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Making an IMPRESSion: mapping out future directions in modern physics education

Magdalena Kersting[1,*], David Blair[2], Stefano Sandrelli[3], Jacob Sherson[4,5] and Julia Woithe[6]

[1] Department of Science Education, University of Copenhagen, Copenhagen, Denmark
[2] School of Physics, University of Western Australia, Perth, Australia
[3] Astronomical Observatory of Brera, INAF, Milan, Italy
[4] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[5] Department of Management, Aarhus University, Aarhus, Denmark
[6] CERN, Physics Education Research & Science Gateway Education, Geneva, Switzerland

E-mail: mkersting@ind.ku.dk

Abstract

Modern physics is an exciting and rapidly progressing field, prompting significant shifts in how we teach physics across all educational levels. While there is broad agreement on the need to modernise physics education and support physics teachers in this transition, existing initiatives often remain scattered across different educational contexts. In response, this directions paper synthesises insights from the International Modern Physics & Research in Education Seminar Series symposium to guide the efforts of our global physics education community and to increase their impact and reach. We bring together viewpoints from the symposium's panellists and discuss these views as visions for the future of our field, mapping out pathways for navigating the challenges and opportunities ahead. Ultimately, we hope this paper will serve as a roadmap for teachers, educators, and physicists wishing to enhance modern physics education research and practice.

Keywords: physics education, modern physics education, Einsteinian physics education

* Author to whom any correspondence should be addressed.

1. Introduction

Modern physics is progressing rapidly, and so is modern physics education. Within the last decade, we have witnessed the discovery of the Higgs particle and the detection of gravitational waves. Now, we find ourselves at the dawn of a second quantum revolution and are poised to explore new cosmic frontiers. Inevitably, such exciting developments affect physics education both locally and globally and necessitate changes in what and how we teach physics across all age levels. Indeed, recent calls to expand and modernise physics education [1, 2] have gone hand in hand with significant shifts in the physics education landscape.

Today, teachers and educators embrace opportunities to teach modern physics topics in schools: they can choose from a growing number of learning resources, lesson plans, and professional development programmes (e.g. [3–22]). These resources and programmes are often developed by education and public outreach teams of large-scale physics collaborations or institutes that connect cutting-edge physics with curriculum content. In parallel, physics education researchers study students' learning processes, conceptual understanding, and attitudes that feed into the development and continuous refinement of these resources (e.g. [23–33]). The result is an active and stimulating field: modern physics education.

There is ample evidence of the progress our field has made in the last few years. However, with ongoing developments scattered across different educational contexts, our growing modern physics education community stands at a critical junction. Our efforts, albeit promising, run the risk of fragmentation without a shared vision. To prevent this, we need a broad overview of current developments and emerging trends to ensure that our efforts become cumulative and realise their full educational impact.

In response, the International Modern Physics & Research in Education Seminar Series (IMPRESS) hosted a symposium[7] on the future of modern physics education. IMPRESS is a joint initiative by the Physics Education Research team of the European Organization for Nuclear Research (CERN) and the Physics Education Research Group of the University of Copenhagen (KUPER). The initiative aims to bridge the gap between those who know, teach, and learn physics and strengthen connections among the modern physics education community.

This directions paper, a key outcome of the IMPRESS symposium, aims to provide visions for our field and serves as a roadmap for shaping the future of modern physics education.

First, we present the viewpoints of four leading physics educators, each affiliated with major modern physics education initiatives, who acted as the symposium's panellists. These viewpoints allow us to reflect on the past and probe possible paths for the future. Second, we contextualise and integrate these views with wider themes from the symposium presentations and interactive discussions. By identifying current and evolving trends, we wish to stimulate conversations that will give impetus to modern physics education research and practice.

2. Four viewpoints from the frontline of modern physics education

We invited four physics educators, each affiliated with a prominent modern physics education initiative, to reflect on past achievements and new directions in modern physics education.

2.1. Building a science revolution in Australian classrooms

David Blair (Einstein-First): Modern science has had profound effects on all our lives, yet, its remarkable revelations remain within the domain of experts. About ten years ago, a small group of physicists and educators, myself included, decided to challenge this status quo with a key question: could primary school students comprehend the concepts of modern physics?

The first trial with a class of 11-year-olds yielded an astonishing result: the children were not bemused or mystified; they were completely open to quantum thinking [34]. The Einstein-First

[7] The recording of the symposium is available at https://indico.cern.ch/event/1240261/.

project was born—its name defining its key idea: start kids off with our best modern understanding of physical reality. Abandon the 19th-century clockwork Universe in schools and replace it with Einstein's new Universe, where the Newtonian conception of physical reality is overthrown.

In developing Einstein-First, we followed the precepts of the Harvard educator Jerome Bruner, who boldly stated, 'Any subject can be taught effectively in some intellectually honest form to any child at any stage of development' [35]. Through hands-on activities, toys, role-plays and human stories of heroic discoveries in science, we created a spiral curriculum: Eight Steps to Einstein's Universe spans Year 3 to Year 10, the last compulsory year of science in Australian schools. Early introduction to Einsteinian physics cements the language of modern science, creating a foundation for introducing more complex ideas later on.

In year 3, songs, plays, and activities bring reality to atoms and molecules, electrons and photons. By year 6, students can grasp how the vibrational properties of CO_2 molecules cause dark photons from the Earth to be absorbed—the key science behind climate change—and by year 10, they understand the scale of the Universe, why quantum computers are statistical machines, and that space and time began in the big bang and end in black holes.

A crucial part of Einstein-First has been the training of teachers. This began with live workshops where we discovered that hands-on activities were as effective for the teachers as for the students in understanding Einsteinian science: the activities and the toys bring concepts to life. We have rolled out micro-credential courses for teachers at all levels, allowing those with no prior science to feel confident to teach students up to the year 10 level.

The Einstein-First team gives schools free access to all the lesson plans and has created several books to help give teachers background knowledge without needing a university degree in physics.

Impressive results across 38 partner schools in Western Australia led to the national launch of Einstein-First at the Australian Academy of Science in Canberra in June 2023. Besides, the outstanding improvement in teenage girls' attitudes to physics provided the incentive to create a national programme called Quantum Girls, designed to boost STEM (science, technology, engineering, mathematics) education and redress the gender imbalance in STEM disciplines.

Working together, we know that we will not only inspire but also help create the next wave of bright young scientists that every nation needs and deserves. It is a revolution: but one we can all get behind and which will set Australia up for the opportunities of the 21st century.

2.2. *How modern physics can help overcome major challenges in physics education*

Julia Woithe (Science Gateway): Children are naturally curious, and exploring the laws of physics brings them immense joy and wonder. However, as they progress through formal education, their interest in physics and belief in their physics-related abilities decline. This is especially true for girls, who, from a very young age, start learning about gender stereotypes, including the notion that physics is not for them. Consequently, I am afraid of sending my daughter to school because we are destroying especially girls' science-related self-concept with every year they spend in school. I believe that modern physics education has the potential to counteract this concerning trend and positively impact students not only in their interests and career aspirations but also in their fundamental understanding of the nature of science. Studies have shown that high school students are fascinated by the unanswered questions of humankind and unexplained scientific phenomena [36]. Modern physics topics, such as the history of the Universe and space science, spark particularly high levels of interest among students [37–39].

One significant challenge in introducing modern physics in classrooms is that the advanced mathematics underlying the theories of modern physics may not be accessible to school students. Consequently, educators must employ conceptual instead of purely quantitative teaching approaches and use active learning strategies, such as group work and hands-on activities.

Another hurdle lies in the abstract nature of modern physics. Particularly, particle physics deals with many unobservable entities that are impossible to observe (or visualise) directly. This necessitates the development of suitable educational models and open discussions about the nature and limitations of scientific models in general. Despite these challenges—or rather because we as educators need to creatively overcome these challenges—modern physics education offers a unique opportunity to teach about science in the making. It introduces exciting physics topics and contemporary scientific practices, such as global research collaborations, which dispel stereotypes about scientists. Learners are exposed to the reality of modern scientific research, where communication and teamwork play vital roles in advancing knowledge. Students even get the chance to meet active physicists in the framework of numerous education and outreach initiatives. Here, educational research shows that even short encounters can help address the still-prevalent stereotype of scientists and positively impact students' aspirations to pursue a scientific career [40–42].

The progress made in modern physics education and research is noteworthy. A decade ago, we knew very little about how students learn particle physics and how to teach this topic best. However, by involving physics education experts and researchers, the field has evolved from outreach initiatives to evidence-based education. The next step is to implement the knowledge gained from small-scale exploratory research projects into larger, more systematic, and comprehensive initiatives. For example, CERN's new state-of-the-art education and outreach facility, Science Gateway, connects up to 300 000 visitors per year to the fascinating world of particle physics[8]. Visitors will be able to interact with members of CERN's scientific community while exploring new interactive exhibitions about the science and technologies at CERN, the Universe, and the quantum world. Science Gateway also hosts science shows, which tell the stories behind CERN's discoveries in a theatre-like setting. Finally, education labs encourage visitors of all ages to explore the abstract concepts of particle physics hands-on to foster their scientific curiosity and show them that science is for everyone.

[8] https://sciencegateway.cern/.

2.3. Quantum technologies bring exciting opportunities to physics education

Jacob Sherson (QTEdu Project): As an experimental physicist exploring remote entanglement and quantum teleportation in the 2000s and single resolved neutral atom quantum simulators and computers in the 2010s, it has been exciting to witness the transformation of the field: we have seen a shift from cutting-edge research to supporting an upcoming second quantum industrial revolution with potentially millions of jobs over the coming few decades. This means we must expand the entire educational pipeline dramatically, from raising general awareness to increasing the number of quantum specialists in physics and related disciplines (e.g. engineering, computer science, and biochemistry). In addition, quantum competencies must be broadened to encompass business support functions and decision-makers within industry and policy. These are exciting prospects for physics educators!

However, a significant challenge I have observed as a university lecturer is that students excel mathematically but often lack an intuitive grasp of quantum mechanics' intricacies. Consequently, we developed a visual, node-based quantum programming language, quantum composer, allowing students to quickly assemble blocks like Hamiltonian, time evolution and plotting [43]. The results, often strikingly similar to a game, led us to encapsulate quantum research challenges as citizen science games for the general public in the early 2010s. Within the ScienceAtHome.org platform, we have since launched games within quantum computing [44], turbulence, remote quantum experiment optimisation and a dozen other natural and social science topics, reaching more than 300 000 citizens.

Attempting to harness this energy within the formal educational system, we introduced Research Enabling Game-Based Education (ReGAME), which extends the inquiry-based science education approach by embedding unsolved research challenges into the core curriculum[9]. The goal is to inspire students struggling academically with relatable content and challenge high achievers to explore beyond their grade level. We showcased this approach in ReGAMEcup 2018, with thousands of students competing in various scientific themes.

Nowadays, interest in quantum games and educational simulations is exploding [45], leading to the second challenge facing the field: coordination. It is mainly up to individual teachers and lecturers to locate and adapt educational material to their specific needs. Recognising the need for stakeholder alignment, the EU Commission has committed to substantial education and training funding alongside their Quantum Technologies Flagship investment.

This has resulted in the Coordination and Support Action (CSA), QTEdu, 2020–2022, followed by formal integration of education into the flagship CSA QUCATS 2022–2025. Achievements so far have been (i) assembling a quantum education community of +300 stakeholders, (ii) efforts to collect available educational resources and most notably, (iii) the establishment of a community-driven unifying language for quantum skills and competencies through the entire educational pipeline, the European Competence Framework (CF) for Quantum Technology [46].

As quantum technology is increasingly introduced within steps in the educational ladder and for industry hiring and training, the CF will continuously evolve to remain updated with all relevant topics and transversal skills. This would enable unprecedented transparency and allow schools and higher education institutions to formulate and experiment with their unique contribution to the quantum education ecosystem. I envision this CF addressing a prevalent issue: while most physics graduates secure good jobs shortly after graduation, many are unclear about how their acquired skills align with job market demands.

[9] www.scienceathome.org/education/regame/.

2.4. Beyond storytelling in modern physics: cultivating critical minds through dialogue

Stefano Sandrelli (International Astronomical Union (IAU) Office of Astronomy for Education): the famous Argentinian writer Jorge Luis Borges talks about dragons as 'necessary monsters' [47]. I love the idea of a necessary monster. And it is easy to recognise that stories are our necessary monsters in the realm of communication and education, just as dragons are indispensable in mythology. Stories are the tools humans use to pass down knowledge and experiences. Even theorems and scientific laws can be presented as short stories, making abstract ideas emotionally relevant: think of angles or triangle as characters; thinks of their relations as interactions, and here you have the theorem as the whole plot. Or consider that the concepts of space and time are not mere geometrical issues; they pertain to our whole person since we are in space and time. Their changes in the presence of gravity mean something about ourselves, not only about physics.

Although necessary, there must be more than storytelling for good physics education or communication. A story works if it evokes a new experience in the listener, pulling them from the known towards the unknown [48]. Creating new experiences requires dialogue among peers: exchanging visions, sharing ideas, developing different points of view. This dialogue can be done not only with words but with the mind, the hands, or the whole body.

One of our most impactful projects at the IAU Office of Astronomy for Education Centre Italy, the STEAM-Med initiative, exemplifies my deep belief in dialogue as the highest form of communication for education. In STEAM-Med, we worked closely with the Mediterranean community to co-design educational activities, sharing values, methods, and visions, thanks to a shared history and tradition, and despite—or thanks to—our linguistic differences[10]. Following a more than one-year-long process, run in the Mediterranean area during 2021 and 2022, we held two peer-to-peer meetings in Lampedusa (July 2022) and Morocco (June 2023). These meetings are a testament to the power of dialogue in physics education.

Dialogue does not always mean agreement, particularly in education. Dialogue obliges to doubt, to analyse, to be humble. Perspectives can be very different. For example, easy access to astronomical data allows scientists and educators to engage students in activities akin to those of researchers. But can students really grasp the deep meaning of these discoveries? In my opinion, easy access to data does not warrant the inclusion of cutting-edge astrophysics in the school curriculum. Cutting-edge astrophysics always relies on some basic physics concepts, which a student can use to approach discoveries nowadays. In fact, I believe that the biggest task of future educational efforts is fostering critical thinking and the skill to make connections among different—and sometimes far—fields. We should change our perspective from a disciplinary one to a transdisciplinary one.

This transdisciplinary approach to education leads me to believe that modern physics education research can serve as a compass to evaluate our effectiveness. Physics education research solidly relies on many aspects of the human being that are often neglected, such as psychology or neuroscience. By recognising the crucial role of these aspects, we can work towards educating physics students who can think critically and holistically across disciplines.

3. Mapping out future directions in modern physics education

Taken together, the four viewpoints cover a breadth of age groups, contexts, and regions, providing a wide-ranging insight into the dynamic landscape and ongoing evolution of modern physics education. Distilling key themes from these viewpoints and integrating them with broader discussions from the symposium, several trends emerge.

First, we see a strong focus on holistic approaches and collaborative efforts. Be it Western Australia's broad curriculum integration starting in primary school coupled with extensive support for and input from teachers, the development of the European CF for Quantum Technology in close collaboration with stakeholders from universities, industries, and government bodies, CERN's efforts to create informal learning spaces where scientists and the public can meet, or STEAM-Med's approach to co-designing educational activities with cultural attunement: what cuts across these examples is the recognition that we can only succeed in modernising physics education if we pool expertise and partner with fellow physicists and educators, teachers and curriculum developers, industry professionals and policymakers. Recognising that there are many opportunities for physics educators to work synergistically, drawing from diverse perspectives and disciplines, underscores the importance of sharing common goals and visions to guide our collective efforts.

Second, we see a strong commitment to research-based initiatives. The viewpoints' acknowledgement of the progress in physics education research finds support in the many excellent symposium contributions that showcased the diversity and creativity in using research methods to improve physics education. From large-scale surveys to eye-tracking technology and lesson study as a research approach, there is a shared understanding that educational research is needed to make meaningful progress. As modern physics education research continues to mature and professionalise, we can expect a more extensive knowledge base of students' conceptions, learning processes, self-concept, and motivation and how these affect the quality of teaching and learning. Such knowledge will further feed into evaluating and refining instructional approaches and, ultimately, maximise their educational impact.

Third, we see a strong emphasis on cultivating inclusive learning environments. Indeed, a cross-cutting theme in both the viewpoints and the symposium was the potential of modern physics

[10] The Mirto/STEAM-Med codesign process is explained here: https://edu.inaf.it/oae_italia/mirto-steam-med-co-design-process/.

to make physics education more accessible and attractive to a broader range of students. Modern physics topics have excellent potential to promote gender equality in physics since these topics have been shown to increase young girls' attitudes and interest in physics. Besides, hands-on activities, role plays, and a deliberate focus on the nature of science and science in the making are likely to appeal to students who otherwise feel that science is not for them. Attempts to leverage the meet-the-scientist effect in informal learning spaces testify further to the wish to catalyse diversity and shake cultural norms of what a physicist may look and act like. Finally, it is exciting that technologies are used to expand the reach of our efforts, e.g. by engaging students in remote communities who only have limited opportunities to visit science centres or meet scientists.

In summary, these themes suggest a future of physics education that is relevant, accessible, and closely tied to the broader scientific and societal landscape. While our directions paper offers a starting point to stimulate discussions on our visions for modern physics education, we do not suggest a conclusive path towards the future of our field. Instead, we wish to embolden physics teachers, educators, and researchers to take the next steps towards a promising future in modern physics education.

Data availability statement

No new data were created or analysed in this study.

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ORCID iDs

Magdalena Kersting https://orcid.org/0000-0003-3568-8397
David Blair https://orcid.org/0000-0002-1501-2405
Stefano Sandrelli https://orcid.org/0000-0001-8003-2229
Jacob Sherson https://orcid.org/0000-0001-6048-587X
Julia Woithe https://orcid.org/0000-0002-4772-2989

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Magdalena Kersting is an educational researcher and physics educator, currently working as an assistant professor at the University of Copenhagen. Editor of 'Teaching Einsteinian Physics in Schools' and recipient of the International Astronomical Union PhD Prize, she is passionate about the transformative potential of education.

David Blair is a gravitational wave research pioneer, who founded the Australian International Gravitational Research Centre and the Gravity Discovery Centre. Now part of the ARC Centre of Excellence for Gravitational Wave Discovery, OzGrav, he leads the Einstein-First Project and has recently championed the Quantum Girls initiative.

Stefano Sandrelli serves as the Head of the Office of Astronomy for Education Italy (IAU) and Outreach and Education Coordinator at the National Institute for Astrophysics. With degrees in physics and astronomy, Stefano's expertise extends to science journalism for the European Space Agency and authorship of award-winning popular scientific books.

Jacob Sherson is a dual professor at Aarhus University and the University of Copenhagen, co-leading the pan-European Quantum Technology workforce efforts. He is the director of the European Quantum Readiness Centre and co-ordinator of the QTEdu project. He has earned many accolades, including the 2020 Falling Walls in Science and Innovation Management.

Julia Woithe is a multifaceted physics educator, researcher, and communicator, coordinating the educational activities at Science Gateway, CERN's new flagship project for science education and outreach. Previously, she managed #SCoolLAB, CERN's hands-on lab for high-school students and teachers.