Einstein's general relativity as more exact theory.
3. Physics as a natural science: 'The skills and methods used to make measurements are an integral part of physics. The final test of the validity of any theory is whether it agrees with experiment. Many important discoveries are made as a result of the development of new experimental technique. For example, techniques developed to liquefy helium subsequently led to the totally unexpected discovery of superconductivity, superfluidity and the whole field of low temperature physics. Instruments developed originally in physics frequently find applications in other branches of science; for example, electromagnetic radiation emitted by electron accelerators, which were originally designed to study elementary particles, is now used to study the properties of materials in engineering, biology and medicine'
4. To make quantitative predictions, physics uses mathematical models. The types of approximation used to find satisfactory models of experimental observations often turn out to be very similar, whether the underlying laws are those of classical physics, statistical mechanics or quantum theory. Typically, an idealised model of some phenomenon is established, the equations describing the model in mathematical terms are solved (often with further approximations) and the results compared with experimental observation. Sometimes a model is applicable to very different circumstances. For example, the same statistical model applies to the behaviour of electrons in metals and to white dwarf stars.
5. Computational approaches are also central to physics. They have become essential in modelling systems from the subatomic, through materials, to the cosmological scale and in the analysis of large data sets. Increasingly, physics develops deep-learning algorithms and artificial intelligence (AI) to understand and simulate physical systems.
6. Progress in physics requires imagination and creativity. It is often the result of collaboration between physicists from a diverse range of backgrounds (both culturally, and, in the sense of sub-fields of physics as well as experimentalists, computational physicists or theorists) and can involve the exchange of ideas and techniques from outside physics.
7. Studying physics at a university brings benefits that last a lifetime and knowledge and skills that are valuable outside the field of physics. Such benefits include a practical approach to problem solving, often using mathematical formulation and solution, the ability to reason clearly and to communicate complex ideas, digital and self-study skills, along with the pleasure and satisfaction that comes from being able to understand the latest discoveries in physics or natural science. Additionally, students develop a strong sense of professional ethics, including scientific integrity, responsible conduct of research, and a commitment to honesty and objectivity in their work.

8. After graduation, physicists pursue diverse careers across industry and academia—spanning research, development and education, —as well as increasingly in business and finance, where their analytical and synthetic problem-solving skills are highly valued.

9. Physics has a special social role for democratic `Knowledge Societies´: Democratic decision-making can succeed only when society understands the issues at stake. Physics, as a fundamental science, provides an understanding of essential concepts and relations, as well as of the scientific approach to the acquisition and validation of knowledge in general. This is the only way to counter disinformation and to provide a reliable basis for decisions of societal importance (such as the energy supply system, climate change, *etc.*).

2 Programme Structure and Delivery

2.1 General considerations

2.1. Physics is a highly structured discipline that requires systematic and well-thought exposure to and acquisition of knowledge. It is a subject which relies on experiment and observation as the source of our knowledge of the physical universe but which complements this with theoretical constructs based on a fairly small number of all-encompassing principles and laws often expressed and developed using mathematics. Practical skills and the ability to analyse and model experimental data must be developed as does an appreciation of the link between theory and experiment. Moreover, the programme objectives should encompass both specific competences (*e.g.* in experimentation) and generic competences (*e.g*. problem solving), developed within the physics context (sect. 3; [TP09]). Note that the present specification does not contain an explicit allocation of Credit Points, in line with current practices [see e.g. QAA25]; the reasoning behind this is that it is a priority to specify the competences [OECD++], which then entail the necessary workload in a given teaching approach.

2.2. In the *TUNING* methodology [GW03&05], the use of learning outcomes and competences is necessary in order to make study programmes and their course units or modules student-centred and output oriented. This approach requires that the key knowledge and competences that a student needs to achieve during the learning process determine the content of the study programme [KE09].

2.3. Development between levels of study should be evident; for example, laboratory work may become open-ended with more demanding reporting criteria at the higher levels.

2.4. The European Higher Education Area has defined descriptors (so-called 'Dublin Descriptors') to determine when students in their learning process have attained the bachelor's level [EHEA25, EHEA18]: "Qualifications that signify completion of the first cycle [i.e. bachelor] are awarded to students who:

- Demonstrate knowledge and understanding in a field of study that builds upon their general secondary education, and is typically at a level that, whilst supported by advanced textbooks, includes some aspects that will be informed by knowledge of the forefront of their field of study;
- apply their knowledge and understanding in a manner that indicates a professional approach to their work or vocation, and have competences typically demonstrated through devising and sustaining arguments and solving problems within their field of study;
- acquire the ability to gather and interpret relevant data (usually within their field of study) to inform judgments that include reflection on relevant social, scientific or ethical issues;
- communicate information, ideas, problems and solutions to both specialist and non-specialist audiences;
- develop the necessary learning skills for them to continue to undertake further study with a high degree of autonomy.

We will now turn to the central features of programme structure and delivery: quantitative aspects, content, educational approaches, evaluation, and evidence-based practices.

2.2 Quantitative aspects: duration, credit points

Typically, physics bachelor's programmes have a duration of three years (180 ECTS credits), but there are also countries with four-year programmes (240 ECTS credits), for example Scotland, and Spain, and in some countries both types coexist (Germany). A systematic study of 155 PBPs from 24 countries in 2009 found that almost 90% were three-year programmes [KE09].

Institutions which apply the European Credit Transfer and Accumulation System (ECTS) [DGE15] publish their course catalogues on the web, including detailed descriptions of study programmes, units of learning, university regulations and student services. Course descriptions contain learning outcomes (what students are expected to know, understand and be able to do) and workload (the time students typically need to achieve the learning outcomes), expressed in terms of credits. In most cases, student workload ranges from 1,500 to 1,800 hours for an academic year of 60 ECTS, and one credit corresponds to 25-30 hours of work. Credit transfer and accumulation are helped by the use of the ECTS key documents (course catalogue, learning agreement, and transcript of records) as well as the Diploma Supplement [EEA25].

2.3 Core physics topics/concepts

2.3.1 *Fundamentals*

The *fundamentals*, which all students need to cover to some extent, include:

- (classical) mechanics
- electromagnetism
- quantum physics
- thermodynamics, statistical physics
- wave phenomena
- optics
- properties of matter: its elementary constituents and their interactions, both on the atomic and subatomic level.

2.3.2 *Applications to more advanced areas*

Study programmes should also offer students the opportunity familiarise themselves at an introductory level with the application of the fundamental principles to several more advanced areas. First, these areas can provide a strong source of student motivation (particles, cosmology, chaos, etc.). Second, they offer a basis for a reasoned choice of specialization and thus for orientation toward master's programmes (see sect. 5.2). Typical areas (from which students make a restricted choice) include:

- atomic physics
- condensed matter physics
- physics of materials
- nuclear and particle physics
- plasmas
- physics of fluids
- chaos and nonlinear phenomena.

In cases astrophysics and astronomy courses are part of the programme, these may include the application of physical principles to:

- cosmology
- structure, formation and evolution of stars and galaxies
- high-energy phenomena in the universe
- exoplanets, planetary systems, life in the universe.

2.4 Additional physics topics/concepts

2.4.1 *Elective courses*

Elective courses have an important role in PBPs, serving multiple purposes:

- providing degrees of freedom for students' personal scientific interests;
- addressing current scientific and societal questions;
- preparing the transition to master's degree programmes;
- sometimes serving as the beginning of the long-term scientific career.

For this, traditional (see sect. 2.3.2) and newer elements (see sect. 2.4.2 and 2.4.3) of elective courses can work together to create flexible pathways that accommodate both individual academic trajectories and evolving disciplinary and societal demands.

2.4.2 *Interdisciplinarity*

Interdisciplinarity is of increasing importance within physics and physics study programmes, due to profound changes in both the physics research and education landscapes, and the job market [Dar24]: physics, like many other STEM fields, has become progressively more interdisciplinary, making it essential for students to develop knowledge and competences in domains that extend beyond its traditional boundaries (JTUPP16; a particularly important example sustainable development goals, see sect 2.4.3). Moreover, most physics bachelor's degree holders are employed in non-academic positions in a wide variety of professional settings ([ZRM24, JTUPP16]; see also 3.2). Further arguments strongly support the integration of interdisciplinary aspects in physics study programmes, see [Dar24] and Box 2.

– Prepare students for real-world problems that are inherently interdisciplinary (*e.g.* climate change, energy systems, biomedical applications; [JTUPP16, UNESCO22; QAA25]).
– Align education with employer expectations: graduates need disciplinary and cross-disciplinary knowledge and competences, as well the general ability to apply physics methods across contexts [JTUPP16].
– Promote innovation by combining physical modelling with computational, biological, or social science methods [NASEM18b].
– Increase student motivation and meaningful learning by situating physics concepts in authentic interdisciplinary contexts [JTUPP16, TS19].
– Support societal relevance and responsibility: interdisciplinary content and modules (see above) enable and encourage graduates to contribute to societal and global challenges [JTUPP16, NASEM18a].
– Provide interdisciplinary study elements as a natural field of action to develop generic competences as discussed below (sect. 2.4.2). [Fed21].

Box 2: Rationale for integration of interdisciplinary aspects in physics study programmes

Of course, a balance must be found between the core physics topics [2.3] and the interdisciplinary aspects that add further requirements and workload [NASEM25].

An apt expression for a synthesis of both components is the concept of "T-shaped skills", see Figure 1; in a review on research at IBM, this is considered a "pillar of innovation" [Coh15].

Figure 1: T-shaped skills: deep in one field but with a breadth that enables collaboration and application across many fields [Gro18; see also Dar24; illustration inspired by the "Vitruvian Man" by Leonardo da Vinci].

Recommendations:

Interdisciplinarity can be implemented in PBPs at least at three levels; in this way, many of its benefits can be attained at a low-threshold scale and with manageable effort:

– Within existing courses, interdisciplinary connections can be made systematically—an apparently simple step that nevertheless requires well-informed rethinking and rewriting of course materials.
– Providing courses that integrate physics content with other disciplines, often aligned with the research fields of physics departments (see Table 1a for typical examples).
– Finally, interdisciplinary development can take the form of PBPs that explicitly combine two or more disciplines (see Table 1b for representative cases).[2]

a) Some typical topics of interdisciplinary PBPs courses *Existing also as full-fledged interdisciplinary study programmes, see b)	***b) Some typical bachelor programmes with physics as main component*** [DPG++]
–complex systems	–biophysics
–computational physics	–medical physics
–nanophysics/science*	–physical engineering
–material science* [KW23]	–quantum technologies
–soft and granular matter	–physics and digital technologies
–physics and the environment, physics and climate*	–physics and green technologies
–life in the universe	–econophysics
	–physics teacher education (see 2.4.4)

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[2] While these programmes are not the topic of the present position paper, they are of interest for all full picture of the breadth of physics study programmes at the bachelor level.

Table 1: Examples of typical a) interdisciplinary courses and b) study programmes related to physics at bachelor's level (a database with detailed information on such study programmes is provided *e.g.* by the German Physical Society, [DPG++])

2.4.3 *Sustainability and sustainable development goals*

Physics is essential for many of the Sustainable Development Goals (SDGs; [UNESCO22, QAA25]. The combination of discipline-specific and generic competences developed during PBPs makes students well prepared to contribute to a more sustainable world. Throughout their studies, students gain experience in critically analysing information and drawing evidence-based conclusions, both crucial for most SDGs.

In addition to providing a habit of mind, physics offers crucial measurement and modelling techniques for collecting and analysing SDG related data (*e.g.* concerning global warming), thereby guiding potential solutions. Physics is also foundational for many of the current and emerging technologies required to achieve SDGs in areas such as energy, transport and health. For example, thermal and statistical physics form the scientific foundation of the energy and climate SDGs. The integration of SDGs into PBPs can be achieved in multiple ways, be it through carefully designed examples in problem sheets or lab courses, project work addressing sustainability themes, or lectures on sustainability topics. Such initiatives may also involve collaboration with other departments or external stakeholders.

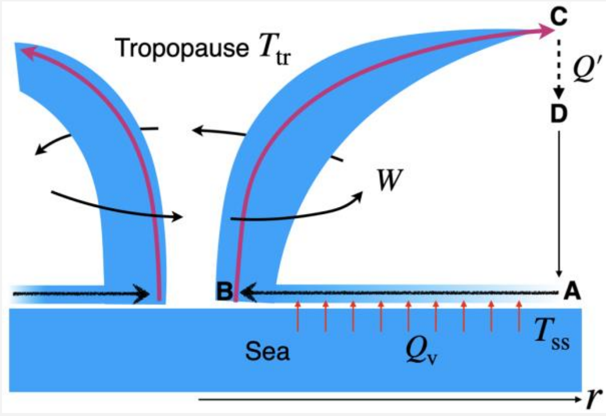

Figure 2: Hurricanes as thermodynamic cycle (Carnot engine), in which air undergoes four processes: isothermal inflow and take-up of moisture (AB); adiabatic ascent (BC); isothermal expansion (CD); adiabatic descent (DA) [Poo23].

- A textbook with systematic links to climate and sustainability, *e.g.* treating hurricanes & global warming as major application (see Figure 2); [Poo23])
- The EPS volume "EPS Grand Challenges—Physics for Society in the Horizon 2050" [Hid24] has an entire chapter on environment and sustainability, with important applications to *e.g.* energy supply, environmental safety, green cities, modelling and prediction.

Box 3: Best practice approaches for integration of sustainability and sustainability goals in PBPs.

2.4.4 *Physics teacher education*[3]

School teachers are key agents of educational improvement and innovation: they introduce new scientific content and experiments, develop novel educational formats, and female physics (science) teachers serve as role models for a better gender balance in these fields. Moreover, teachers and their education are foundational for educating many generations of students. Quantitatively, a full-time teacher typically reaches 3000 - 6000 students over a 30-year career (100 - 200 students per year).

In order to prepare for this pivotal role, physics teacher education has to be designed in study programmes *sui generis,* not just as a reduced or diluted version (in breadth and difficulty) of the scientific studies, but a specifically enhanced version integrating educational professional knowledge (such as effective approaches to support interest and learning among young people; methods to measure the impact of their teaching (and possible changes) on pupils' motivation and learning, in particular regarding diagnosis of learning difficulties, *etc.*). Physics teacher education *sui generis* is best understood in terms of pedagogical content knowledge, a systematic integration of knowledge of physics, knowledge of pedagogy, and knowledge of how to teach physics [Etk10]. Accreditation procedures for teacher education increasingly require convincing approaches to cover these aspects in a well-thought and structured way.

There are many ways to design specific units in physics teacher education, such as dedicated tutorial groups; physics education courses accompanying experimental physics lectures; dedicated theoretical physics or "modern physics" lectures; specific lab courses for classroom experimentation (see Box 4 for further best practice sources).

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[3] Note that this section only applies to countries where there are PBPs with a teacher education component. (e.g. Germany).

Recommendations:

- develop a concept for a physics teacher education offer *sui generis* at your department or in the national society;
- adopt a stepwise approach through individual dedicated units, taking into account existing best practice examples;
- contribute support measures for initial and continuing professional teacher education, preferably in coordination with your national society.

- In view of the decisive role of teacher education, the UK Institute of Physics (IOP) has developed exemplary support programmes for initial teacher education and continuing professional development (CPD) in physics over recent decades [IOP++].
- The German Physical Society (DPG) has elaborated several extensive analyses and recommendations regarding physics teacher education, providing data, rationale, good practice examples and an example curriculum for a physic teacher education sui generis [DPG10, DPG23].
- A recent review on strategies for enhancing physics teacher education is available in [MFP23]

Box 4: Good practice and best evidence approaches for physics teacher education

References:

DPG10 Deutsche Physikalische Gesellschaft/German Physical Society (2010). Theses for a Modern Teacher's Education in Physics. Bad Honnef: Deutsche Physikalische Gesellschaft; https://www.dpg-physik.de/veroeffentlichung/broschueren/studien/lehramt-eng_2010.pdf

DPG23 Deutsche Physikalische Gesellschaft/German Physical Society (2023). Das Lehramtsstudium Physik in Deutschland. Bad Honnef: Deutsche Physikalische Gesellschaft, https://bit.ly/451aDr7

[IOP++] Institute of Physics, Bristol; https://www.iop.org/education/support-school-college-physics-teachers

MFP23 McLoughlin, E., Feldman, G., & Peeters, W. (2023). Strategies for Enhancing Physics Teacher Education at Secondary and University Level. In: Marks, J.B, Galea, P. (2023). *Physics Teacher Education: More About What Matters* (pp. 115-131). Cham: Springer Nature Switzerland.

3 Physics bachelor discipline and generic competences

The term "physics bachelor's discipline competences" encompasses specific knowledge and skills directly related to physics content and methods, while "generic competences" refers to broader skills that span across all specific content areas and are valuable for successful study, research, and professional life.

3.1 Physics bachelor's discipline competences

3.1 Physics curricula usually distinguish between fundamental ideas and principles, and the description and modelling of phenomena. Hence, the ability to recognise fundamental ideas and to apply them in different contexts constitutes a core competence to be acquired, along with being well-versed in various methods for modelling specific phenomena (this applies to all fundamental topics mentioned in sect. 2.3.1). In addition, the bachelor's curriculum should enable students to develop a qualitative understanding of current developments at the frontiers of the physics discipline (sect. 2.3.2, advanced topics).

3.2 Students should learn that physics is a quantitative discipline and appreciate the use and power of mathematics for modelling the physical world and solving problems. Mathematical competence is an essential part of a physics degree.

3.3 Physics curricula should expose students to the experience of the empirical and practical nature of physics [IUPAC08]. They should provide students with the skills necessary to plan investigations and collect and analyse data (including estimation of inherent uncertainties). These skills may be acquired as part of a course in a laboratory or by a range of alternatives including computer simulations. These experimental competences could also be acquired by providing opportunities for student internships in national or multinational laboratories or industrial research and development centres. Practical work should thus be a vital and challenging part of a physics degree, and all undergraduates in physics should have an appreciation of natural phenomena in an experimental context. Students should also become proficient in presenting experimental results or theoretical conclusions and in the writing of scientific reports. Independent project work should be used to facilitate the development of students' skills in research and planning (by use of data bases and published literature) and to enhance their ability to assess critically the link between theoretical results and experimental observation.

3.4 Physics bachelor's graduates should be able:

- to formulate and tackle problems in physics. For example, they should be able to identify the appropriate physical principles, to use special and limiting cases and order-of-magnitude estimates to guide their thinking about a problem and to present a solution by making their assumptions and approximations explicit;
- to plan and execute an experiment or investigation and to report the results. They should be able to use appropriate methods to analyse their data and to evaluate the level of uncertainty. They should also be able to relate any conclusions they make to current theories of the physics involved;

- to use mathematics to describe the physical world. They should have an understanding of mathematical modelling and the role of approximation. They should be able to compare critically the results of model calculations with those from experiment and observation. They should also be able to make error and statistical analysis of experimental data to ensure the validity and significance of results.

3.2 Physics bachelor generic competences

The majority of physics graduates are employed in non-academic positions (according to representative statistics inside and outside Europe, *e.g.* in Germany [ZRM24] and the U.S.A. [JTUPP16] > 80 % of positions). In order to meet workplace, public, and student expectations of adequate preparation for careers in a broad range of settings and for the role of scientists in the society, physics bachelor's degrees should develop a series of generic competences strongly based on, but beyond and across the disciplinary ones ([JTUPP16; QAA25]; see also 2.4.2, An important group of such competences is widely discussed in the literature on undergraduate education under the umbrella term of "higher order thinking skills" (HOTs; autonomy, curiosity, creativity, problem solving, critical thinking; [ZB15; MB19; WQW19]).

Problem-solving

Students have acquired fluency in solving problems with well-defined solutions. Moreover, they also gain experience in tackling open-ended problem and are able to formulate such problems in precise terms and to identify key issues. They should develop confidence in pursuing different approaches in order to make progress on challenging or non-standard problems.

Analytical skills and critical thinking

Students pay attention to detail and can manipulate precise and complex ideas; construct logical arguments; and use technical language correctly. Students can conscientiously and systematically evaluate the validity of data, evidence, and arguments; make inferences using inductive or deductive reasoning; and make decisions regarding experiments, calculations, and problem-solving approaches [ABB15; WQW19; VD20].

Investigative skills

Students have developed and can apply skills to extract important information from textbooks and other literature; search databases effectively; and conceive and carry independent investigations.

Creativity

Creativity is central to physics since it allows one to imagine scenarios outside current frameworks. Students can generate and refine new ideas and approaches to physics problems and to observing or measuring phenomena, while evaluating the soundness and usefulness of their solutions. They are able to view established concepts in novel ways, integrate concepts across topics, and identify new problems to solve.

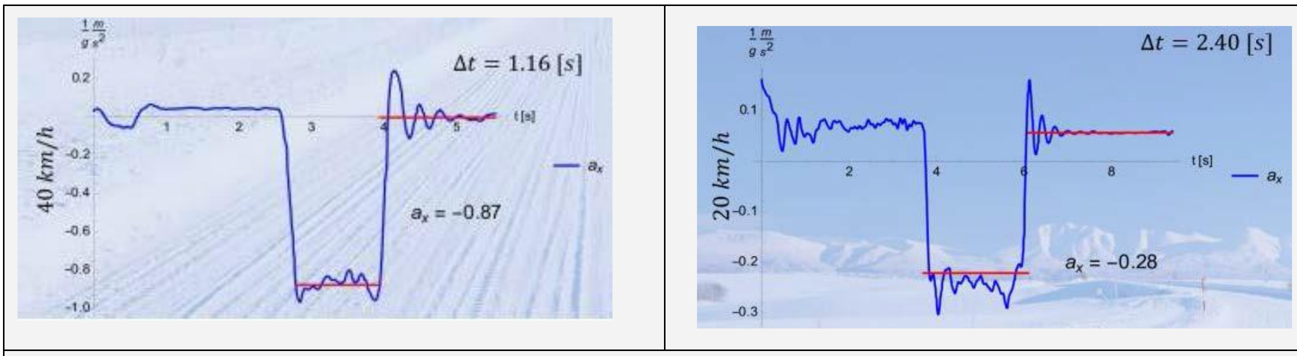

Figure 3: Undergraduate research is an effective way to foster students' creativity. The example shows measurements of a car's acceleration and friction coefficient using a smartphone accelerometer under different road conditions: dry (left) and snow (right). Friction coefficients can be inferred from the measured acceleration values, as covered in a standard mechanics course (see [BBB23] for further examples). Such activities can be implemented as a component of traditional experimental physics courses or laboratory classes, including their assessment.

Data literacy, information technology skills

Students have developed and can apply computing and IT skills in a variety of ways; they have the ability to use appropriate tools including programming languages and software packages. Students are able to apply various methods to collect, evaluate, analyse and interpret experimental and computational data, using appropriate statistical methods and visualization techniques. They can evaluate data quality, identify uncertainties, and document data handling procedures following scientific standards (see also 4.2, 4.3).

Communication skills

Students can listen carefully; read demanding texts; and present difficult ideas and complex information in a clear and concise manner, recognizing that good communication is essential when dealing with surprising ideas and difficult concepts in physics and mathematics.

Language skills

Students have good knowledge of oral and written English, the *lingua franca* of physics. They recognize that multilingualism contributes to personal development, reinforces social cohesion, and enables a mobile labour force crucial for economic growth and effective competition in the global marketplace.

Professional and workplace skills (see 5.3)

Students

- have developed autonomy, self-management and resilience (self-directed learning, working independently with limited supervision, using one’s initiative; coping with adverse events);
- are able to work effectively, responsibly and safely: they know how to take responsibility for themselves and others; understand of time management for themselves and to fulfil their role as part of team projects;
- are aware of relevant regulatory frameworks and the reasons for them;
- can function effectively as members of physics or multidisciplinary teams and appreciate that physics is primarily a collaborative activity;
- are able to engage in constructive interaction and collaboration with other people, including the development of networking skills;
- have developed a professional identity* as physicist;
- know career options and job search strategies for physics graduates.

Ethical behaviour, scientific integrity

Students

- recognise the ethical frameworks in which they operate;
- understand their social and cultural responsibilities as they investigate the physical world and are aware of the role of physicists as responsible experts in science- and technology-based societies, regarding current and developments and challenges (such disinformation, artificial intelligence, sustainable development, and others) [DGR13; BR24];
- appreciate that fabricating, falsifying or misrepresenting data or committing plagiarism constitutes unethical scientific behaviour; demonstrate objectivity, lack of bias and truthfulness in all aspects of their work; and recognise the limits of their knowledge [ALLEA23];
- gain awareness of the objectives of equity, diversity, and inclusion; understand their role in professional settings; and behave accordingly.

4 Educational approaches

4.1 Teaching for active and meaningful learning

Growing emphasis has been placed on the necessity to integrate content and competences (sect. 2.1) and on the requirement of active and meaningful learning in science study programmes [FEM14, Wie17]. Moreover, there is growing insight and research basis into the limitations of conventional teaching approaches on the one hand, and the positive outcomes of alternative approaches on the other hand. A striking example is provided in [FEM14], see Figure 4.

These developments have led to a wealth of evidence-based approaches for the improvement of teaching and learning in physics study programmes [DM14, Wie17]. While this applies also to the traditional triad of lecture-tutorial/recitation groups-lab courses, it extends beyond to innovative forms of university physics teaching and learning. Table 2 provides an overview over traditional and recent teaching and learning methods within PBPs [QAA25], together with complementary information regarding research and best practice evidence for these various approaches. Note that teaching/learning and assessment (sect. 4.4) form a natural unity and should be seen in a very close alignment.

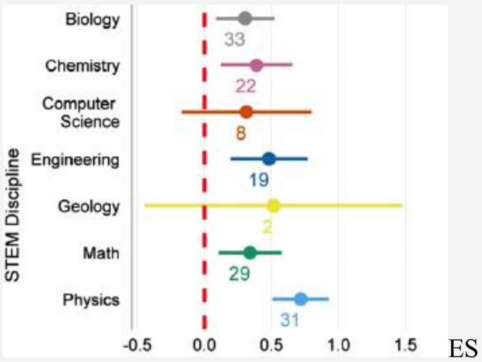

Figure 4: "Active learning courses" are designed for enhancing the active intellectual participation of students in lectures. Typical elements are, among others [DSW11; FEM14]: pre-class reading assignments with quizzes, in-class clicker questions combined with student–student discussion, targeted in-class instructor feedback based on clicker data, flipped-classroom formats with in-class active tasks (further best practice examples of active learning approaches can be found in Table 2; also, FEM14 provide a comprehensive list in their methods section and the supplemental information).
The graph presents a comparison of active learning courses versus traditional lectures in terms of meta-analytic effect sizes (ES[4]) for learning outcomes (examination scores, concept inventories, or other measures; 225 studies, ≈ 46000 students) across disciplines [FEM14]. Error bars represent 95% confidence intervals, the number of included studies is indicated below each data point. Note that reported effects for physics are the largest in the STEM field.

Recommendations:

- avoid relying on traditional teaching methods solely because they require less effort and time;
- consult best practice examples and empirical research (Table 2) to guide the selection and integration of promising teaching practices.

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[4] The basic definition of an effect size (ES) is $(M_T - M_C)/SD$, where M_T and M_C are the means (of some variable of interest) for the treatment and control group, respectively, and *SD* is the either the pooled standard deviation or that of the control group [Coh88]. In simple terms, d thus measures the impact of an intervention in units of standard deviations of the sample under consideration. Usual effect-size levels (as established from comparison of a great many of studies in different areas) are small ($0.2 < d < 0.5$), medium ($0.5 \leq d < 0.8$) or large ($0.8 \leq d$) [Coh88]. Many modifications and refinements of the concept of "effect size" haven been developed and are used in the literature [FMR12].

Teaching and learning methods within PBPs	Research and good practice informed approaches
lectures together with tutorial/recitation problem solving groups	interactive lecture formats [DM14, sect. IV.A.; Wie17] interactive lecture demonstrations [ST04; ZA07] active learning strategies for tutorials and recitations: [TH23, sect 23.3.2]
lab courses	lab courses for acquisition of experimental design and data analysis skills: [KE07], [CMG21] Focus collection on instructional labs: [PR-PER22+]
integrative formats for lecture-tutorial/recitation groups-lab courses (usually isolated)	holistic learning environments: [BEN23], [GH23] common lecture, recitation, and laboratory learning spaces (with students and instructors moving freely between these learning formats): significant conceptual learning gains compared to traditional instruction [HOT17]
use of textbooks, electronic resources and other self-study materials	student engagement in reading assignments: [HBW14|
computational lab courses	see also 4.2
activities devoted to physics-specific and generic competence development, including science dissemination-activities oriented towards other educative levels or towards general society	
open-ended project work (partially as group work); undergraduate research	[MAB22]

Table 2: Teaching and learning methods within PBPs. Left: overview of traditional [QAA25] and recent methods; right: complementary information regarding research and best practice evidence for these various methods.

Note that this list is neither exhaustive nor compulsory; these examples are meant to illustrate active and meaningful learning approaches in a wide range of settings. Their use depends on the specific content and context, and they are not meant to be applied in every situation. However, given the wealth of inspiring instructional formats and supporting empirical evidence nowadays available, it would no longer be acceptable to continue with “teaching as usual” without awareness and careful consideration of these evidence-based alternatives.

4.2 Computation, data science and digital technologies

Data science, computational methods and other digital technologies are now central to physics as both a research discipline and an applied science. Acquiring a deep knowledge of programming languages for algebra, data analysis and basic machine learning are of critical importance. Digital skills are also essential for the use of computer techniques to control the flow of experiments, data acquisition and other laboratory related techniques, such 3D-printing. Despite this, recent research shows that computational instruction remains inconsistently implemented in physics bachelor's [5].

To prepare students for contemporary physics and interdisciplinary careers, bachelor programmes should integrate digital skills as a core competence, not merely as an elective or isolated module [CO24; NASEM18b]. This includes introducing programming, computer algebra, data analysis, numerical modelling, and algorithmic thinking across experimental and theoretical courses (see section 4.3 for AI). The use of open-source tools (*e.g.* Python, Jupyter, Git) and active learning formats (*e.g.* computational labs, interactive notebooks) fosters engagement and skill retention. A recent nature article [CO24], a comprehensive resource letter [Ath23] and Box 5 provide good practice examples for the integration of computing in PBPs.

Institutions should also support faculty development, as lack of training, time, or institutional support are frequent barriers to implementation. A recent expert panel report provides valuable information on the importance, the central issues, implementation, and other key aspects in the field [NASEM18b].

#	Scenario / Practice	Tools & Methods	Learning Objectives / Benefits
1	*Smartphone experiments with Jupyter notebooks*	Smartphone sensors (*e.g.* accelerometer), Jupyter, NumPy/Matplotlib	Connect signal processing (DFT) with real-world data; promote autonomous experimentation
2	*Simulating classical mechanics*	Python, Euler/Runge-Kutta, matplotlib	Deepen understanding of ODEs; compare numerical methods; visualize physical systems
3	*Lab data analysis using microcontrollers*	Arduino, Raspberry Pi, Python, pandas	Learn data acquisition, cleaning, and error analysis in real time
4	*Monte Carlo simulation of the Ising model*	Python, NumPy, Matplotlib	Explore statistical physics concepts through computational experiments
5	*Collaborative coding with Git*	Git/GitHub, Python packages	Practice version control and teamwork in scientific programming
6	*AI-based data classification*	Scikit-learn, Jupyter, example datasets (*e.g.* CERN open data)	Understand machine learning basics, model training, and evaluation in physics contexts
7	*Live coding and interactive notebooks in lectures*	Jupyter, ipywidgets, Binder	Promote conceptual understanding with dynamic visualizations; support interactive learning

Box 5: Best practice examples for the integration of computing in physics bachelor's programmes

Recommendations. Embedding digital technologies throughout the physics curriculum equips students for data-rich environments across academia, industry, and public sectors. It also aligns physics education with current research practices and opens space for interdisciplinary collaboration with computer science, engineering, and beyond. The EPS recommends that computation be structurally embedded in physics bachelor's curricula, with sustained support for curricular innovation, infrastructure, and instructor training.

4.3 Artificial intelligence

Physics has made important contributions to artificial intelligence (AI) and has been profoundly influenced by its development [EPN25a]. The 2024 Nobel Prize in Physics was awarded for pioneering work in neural networks conducted forty years prior. Derived from these, generative AI reached maturity in 2022 with widespread public availability of Large Language Models (LLMs). Today, AI models demonstrate surprising performance in physics problem-solving, signalling fundamental shifts in physics education. Neuroscientist V.Ming's study [MV26] of UC Berkeley students found that when AI provides answers to well-posed, routine problems—such as basic

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[5] Surveys in the U.S. [CM18, CO24] reveal that while a majority of faculty have experience with computational physics, only a minority report integrating computation systematically into formal coursework—particularly at the introductory level.

coding, summarizing data, or solving for a single correct answer—students tend to act as "exploiters," accepting the AI output without thinking, with consequent skill erasure. Instead, when faced with an open problem and students use AI to challenge, question, and explore, rather than merely providing answers, this interaction with AI to explore ideas and identify flaws in their own reasoning, creates "productive friction" and leads to better results that the best AI modules alone or the human without AI. Only a very small percentage of students (5-10%) used AI as a collaborator to improve performance. Hence a substantial effort is needed to increase this percentage by shifting education more toward "ill-posed" or open-ended problems that require creativity, critical thinking, and negotiation between the student and AI. However, students must still grasp core concepts and their interconnections; comprehend the interplay of theory and experiment; and develop understanding of truth and proof. Higher order thinking skills (3.2) like problem-solving strategies, estimation, and critical thinking remain essential. The education should not compete with AI in information processing, but instead cultivate distinctly human capabilities—resilience, creativity, judgement, and purpose-driven thinking—while training students to collaborate effectively with intelligent systems. Responsible and inventive action by physics educators is necessary to ensure students achieve genuine mastery.

Recommendations: Curricula must integrate AI in constructive ways, including but not limited to generative models. Just as computational skills became foundational, machine learning methods demand greater integration. The community must master these new "spirits," ensuring AI enriches rather than undermines physics education 4.4. Students should be regularly exposed to open-ended, real-world challenges that mirror the complexity of scientific and societal problems, often in interdisciplinary and collaborative settings. At the same time, they must be explicitly trained to work effectively with AI tools—understanding their capabilities, critically assessing their outputs, and using them as partners in scientific reasoning rather than as shortcuts. Embedding reflection and iterative learning will help students develop resilience and the capacity to learn continuously in a rapidly evolving technological landscape. Ideas for research-based teaching approaches can be found in the focus collection [PR-PER24+]; for aspects regarding assessment, see sect. 4.4.

4.4 Assessment*

Well-designed assessments are essential for educators and departments to ascertain whether teaching and teaching innovation efforts are effective. Assessment must be taken seriously and must integrate both content and competencies if it is to play its key intended role. A variety of assessment methods for both content knowledge and competences are well established within physics programmes, some of which are more suitable for formative* assessment (see Table 3 for an overview). Comprehensive reviews of resources for research-based assessment are available for a wide range of learning and other outcomes [MMS17, MMS19]. A discussion of a modern understanding of assessment can be found in [McL24; 8.2.1.3]. Conceptual assessments are especially important, as there is solid evidence that many students have trouble with conceptual understanding even when they perform well on quantitative tests of problem-solving [vKAG16]. Regarding the bachelor's thesis, the following comment is in order: Due to limited lab space, the high cost of equipment, and, where present, high student enrolment, there is a tendency among universities in Europe to move away from requiring original, experimental or theoretical research in the final year of a physics bachelor's degree. In place of this, literature-driven topics are offered, intended to teach literature analysis and synthesis, and scientific communication rather than an initiation to research. This approach falls short in developing the student's competence in performing original research (under supervision) on an open problem and should therefore be strongly discouraged. Moreover, a gap in essential competences created in this way can lead to a problem for the reciprocal recognition of PBPs.

Studies on the assessment of individual projects generally indicate that when properly designed and implemented, rubrics improve the reliability, transparency, and fairness of assessments while also fostering student learning, self-regulation, and critical thinking [see PJ20 for an extensive literature overview].] EPS therefore strongly recommends their use.

Today, the generalised access that students have to generative AI resources preclude sole reliance on unsupervised examinations due to AI assistance; anti-cheating technologies prove ineffective. A solution is prioritizing supervised in-class problem-solving with peer discussion. Exams may require supervised, pencil-and-paper formats, where AI can assist educators to decrease the marking/grading workload. In view of better training for an AI-rich world, traditional assessment methods should be complemented by project-based and portfolio evaluation that rewards process, creativity, and independent thinking.

- Time-constrained examinations
- Closed-book and open-book tests
- Concept tests
- Oral examinations & *viva voce* interviews
- Oral and/or poster presentations, including seminar presentation
- Laboratory and computational tasks reports
- Individual or team project reports, in particular particularly on research performed in project-based learning context
- Project outcomes such as student research papers, computer programmes, electronic circuits, or other hardware
- Essays
- Peer and self-assessment
- Bachelor's thesis

Table 3: Variety of assessments formats in physics studies [QAA25]

4.5 Evaluation[*]

Student course evaluation (SCE) is (i) an economical and convenient method to assess faculty teaching; (ii) necessary for accreditation purposes; and (iii) useful for demonstrating a department's commitment to transparency and public accountability. Moreover, (iv) SCEs allows students to take an active role in the evaluation of faculty teaching, and, perhaps most importantly, (v) students are best placed to provide informed feedback on their experiences and perceptions related to teaching [UWW17]. However, simple SCE approaches using end-of-term questionnaires are controversial and have been found limited in scope, and prone to bias, and they can be unreliable indicators of teaching quality [UWW17, WAF20]. On the educator side, SCEs are often based on simplistic transmission models of teaching, neglecting questions about active and meaningful learning [OHK23]. On the student side, course perceptions are influenced by several factors irrelevant to learning [UWW17].

In short, student *satisfaction* does not equate to student *learning*, especially when considering competencies beyond routine calculation tasks, such as conceptual understanding and problem solving (see 3.2). Most physicists regard these competencies as essential, and improving teaching evaluation is a strategic lever for enhancing teaching quality itself, supporting faculty development, and ultimately advancing student learning and success across diverse populations. To address this requirement and counter the limitations mentioned above, there are easy first steps that can be taken. These include using already easily available data beyond end-of-term questionnaires (*e.g.* student responses in tutorial groups or lab reports); mapping evaluation questions to a few important learning goals; differentiating questions for different course types and content (learning goals are different *e.g.* for lectures and lab courses); and identifying a few next SCE-informed actions. Box 6 contains further good practice approaches.

Teaching is a complex process that involves significant work beyond classroom instruction, including course design, mentoring, reflection, and curricular alignment with assessment within a study programme [WAF20] not visible in simple end-of-term questionnaire evaluations. As physicists, we are accustomed to critically examining data, using multiple measurement times and methods, and cross-validating findings, especially in complex processes. Reliable monitoring and improvement of teaching quality require consideration of the same factors. As this demands substantial effort and time easily in conflict with other priorities, the following guides and resources are useful:

- a guide for the selection and use of different evaluation methods by the American Physical Society [APS25];
- A guide on effective instruction in undergraduate science and engineering, including a chapter on programme evaluation and adaptation [NRC15];
- TEval (Transforming Higher Education – Multidimensional Evaluation of Teaching; https://teval.net/), a multi-institutional programme focused on programme evaluation STEM [WAF20, AFF25]
- A set of “Guides to Advance Teaching Evaluation » (GATEs) for STEM Departments [KGL22]. The GATEs cover three perspectives (educators, peers, and students) —and provide a list of target practices across three main dimensions (structured, reliable, and longitudinal evaluation processes). They also offer characterizations of common starting points and first steps, as well as ideas and resources to support development toward the target practices.

These resources provide guidance by the following elements:

- Structured improvement cycles of evaluation, reflection, and action are exemplified, starting from easily actionable steps [AIP25, TEval].
- Use of already or easily available data to complement end-of-term questionnaires is described as as one such initial step; the idea is to embed evaluation in student activities and productions (*e.g.* weekly problem sheets, or lab reports), thus providing timely information on what students learn. Digital technology offers further possibilities (*e.g.* online platforms for reading and homework assignments, audience response systems (“clickers”)) [AIP25, TEval].
- Another relatively easy step in this sense is to systematically link evaluation (of teaching) and assessment (of learning). These can be powerful perspectives when considered in a coherent and continuous manner for programme improvement (they are often analysed separately and not within a systematic approach).

Guidance and examples of best practice for progressing to more advanced approaches to evaluation are provided on the following topics:

- Competencies beyond routine calculation tasks: a wide range of methods and comprehensive reviews of research-based assessments are available [MMS17]; this is of particular interest when combining evaluation and assessment (see above) into a coherent analysis of teaching efficiency;
- Factors (such as self-efficacy, sense of belonging, physics identity, *etc.*) as important influences of gender equity, persistence, and student well-being (see sect. 6 and MMS19 for a compendium of research-based assessment instruments);
- Formative* evaluation embedded in practice [APS25, TEval: s.o.];
- Cross-validating findings from multiple evidence sources [APS25, TEval: s.o.];
- An advisory committee composed of external experts (alumni, representatives of industry R&D labs, high schools and public administration, science communication experts, *etc.*) can provide valuable feedback on teaching quality and other key objectives of PBPs (QAA25; see also 5.3);
- Creation of a network to foster cross-institutional exchange, enabling departments at different universities to share experiences, tools, and lessons learned about evaluation [WAF20, TEval: s.o.]

AFF25 Austin, A. E., Finkelstein, N. D. M., Follmer Greenhoot, A. F., Ward, D., & Weaver, G. C. (2025). Transforming college teaching evaluation: a framework for advancing instructional excellence. Harvard Education Press.

APS25 American Physical Society (2025) Effective Practices for Physics Programs (EP3). How to Select and Use Various Assessment Methods. https://ep3guide.org/guide/how-to-select-and-use-various-assessment-methods

CHJ25 Craig, D., Hodapp, T., & Jackson, M. (2025). Helping physics departments thrive. Physics Today, 78(2), 46-52.

KGL22 Krishnan, S., Gehrtz, J., Lemons, P. P., Dolan, E. L., Brickman, P., & Andrews, T. C. (2022). Guides to Advance Teaching Evaluation (GATEs): A resource for STEM departments planning robust and equitable evaluation practices. CBE—Life Sciences Education, 21(3), ar42.

NRC15 National Research Council 2015. Reaching Students: What Research Says About Effective Instruction in Undergraduate Science and Engineering. Washington, DC: The National Academies Press. https://doi.org/10.17226/1868

QAA25 Quality Assurance Agency for Higher Education. (2025). Subject benchmark statement: Physics, astronomy and astrophysics. Quality Assurance Agency for Higher Education. https://www.qaa.ac.uk/the-quality-code/subject-benchmark-statements/subject-benchmark-statement-physics-astronomy-and-astrophysics

WAF20 Weaver, G. C., Austin, A. E., Greenhoot, A. F., & Finkelstein, N. D. (2020). Establishing a better approach for evaluating teaching: The TEval Project. Change: *The magazine of higher learning, 52*(3), 25-31.

Box 6: Best practice and best evidence approaches for course evaluation

Recommendations:

- Recognize teaching evaluation as a strategic lever for enhancing teaching quality, supporting faculty development, and advancing student learning and success.
- Design evaluation that yields acceptable evidence of students meeting stated goals; evaluate also
  - o outcomes beyond routine calculation tasks (e.g. conceptual understanding and problem solving; see 3.2)
  - o affective* outcomes (attitudes, motivation, sense of belonging, see sect. 6).
- Be aware of the limitations of end-of-term student questionnaires, including their restricted scope, susceptibility to bias, and limited reliability as indicators of teaching quality.

- To go beyond, adopt a “start with what you have” approach by utilizing already or easily available data sources and focus on a small number of realistic goals that are aligned with departmental priorities.
- Foster a culture of evaluation by incrementally adopting additional good practices (e.g. multiple data sources; long-term effects?).
- Prioritize evaluation early in the scale-up of innovations to provide empirical evidence that can support and justify broader implementation; acknowledge that initial evaluations of innovative practices may yield negative results, especially when students encounter unfamiliar elements.
- Ensure evaluation results are visible and actionable by reporting longitudinal findings to faculty and using outcomes to inform curriculum and instructional improvements.

4.6 Educator support and incentives for teaching initiatives

Over the last decade, teaching in many departments has shifted substantially from a largely discipline-centric, lecture-based paradigm towards one that foregrounds professional pedagogic practice, continuous pedagogic innovation, and structured development of teaching competencies: many countries now require formal teacher training or professional development for university faculty, with institutions embedding reflective teaching approaches, student-centred learning designs, and evidence-informed assessment practices into academic careers (as documented comprehensively by the Eurydice Network, the European Commission’s education information network https://eurydice.eacea.ec.europa.eu/eurypedia). Specific initiatives at national and EU levels have established centres and funding for teaching excellence, innovation projects, and networks that share best practice and professional development resources within and across institutions. In physics and other STEM disciplines this has translated into a stronger emphasis on active and problem-based/project-based learning, integration of digital laboratories and simulations, blended learning formats developed during and after the pandemic, and a growing focus on student skills such as critical thinking, collaboration, and data literacy.

However, the academic incentive system remains a large barrier to change. Most faculty aim at high teaching quality, but the incentive system (bibliometric indicators, obtained funding, *etc.* as success indicators) makes them perceive it as "penalizing any time taken away from research to improve teaching or make use of innovative teaching methods" [Wie17].

In addition to this structural barrier, current challenges include the rapid proliferation of generative AI, which is reshaping how students interact with content, learn problem-solving, and are assessed, raising concerns about academic integrity and the validity of traditional assessment formats (see 4.3, 4.4); the demands of hybrid and blended teaching, requiring robust infrastructure and teacher support; and the intensifying focus on student well-being and inclusive learning environments, given evidence that workload, digital fatigue, and mental health concerns affect learning outcomes (see 6.3).

- The Science Education Initiative, founded by Nobel laureate Carl Wieman, has developed a large-scale programme to support departments in systematically redesigning undergraduate science programmes around clearly defined learning goals and evidence-based teaching approaches. The book on “Lessons from the science education initiative” [Wie17] covers: a model of institutional development and implementation; a detailed exposition of key factors regarding funding, course design, and evaluation; outcomes and a critical evaluation (successes, failures, underlying reasons); and a compact implementation guide in the appendix.
- From the same initiative, a handbook is available sharing the accumulated best-practice experiences and guidance on how to effectively implement a model of change in programmes and faculty [CC18].
- A report from the US National Research Council offers a research synthesis on undergraduate teaching and learning in physics and other STEM disciplines, and a chapter on translating this research into the teaching practice of undergraduate science and engineering programmes [NRC12].

Box 7: Best practice and best evidence approaches for educators support and incentives for teaching initiatives

CC18 Chasteen, S. V. & Code, W. J. (2018). The Science Education Initiative Handbook. https://pressbooks.bccampus.ca/seihandbook/ (Creative Commons License 4.0); print edition British Columbia Pressbooks, ISBN: 978-1-7294-6656-8

NRC12 National Research Council (Edt.) (2012). Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering. National Research Council. Board on Science Education. Washington, DC: National Academies Press.

Wie17 Wieman, C. (2017). Improving how universities teach science: Lessons from the science education initiative. Harvard University Press.

Recommendations:

- Establish clear institutional policies on teaching and teaching innovation, with scaffolded support for both learners and teachers to navigate its integration into teaching and assessment.
- Support academic staff through pedagogic training programmes, teaching and learning centres, peer mentoring, communities of practice, and dedicated funding for course redesign and innovation [NRC12].

- Professional societies can and should play a key role in the development of undergraduate programmes by helping to establish an outcomes-focused, evidence-based cycle of observation, evaluation, and improvement of instruction [NRC12].

4.7 Evidence-base physics education / physics education research (PER)

Over the past three decades, extensive educational reform efforts have reshaped PBPs in many countries. Adopting an evidence-based approach, Physics Education Research (PER) has grown as a disciplinary field of research involving the systematic and intentional collection of data to make evidence-based decisions on learning as a dynamic process driven by forces and interactions that transform an initial into a final state – a concept well captured by the metaphor of a "learning trajectory" [2], [3]. Like physics itself, PER seeks to understand such trajectories, and to design them to attain a given target (this holds both for learning and motivation). Following C. Wieman's idea of "a scientific approach to science education" [Wie07], this field of research has produced a wealth of carefully designed, evidence-based instructional methods (see 2.5.1) and assessment strategies (2.5.4) and draws on important results from other research in STEM education. It is also the driving force behind research-informed initiatives and innovation regarding digital technologies (4.1.2); artificial intelligence (4.1.3); low enrolments (6.1), gender inclusion and equity (6.2), study stress and dropout (6.3), preparation of physics teachers and educators (4.6) and many more important aspects relating to PBPs. PER studies report on current understanding of effective and engaging physics learning and teaching and cannot be ignored in any serious effort to offer a modern study program.

Publications of PER have grown significantly over the past five decades, e.g. the European Journal of Physics (EJP), a journal of the European Physical Society, has a primary mission of maintaining and improving the standard of taught physics in universities and other institutes of higher education [https://publishingsupport.iopscience.iop.org/journals/european-journal-of-physics/about-european-journal-physics/].

A 2024 special issue in Physics Nature on PER highlight the important role that PER has in "using evidence-based approaches to improve the teaching of physics can help students achieve more and improve equity", including [Unlock the potential of a physics education (2024) *Nature Physics* **20**, 335 (2024)https://doi.org/10.1038/s41567-024-02458-4].

The *International Handbook of Physics Education Research* (IHPER), published in 2023, is a comprehensive three-volume set, with the first volume focussing on Learning Physics (cognitive aspects, conceptual understanding, and student learning processes), the second volume focuses on Teaching Physics (instructional methods, teacher education, and learning environments) and the third volume Special Topics in PER includes research methodologies, history, and philosophy of physics education.

[The *International Handbook of Physics Education Research* (IHPER), published by AIP Publishing in 2023, is a comprehensive three-volume set edited by Mehmet Fatih Taşar and Paula R. L. Heron, https://www.ijpce.org/index.php/IHPER].

GIREP (Groupe International de Rechearche sur l'Enseignement de la Physique), founded in Europe in 1966 as a small working group to encourage the renewal of Physics teaching, has grown to become on international community of researchers, educators and policy makers focussed on improving physics education across all education levels (https://www.girep.org/). GIREP hosts physics education conferences annually, with each biennial conference co-hosted with European Physical Society Physics Education Division (EPS-PED) and a World Conference in Physics Education every four years. Publications from these conferences provide rich insights into different perspectives on physics education from across the globe.

Recommendations:

- curriculum development and instructional practices should be evidence-based and utilize research from Physics Education Research (PER) and related fields of STEM education.
- research-informed and research-led practices should be adopted in the design and delivery of physics study programs, in particular for emerging areas such as, digital technologies, artificial intelligence, gender equity and inclusion in physics.

- physics teacher preparation and professional learning is critical for the delivery of high-quality physics education and the use of effective learning, teaching and assessment approaches in a PBP.
- Data collection and evaluation should be an essential feature of adaptation and reform of educational practices, to ensure an evidence-based approach is adopted to physics teaching and learning in a PBP

5 Interfaces and transitions

As physicists, we are familiar with the fact that interfaces govern interactions and features in interacting systems; hence the importance of interfaces of PBPs to other educational and societal domains.

5.1 Interface with secondary* education

The interface of PBPs with secondary education is two-way. First, the transition from secondary level to bachelor studies is a critical step for students. Regarding the first semesters at university, unrealistic expectations and inadequate preparation have been found to be a major source of study stress and student dropout (5.3). This concerns mathematics, but also inaccurate ideas about what it is to study physics in general. Second, the interface also runs from PBPs to secondary school, as many departments are involved in initiatives to counter issues like low interest and low enrolment in physics studies, in particular among women. In the following, some useful approaches to shape this interaction in a constructive way are presented.

Bridging (remedial) courses support students at the end of secondary school or beginning students consolidating and assessing their knowledge of school mathematics before or while entering university [PN13, BBB14]. The OMB+ consortium, comprising more than 50 universities in several countries and based at RWTH Aachen in Germany, has over more than a decade developed both the content and an online platform for such courses [OMB+]. The platform covers the mathematical background necessary for initial university physics courses (and other disciplines) and includes various formats for self-assessment. It is available in English, French, and German. The courses are online and free of charge. Registration is fully voluntary and anonymous and has no impact on assessment or enrolment at university.

Pre-university study (or "advanced placement") programmes [DTS11; APP+] allow students in the final or penultimate year of Secondary level II to take regular introductory university courses and to discover and explore university-level studies in various disciplines have become common in several European countries. In many programmes students have the option (but not the obligation) to participate in course exams and to gain credits valid for later university studies.

Various offers for the hard sciences aim to enhance students' interest, especially among women, and to promote a perspective of a scientific career to young people. At the same time, by providing experience in a study field of interest, they facilitate the transition between school and university. In Germany, the first experiments were made around 2000 [Hal11], and with the support of a large funding agency [DTS11], the programme has developed into a successful, permanent opportunity at over 60 universities, involving more than 2000 students annually [DTS++] and being particularly popular in physics and other STEM subjects. In Switzerland, an early study programme accompanied by an evaluation has been running in the Physics and Mathematics sections of the University of Geneva for nearly a decade, with excellent evaluation by the participants and a gender ratio of 0.64, to be compared with the Swiss average GR ≈ 0.3 ([MBS22], see also sect. 6.2).

Enrichment initiatives by physics departments and other research institutions are targeted science outreach initiatives, providing richer and more varied content and experiences beyond regular school classrooms [MS13]. Examples are science outreach labs, field trips, researcher visits and talks, student research projects, and others. They can take place in school and out of school. Such initiatives address secondary school students and other target groups, and exhibit a wide variety of scope, objectives, formats, and implementations. Beyond content, they are an excellent opportunity to provide information about and orientation for PBPs. Research provides evidence that enrichment programmes positively influence student performance, degree completion, interest, and enrolment in graduate studies; moreover, they may increase the degree to which students identify as scientists [MS13]. A series of practical recommendations can be found in [PCI24, 28pp].

Recommendations

- Initiatives at the interface with secondary education allow physics departments to address issues like lack of preparedness, low enrolment, and gender imbalance in a systematic and long-term way. Bridging courses, pre-university study programmes, and enrichment initiatives provide a wide choice of approaches.
- Existing evidence and best practice examples make it possible to greatly enhance the chances of success; for example, one-off activities are known to have little effect.
- Consider also offers for younger students at secondary level I ($\lesssim$ 15-16 yrs), and in particular at the transition to secondary level II, as interest development and academic track decisions mostly take place already at this critical stage [LWH24].

5.2 Transition to post-graduate programmes

For bachelor's students it may be difficult to make an informed and reasoned choice of specialisation at the transition to a master's programme, the contents of which are still largely unfamiliar to them. The problem parallels that of insufficient information and orientation at the transition from secondary school to PBPs (see above). Moreover, in some countries a considerable number of capable physics bachelor's graduates do not continue to post-graduate studies.

The American Physical Society has, for more than a decade, run the "Bridge Program" to encourage students to pass on to and to succeed in their further graduate education. It is open to all students, with an emphasis on groups that have historically been underrepresented in physics. Key components are financial support, induction*, mentoring, and progress monitoring. [BP++; HW17].

5.3 Interfaces with and transition to the workplace and employment market

There are multiple and strong reasons for considering such interfaces and links within PBPs [BA19]:

- the large majority of physics bachelor's programme (PBP) graduates will work outside academia (see section 3.2); therefore, clear recognition of and adaptation to this reality is essential for both educators and students;
- this is even more important as shortages in the STEM workforce in general and physics in particular are a widely discussed issue in several countries [DGE25, Mah22, LL22][6], in particular regarding physics teachers [see e.g. DPG23, EJM23, Ski23];
- expectations of employers outside academic research differ significantly from those within, and preparing students effectively for the workplace and job market should constitute a key responsibility for departments and can serve as an asset in attracting students;
- according to expert estimates, approximately 80% of positions are obtained through networking [APS24], highlighting the importance of a strong professional network;
- at the same time, such interfaces can effectively inspire and empower students to contribute positive changes in the world based on their physics knowledge, a goal nowadays contained in many study programme descriptions;
- moreover, understanding what physics studies – and the personal effort invested – can be good for is a powerful source of inspiration and motivation, and is one element of established strategies to counter study dropout (6.3);
- links in form of personal contacts can provide encouragement and role models for underrepresented student groups (6.2).

A main objection against the integration of such links concerns how to incorporate them while contending with already tight study programmes and increasing budgetary and other constraints. However, best practice (Box 8) has shown that such links can be incorporated into the student experience in ways that do not reduce the quality and content of PBPs. A variety of constructive experiences can be organized by departments, delivered in- and out-of-course, and on- and off-campus. These include short in-class interventions (*e.g.* online) by companies (especially startups) in the academic surroundings, student excursions to visit companies, course-related exercises and other course material linked to R&D of such companies (see Figure 5), physics career fairs, and internships. Such activities have been shown to foster inspiration, perspectives and network building for students.

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[6] Note that the shortage of STEM/physics workforce is context-dependent (region, qualification level, subfields).

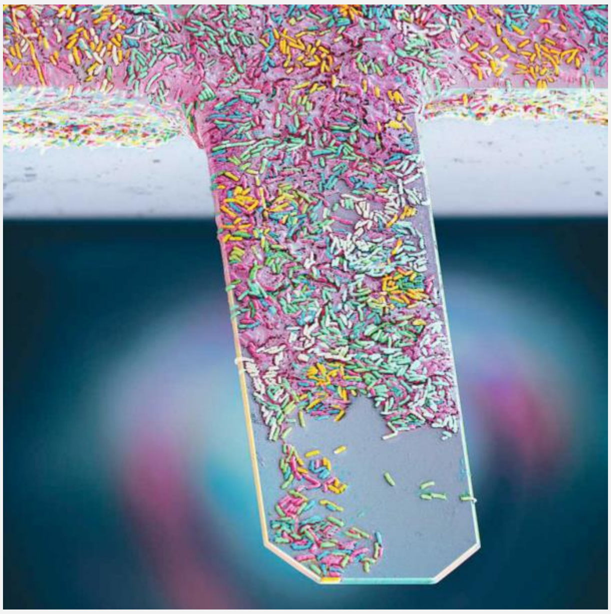

Figure 5: Nanomotion detection of living cells – a fascinating example of a cutting-edge commercial application related to mechanical oscillations.

Living cells show oscillations at the nanometer scale, which can be transmitted to a nano-lever (similar to the one in the image), the motion of which can be read off with a laser and translated into an electrical signal. The absence of a signal flags the absence of living cells.

This method can e.g. test for the presence of living bacteria within minutes rather than hours or days, allowing for rapid assessment of antibiotic efficiency [LAR13, SJP24; https://resistell.com/problem]. This can be crucial for:

- rapid treatment of life-threatening infections;
- reducing the development of antibiotic resistance.

Recommendations:

- Acknowledge workforce realities, recognizing that most PBP graduates will pursue careers outside academia and integrating this understanding into programme design and communication with students.
- Incorporate career-relevant activities (such as those mentioned in Box 8) into the student experience.
- Use interfaces and links with the workplace to communicate purpose and relevance of physics studies to students, and to leverage role models, *e.g.* by inviting alumni and professionals from diverse backgrounds to provide encouragement and perspectives, particularly for underrepresented student groups.
- Start with low threshold approaches realisable with manageable effort.
- Take advantage of the existing R&D environment of your department (alumni, spin-off companies, providers, *etc.*), to create a workplace interface network, providing opportunities for interventions of external experts, internships, establishing employer partnerships, and more; this can also provide valuable information for evaluation of PBPs, see 4.5
- Share best practices by learning from and contributing to the exchange of successful strategies among institutions for integrating interfaces with the workplace efficiently within existing constraints.

- The European Physical Society landmark volume “EPS Grand Challenges—Physics for Society in the Horizon 2050” [Hid24] devotes its entire Part II to state-of-the-art reviews covering a broad range of topics at the interface of physics with society and the economy (health, environment and sustainability, security, *etc.*). This work provides numerous examples for course material, for department information sources on PBPs, for career counselling, and other related purposes.
- Similarly, the Swiss Physical Society has published an in-depth report, “Impact of Physics on Swiss Society” [SPS22], which also provides many such examples and is highly useful for the same purposes. Moreover, the report includes numerous examples from leading innovative companies and employers.
- The German Physical Society has a website for the transition from university to professional career and a programme of dedicated seminars
  https://www.dpg-physik.de/vereinigungen/fachuebergreifend/ak/akjdpg/events/berufsorientierung/berufsorientierung
  https://www.dpg-physik.de/aktivitaeten-und-programme/programme/wochenendseminare-physikerinnen-im-beruf
- The American Physical Society has developed a full spectrum of relevant initiatives and resources for the topic:
  - the websites “Physics careers”, https://www.aps.org/careers, “Educating Physicists for Impactful Careers”, https://epic.aps.org/ and Industry Mentoring for Physicists, go.aps.org/IMPact
  - the report “EPIC. Educating Physicist for Impactful Careers” [Ari21],
  - the leaflet “Find your success in physics A compact guide to physics”, https://www.aps.org/careers/advice/find-your-success
  - a collection for related course material and learning activities, https://epic.aps.org/resources/
- Several national societies and departments provide inspiring collections of physics career profiles, in particular outside academic research:
  - https://www.metiersdelaphysique.fr/
  - https://www.iop.org/careers-physics/
  - https://www.dpg-physik.de/aktivitaeten-und-programme/weitere/175-inspirierende

Box 8: Best practice for interfaces with and transitions to the workplace and employment market

Ari21 Arion, D. (2021). EPIC - Educating Physicists for Impactful Careers. •Menlo Park: American Physical Society, https://epic.aps.org/assets/downloads/EPIC_Report_Digital.pdf
Hid24 Hidalgo (Edt.) (2024) EPS Grand Challenges. Physics for Society in the Horizon 2050. Bristol: IOP; Online at: https://doi.org/10.1088/978-0-7503-6342-6
SPS22 Swiss Physical Society (2022). Focus II: Impact of Physics on Swiss Society (Basel: Swiss Physical Society), Online at: https://sps.ch/en/publications/sps_focus

5.4 Mobility, internationality, collaboration and exchange

Student and staff mobility is an essential part of every accreditation process. They are, in fact, “the overarching political priority” of the entire Bologna Process, “both a right and a structural necessity for building a competitive, attractive European higher education space” [EHEA++].

Far beyond mere fulfilment of formal accreditation criteria, mobility is closely linked to important values of the Higher Education Area in Europe and worldwide, as the following quote convincingly states: “Learning mobility fosters knowledge, skills, competences and experiences, including personal and social competences and cultural awareness, that are crucial for active participation in society and the labour market, as well as for promoting a European identity.” [EU18]

Additionally, and specific for the educational value of physics and the sciences is a fundamental and far-reaching emancipatory idea that the universality of the laws of nature [Ham08] brought with it: a kind of human right to universal access to science—concerning its practice as well as its use—which should not be restricted by any individual, social or political factor, such as ethnic or religious affiliation, gender, political convictions, etc. (Principle of Universality of Science, [ICSU14]). Mobility and student and staff encounters are ways to transform these ideas into lived practice.

Recommendations:

- Motivate students and provide information about study programmes abroad (including summer schools), alongside administrative and funding schemes (such as Erasmus+).
- Promote co-operations and coalitions (such as COIMBRA, https://www.coimbra-group.eu or LERU, https://www.leru.org/) your university is involved in, in order to make these existing channels known among your bachelor students.
- Identify legal, financial, and administrative barriers encountered by your student community, and take institutional and cross-institutional action to address them.
- Strengthen operational enablers: portability of grants and loans, streamlined visa and work permit procedures, recognition of learning units and periods of studies abroad; digitalisation of credentials and interoperability of data systems.

6 Current and persistent issues

6.1 Low enrolment and attractivity of physics programmes

Physics has never been a very popular study subject, and low enrolment in physics programmes has been a widespread problem in many departments [JTUPP16; LWH24]. Shortages of the STEM workforce in general are widely discussed in various countries (see 5.3), and enrolment in physics is particularly low, with less than 2.5% of all STEM bachelor’s degrees in physics (US: [Mas22]; OECD average 2015-2023: 2.3%; [OECD25]; average of 24 countries were full data sets are available).

Low enrolment often places departments under heavy financial and political pressure due to comparison with other disciplines. The situation is aggravated by additional problems like high gender imbalance (sect. 6.2) and high attrition rate (sect. 6.3). In physics teacher education, low enrolment and workforce shortage have turned to a serious problem in the last decade (2.4.4).

Recommendations

Note that there is a strong variation in physics enrolment across countries and institutions, and there is no universal answer. However, for several specific aspects, evidence-based approaches are available:

- for attracting young people at the transition from secondary to tertiary education to physics studies, see 5.1;
- regarding the specific aspects of high gender imbalance and programme dropout, see 6.2 and 6.3), respectively;
- regarding teacher education, see 2.4.4.

6.2 Inequity and underrepresented student groups

The historic and continued underrepresentation of women in physics is an established fact, with only slow change in recent years [McL24]. In the US, the gender ratio (GR = N_F/N_M, ratio of the number of female students to the number of male students) for bachelor's degrees is GR > 1 across all disciplines, but as low as 0.27 in physics [PI19]. Available data for bachelor enrolment in OECD from the last decade (Figure 6; [OECD25]) show the following:

- GR ≥1 across all disciplines, yet much smaller (≈ 0.4) for physics[7], similar to the US; this low participation of women is called the "gender gap";
- GR ≥1.5 for biology, in stark contrast to physics;
- little change of this situation over almost a decade.

Note that the gender gap in physics occurs even though achievement differences between men and women are little to none, or even in favour of women, from lower secondary [LM12, SG18] to tertiary stage [KPF09].

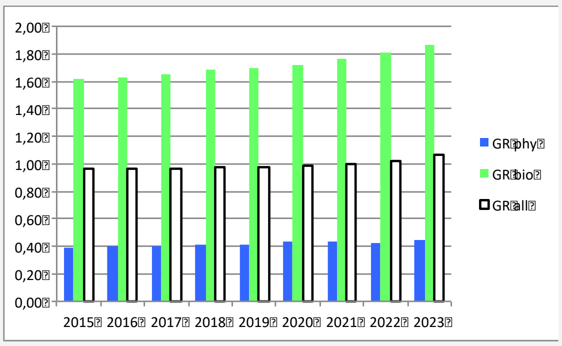

Figure 6: Gender ratio (GR) for enrolment in bachelor programmes in physics, biology, and all disciplines; OECD avg. 2015-2023 for 24 countries with full data sets available [OECD25]

Note also that there is no such thing as a "gender gap in STEM" as is often claimed [WD17]; there is a gender gap in the "hard sciences" (the above results hold similarly for *e.g.* mathematics, engineering, and computing).

Obviously, these findings represent, on the societal level, a major loss of a crucially important workforce (5.3). Plus, on an individual level, beyond a purely utilitarian point of view, a loss of a large area of personal and intellectual development, and of career opportunities across the life span.

Research has identified the key barriers to women's participation in physics: "Their perceptions of the field and what type of person practices physics, their personal experiences of learning physics, and their experiences with gender and physics identity" [McL24]. These barriers inhibit young women's development of "self-efficacy, competence, performance, and recognition in physics" [McL24], thus strongly reducing their participation in further physics studies.

Inequities other than those of gender exist. Educational institutions are increasingly expected to ensure equal learning opportunities to all learners regardless of gender, ethnicity, socioeconomic status, or other factors potentially affecting educational access. In the US, the American Physical Society has a strong tradition of addressing this issue. In Europe, there are several countries with large populations with different ethnicities or migration backgrounds (France, Germany, UK, others), and rising societal tensions related to this. In this situation, contributions by the physics community to ensure equity within their field of action are more important than ever.

Recommendations (partially overlapping with those of sect. 6.3)

- Avoid misconceptions and initiatives ignoring existing evidence (such as one-off activities known to not have lasting impact); a useful overview is provided by [McL24];
- Counter science-related gender stereotypes, such as the geeky male scientist [LSP16];
- Ensure that physics bachelor's students have female teachers throughout the curriculum and especially in the first year;
- Promote role models instead; best practice examples: https://www.aip.org/women-in-the-sciences; https://physicstoday.aip.org/celebrating-black-history; www.physikerin-der-woche.dpg-physik.de; https://www.sfphysique.fr/exhibition-women-pioneers-in-physics/; Biografien bedeutender österreichischer Wissenschafterinnen (https://doi.org/10.7767/9783205205883)
- Support networking; a best practice example is the US National Mentoring Community, which provides "mentoring, professional development, and an inclusive support network to all students pursuing degrees in physics and related fields" [NMC++] or the mentoring initiatives of the German Physical Society [AKC++].
- Implement initiatives that specifically increase a sense of belonging (mentoring, study groups, and learning communities) [CS22, TJH22, SH21], especially for women [LSP16; LSF17];

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[7] The physics programmes taken into account here do not differentiate between more specialised programmes (e.g. medical physics or physics teacher education) and physics programmes as such; the former are known to have higher GR values than the latter [see e.g DR24, DR25]

- Organise an annual national conference for undergraduate women and non-binary physicists following the example of UK and Ireland [https://www.birmingham.ac.uk/events/conference-for-undergraduate-women-and-non-binary-physicists-uk-and-ireland-cuwip]

6.3 Study stress and dropout*

Many departments face high dropout rates in PBPs, with available figures *e.g.* in Germany [LCH24] and the US [SH21] as high as ≈ 60%.[8] Clearly, as low enrolment is a persistent issue for physics programmes (6.1), dropout aggravates the situation. Furthermore, physics is perceived as a study discipline with a very high stress level (among the highest across a variety of disciplines; [LCH24]). Challenges and stress factors identified by research [LCH24] are:

- rapid pace and abstract nature of content;
- large gap between high school preparation and university level expectations, in particular for mathematics [BMW21];
- heavy workload with demanding problem sets (tutorial/recitation groups) and laboratory requirements;
- cumulative nature of the content, making catching up difficult;
- exam stress;
- financial pressures.

While the latter are general to all study disciplines, most of the above points are intrinsic to physics, which requires genuinely demanding and intensive studies (e.g., the workload and mathematical level of problem sets in tutorial groups). Mathematics, in particular, is widely recognized as a major “stumbling block” for studying physics [BMW21]. Empirically, strong correlations were found for between first-semester course success in physics and mathematical knowledge for physics ($r = 0.66$), *i.e.* math alone accounts for more than 40% of the variance in successfully completing introductory courses in physics [MSF18].

As students´ experience of stress is clearly related to dropout, and if one cares about the latter, and about the well-being of students more in general, one cannot disregard the cumulative psychological costs associated with the above factors. This makes course quality even more important, for example in mathematics courses that really support the acquisition of the mathematical tools used by physicists, and in lab courses that should stimulate the curiosity and satisfaction that can be associated with experimental work. It is important to note that instructional quality goes beyond cognitive factors and encompasses affective* factors like learning emotions and sense of belonging as powerful facilitators of study success [CS22, TJH22]; this is especially important for underrepresented groups regarding gender and ethnicity.

A report of the EU provides an overview and best practice examples [VKJ15, ch. 5.3 and ch. 6, respectively] of main measures and policies implemented to increase completion and/or reduce dropout and time to degree across 35 countries at the three level: information and support for students (5 measures); teaching and learning processes (9 measures); and funding and financial incentives (8 measures). Specifically for physics, there is a variety of evidence-based supportive measures, such as tutoring, mentoring*, and counselling* programmes[9], and other approaches [see JTUPP16 for an overview]; several current examples summarized in Box 9. Interestingly, offering different specialisation of PBPs (*e.g.* biophysics or data science / computational physics) is documented as a good way to increase retention [SHB22], as well as to counter low interest and gender inequity (see sections above). Note that the success of all these measures depends on specific design features for which available evidence is key; ignoring this evidence substantially increases the risk of failure for any well-intentioned initiative.

–Bridging/remedial math and propaedeutic courses to raise math readiness [PN13, BBB14]; the OMB+ consortium of about 50 universities has developed content and an online platform for such courses in four languages [OMB+];
–Tutoring* programmes: structured study and problem-solving groups under the guidance of trained peer leaders, systematically aligned with the course syllabus, and sometimes combined with mentoring; evidence and examples of god practice exist for various design formats, e.g. in dedicated sessions (“Peer-Led Team Learning (PLTL)”, [WV16; PLTLIS++]; “Supplemental Instruction (SI)”, [DvdM14, CR24, LSS25]) or integrated within regular class time (“Integrated Peer Leadership Programme (IPLP)”, [MJH21]; “Learning Assistants (LAs)”, [GBK11, CCC16]) courses;
–Mentoring* programmes [SvdH25]

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[8] Dropout is understood disenrollment from university + switch to other fields +non-completion 3 years after scheduled end. Two points should be noted: First, these values are consistent with rates across STEM (48%, [Val14]), with physics being at the high end where comparative values are available [LCH24; PCI24]. Second, while there is strong general awareness of the problem, data sources, in particular for specific disciplines such as physics on national and international levels, are found wanting [VKJ15]; moreover, considerable variation exists across countries and disciplines, with magnitude and drivers differing [LKK13, VKJ15].

[9] See glossary for the differences of these terms

–Programmes that specifically increase the sense of belonging (mentoring, study groups, and learning communities) and target learning-enhancing emotions [CS22, TJH22, SH21], especially for women [LSP16];
–Classroom practices structured to increase students' opportunities to create positive social connections (interactive practices, student centered approaches; [LSP16, RP21, SGS24]);
–Linking to the broader social and societal context students are part of outside the classroom, fostering meaningfulness by insight into the relevance of physics for daily live and for concrete ways it benefits society [LSP16];
–Countering "genius" and "geeky" scientist stereotypes should, instead endorsing effort and sustained work over brilliance [LSP16];
–Instructional changes (structured practice, active learning, early warning, timely feedback) that increase understanding, interest, and self-confidence, and reduce stress and failure (see [PCI24] and sect. 4.1, 4.7.)

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Box 9: Physics-specific intiatives and measures to reduce dropout and time to degree

Recommendations:

- Make reasoned choices and implement available supportive measures, taking into account existing evidence on success factors (Box 9), and evaluate their impact;
- Support a sense of belonging and create welcoming and inclusive environments, in particular for women;
- Monitor students' success and well-being and evaluate the quality and climate of study programmes to create a foundation for institutional action.

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APPENDICES

A1 European Benchmark for Physics Bachelor's Degrees

Background

The previous edition of this document contained a European Benchmark for Physics Bachelor's Degree Programmes, which has served as specification of PBPs for accreditation in several countries. To ensure this possibility of use also for the present edition, the purpose of this annex is to point the reader to the sections of the main report that constitute a specification (core elements used in accreditation procedures).

As in the previous edition, this is meant as an indicative listing, broadly specifying the common programme which can be found in most physics degrees across Europe, and describing the level of physics knowledge and skills physics departments across Europe generally consider sufficient to admit graduates of other universities to their master's programmes without supplementary requirements (except possibly for minor adaptations that do not lead to a net increase in the workload). It is not intended to either provide a fixed and detailed physics syllabus or to replace the national quality assurance systems in place in various countries.

List of core elements of a programme specification for accreditation procedures

- Description of Physics as a Discipline, Box 1
- Core Physics Topics/Concepts, sect. 2.3
- Elective courses, sect. 2.4.1
- Physics bachelor's discipline competences, sect. 3.1
- Physics bachelor's generic competences, sect. 3.2

Implementation

We suggest physics departments self-certify their programmes as being consistent with these benchmarks or not, and if not give their reasons. Similarly, we suggest departments use these benchmarks to specify the knowledge and skills they require for admission to their master's programmes; they may deviate from them but should then point out explicitly where their requirements for some or all their master's programmes differ from those specified above.

A2 Glossary

A Glossary of key terms in higher education can be found in [COE++] & [VGP07], some further terms relevant for the present document are explained below.

Affective is often used in education as an umbrella term that includes emotional and motivational dimensions, as well as learners' attitudes and values [AW03; Rei05]. In psychology in general [DS04, DP05] and science education in particular [Rei05, Als15], the interaction between cognitive and affective processes is considered essential for learning and academic success.

Assessment/evaluation: The terms assessment and evaluation are often used interchangeably [VGP07], but a more precise distinction is useful. Assessment typically refers to measuring student learning, while evaluation is about the quality or effectiveness of teaching.

Counselling: support for psychological well-being and personal adjustment; often delivered by specially trained professionals; confidential and often short term; addresses stress, anxiety, crises, self-management, and referrals; not course instruction.

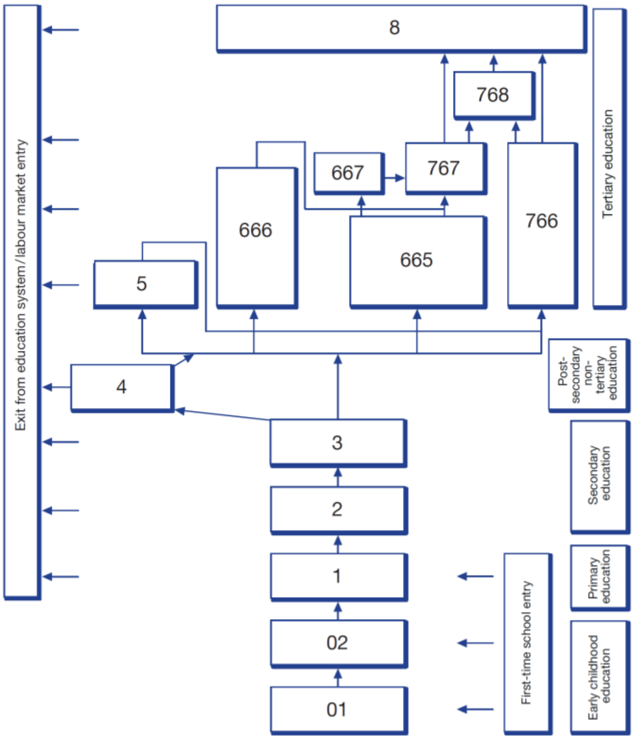
Formative assessment of learning monitors learner's progress during instruction to provide ongoing feedback, while summative assessment evaluates learning outcomes at the end of a course or unit. Applies analogously to formative/summative evaluation of teaching.

Induction (as *e.g.* in the APS Bridge Program) refers to the structured set of support measures provided during the first weeks of graduate studies to facilitate students' academic and social transition. It includes diagnosing preparation gaps, adjusting course placement, and facilitating housing, peer networks, and early integration into the department. It aims to reduce the initial stress of a new environment and ensure that students begin their graduate studies on stable academic and personal footing [HW17].

Mentoring: developmental guidance and professional socialization, close to discipline; provided by faculty, staff, alumni, or trained peers; medium to long term focusing on goals, identity, networking, and career advice; not therapy and not course specific

Physics identity: self-concept as a "physics person", combining interest, competence, and recognition [WHP18].

Secondary education: In the International Standard Classification of Education (ISCED, [UNESCO11]; see figure), secondary education (ISCED levels 2 and 3) is positioned after primary education (ISCED level 1) and provides the necessary literacy and numeracy for professional or university education at the tertiary level (ISCED levels 5–8).



Tutoring: course or skill specific academic support; course specific; provided by peers or staff; short, targeted sessions to clarify concepts, practice problem solving, and build study strategies; not well-being or coping support, nor developmental guidance and professional socialization;

References (Annexes)

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