# Special Section Guest Editorial: Education and Training in Quantum Sciences and Technologies

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Quantum sciences and technologies bring new challenges and opportunities to educators and trainers in academia, industry, and nonprofits in optics and photonics. Over the last decade, there has been a notable growth in reports on the subject matter at the biannual International Conference on Optics Education and Outreach (OEO) and the International Conference on Education and Training in Optics and Photonics (ETOP). The meetings bring together the leading experts from academia, industry, K-12 & vocational education, nonprofit, and government centers representing all leading education and training groups worldwide. Each author's goal is to share the wonders of science and optics to the next generation of scientists and engineers utilizing informal engagement efforts through formal education programs.

The participants expressed a strong need to publish selected presentations in a peer-reviewed journal. This has motivated the guest editors to prepare the first special section in *Optical Engineering* for education and training for quantum sciences and technologies based on optics and photonics. We received submissions based on work presented at ETOP 2021, OEO 2020, previous meetings, as well as several original publications, and after rigorous review, *Optical Engineering* has published this special section in Volume 61 Issue 8.

The barriers for accessibility of quantum sciences and technologies are a recurrent theme throughout this special section. This set of publications consists of ten papers related to advances in education and training methods applied to photonics-based quantum sciences and technologies. Knowing one's audience is key when considering the education and training initiatives, and we are delighted to consolidate reports that present advances for engaging with industry professionals, policy makers, artists, and the public, as well as students in grades K through 12, undergraduate and postgraduate levels.

While quantum optics and Nobel prizes can certainly be intimidating to students, Adams and Charles developed an inquiry-based project to increase awareness and knowledge of photonics and quantum optics amongst college students in Québec, Canada (https://doi.org/10.1117/1.OE.61.8.081805). This formal education project was developed for a Waves and Modern Physics course (equivalent to a freshman-year physics course elsewhere in North America). The students choose a Nobel prize and are led in their inquiry by a scaffold designed for the project. Final presentation and feedback from the teacher also allow the students to reflect on and assess their learning outcomes.

Public engagement can be challenging when it comes to explaining complex and abstract concepts behind quantum optics phenomenon. When the Networked Quantum Information Technologies (NQIT) hub was funded in 2017 through the UK National Quantum Technologies Programme, Gow et. al from the University of Southampton decided to develop an interactive demonstrator to bring quantum photonics technologies to a wider audience (https://doi.org/10.1117/1.OE.61.8.081802). Their demonstration focuses on the entangler unit and accompanying software, as used in the NQIT project. Through trial and error, the team learned that a more hands-on demonstrator was required and suggested a fun way to demonstrate quantum entanglement. Interactivity was also a key concept in the development of the *Do you speak quantum?* physics and art exhibition developed by Decaroli and Malinowski (https://doi.org/10.1117/1.OE.61.8.081807). It features five stand-alone installations that explain various quantum concepts, from quantum error correction to quantum computations, through intriguing visualizations and interactions. The exhibition was also presented during the Davos World Economic Forum in 2020.

The special section also features reports on teaching and research laboratories, including developing curriculum, nurturing collaboration, and implementing pedagogical frameworks to deliver "hands-on" experiences for students in higher education. This includes recent implementation of undergraduate certificate programs in nanoscienceand nanoengineering (Lukishova and Bigelow, https://doi.org/10.1117/1.OE.61.8.081810), as well as a review of more established programs for quantum optics, quantum information and nano-optics (Lukishova, https://doi.org/10.1117/1.OE.61.8.081811) at the University of Rochester in New York, USA. The authors demonstrate how these programs can be used to benefit educational partners with a wide range of technical backgrounds, including community colleges, teaching institutes, immersion programs, as well as visiting scholars. Pedagogical research of student learning and experiences highlight understanding of technical concepts, achievement of learning outcomes and positive attitudes towards careers in quantum technology.

Software simulation tools and quantum games offer a promising avenue for end-users to interact, engage, and build capacity with these challenging concepts. Tang et al. addressed educating students in quantum computing though the FeynamnPAQS software (https://doi.org/10.1117/1.OE.61.8.081804). Modules used in the design of a photonic chip can be connected, and solvers for each of the components simulate chip performance. Case studies provided serve to illustrate how the software was used in course instruction. Migdał et al. developed a virtual workbench to introduce applications based on quantum entanglement (https://doi.org/10.1117/1.OE.61.8.081808). Using a drag and drop user interactive computer simulation, components are assembled into quantum systems with support for up to three entangled photons. The Virtual Lab software is focused on hardware implementations. It is available as an open-source tool for students and educators and can be used by researchers.

Seskir et al. report on the current state of quantum games and interactive tools (https://doi.org/10.1117/1.OE.61.8.081809). Case studies are included, describing platforms using photonics, along with a wider selection of implementations to explore phenomena of quantum gates, quantum circuits, quantum information, measurement, ultracold atoms, superposition, energy levels, and experimental optimizations. Evidence is presented that activities such as quantum hackathons, quantum game jams, and project-based courses are accelerating the rate of creation of interactive content. Storytelling is identified as a route to engage further with end-users, and a pilot project, Quantum Technologies Education for Everyone, will provide tools to design and assess the efficiency and effectiveness of teaching essential concepts.

Addressing industry needs for a quantum-ready workforce is reported. Hasanovic et al. took quantum technology out of the research lab and into commercial manufacturing with education aimed at the quantum technician (https://doi.org/10.1117/1.OE.61.8.081803). Using industry surveys and leveraging knowledge from existing optics technical programs, a set of baseline quantum skills and competencies was developed. This framework will be used to design the curriculum needed to support outcomes of National Quantum Initiative Act research programs. Kaur and Venegas-Gomez note the challenges in designing and implementing a quantum workforce plan, a key bottleneck to the fast-growing industry (https://doi.org/10.1117/1.OE.61.8.081806). This review article highlights job market demands and routes to integrate the quantum industry from different career pathways. A representative snapshot of over seventy quantum education initiatives is reported, covering academic graduate degree programs, online courses, conferences, workshops, hackathons, quantum games, and community-building. The study highlights strategic considerations for businesses to prioritize needs for end-users of quantum technology.

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