Undergraduate program in nanoscience and nanoengineering: five years after the National Science Foundation grant including two pandemic years

Svetlana G. Lukishova[a,*] and **Nicholas P. Bigelow**[a,b]
[a]University of Rochester, The Institute of Optics, Rochester, New York, United States
[b]University of Rochester, Department of Physics and Astronomy, Rochester, New York, United States

Abstract. We describe a coherent undergraduate educational program in nanoscience and nanoengineering at the University of Rochester (UR) based on the Institute of Optics and Integrated Nanosystems Center resources. This project has three main outcomes: (1) developing a curriculum and offering the Certificate in Nanoscience and Nanoengineering (CNSNE); (2) creating an exemplary model of collaboration in nanotechnology between a university with state-of-the-art, expensive experimental facilities and a nearby two-year community college (CC) with the participation of the local Monroe Community College (MCC); and (3) developing universally accessible "hands-on" experiments (mini-labs) on nanophotonics/quantum nanophotonics, learning materials, and pedagogical methods to be introduced in some Institute of Optics classes from freshman to senior levels. The inexpensive mini-labs described herein can be adopted in small colleges. An important outcome of this project is that ∼50% of the 41 awardees of the CNSNE (by May 2021) after graduation continued their career in the field of nanoscience and nanoengineering. For the CNSNE program, UR students must take three courses: Nanometrology Laboratory (a new course specifically created for this program) and two other selective courses. Students should also conduct a one-semester research or design project in the fields of nanoscience and nanoengineering. A total of 52 MCC students (including non-science, technology, engineering, and mathematics major students) participated in two labs at the UR on atomic force microscopy and photolithography in a clean room. Our teaching methodology, the progress of students' learning outcomes, and the investigation of students' attitudes and self-efficacy toward selecting their careers in nanoscience/nanotechnology are also discussed and analyzed. Discussions on the challenges in teaching advanced lab classes during the pandemic, our solutions for preserving the CNSNE program, and lessons learned are also included. [DOI: 10.1117/1.OE.61.8.081810]

Keywords: certificate in nanoscience and nanoengineering; nano- and quantum optics mini-labs; quantum nanophotonics; collaboration between the university and local community college; The Institute of Optics; University of Rochester; Monroe Community College; teaching advanced labs in pandemic.

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1 Introduction

We describe a successful project at the University of Rochester (UR) that addresses one of the most important issues in modern engineering education, geared toward increasingly important technological problems. Nanotechnology offers undisputed potential for creating new materials and devices with wide-ranging applications. A key aspect of government-funded research through the National Nanotechnology Initiative[1,2] is the education and training of students and researchers.[1] Universities are challenged to enable the future workforce to further develop these new ideas, as well as to provide students with "hands-on" experience in nanotechnology methods and tools for today's jobs; see, for instance, some publications on student training in nanotechnology.[3–23]

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*Address all correspondence to Svetlana G. Lukishova, lukishov@optics.rochester.edu

Modern students should be (1) fluent in nanoscience and nanotechnology terminology, (2) able to define nanoscience, nanotechnology, and nanodevices, (3) able to frame nanotechnology questions and propose strategies to answer them, (4) able to operate evolving nanotechnology characterization tools [science, technology, engineering, and mathematics (STEM) majors], and (5) able to choose a research career in nanoscience/nanotechnology (STEM majors). We emphasize that nano-optics is closely connected with quantum optics, which leads to overlapping classes and projects in these two areas; thus, the field is adequately called quantum nanophotonics.

According to Ref. 24, 164 academic institutions around the world offer a total of 279 degree programs in nanotechnology fields (refer to a database with listed universities[24]); however, there is a lack of comprehensive papers on all university programs in nanotechnology.[14–16,18–23]

The novelty of this paper is related to the outcomes of our project:[21–23] (a) creating a coherent educational program at the UR on the Certificate in Nanoscience and Nanoengineering (CNSNE, Sec. 2); (b) creating an example model for other universities of collaboration in nanotechnology between a university with state-of-the-art, expensive experimental facilities and a local, two-year community college (CC) (Sec. 3); and (c) developing "hands-on" experiments (mini-labs), learning materials, and pedagogical methods to educate students with different levels of knowledge, including non-STEM-major CC students (Sec. 4). The mini-labs were introduced into various UR courses from freshman to senior levels. Based on an earlier, National Science Foundation (NSF)-supported collaboration between the UR and Monroe Community College (MCC) in teaching quantum optics laboratory,[25–28] UR and MCC strengthened this collaboration in nanotechnology education. In Sec. 5, we analyze (1) our teaching methodology and compare it with other publications, (2) the progress of students' educational learning outcomes, and (3) the results of surveys of students' attitudes toward selecting their careers in nanoscience/nanotechnology.

Section 6 describes the challenges in adapting the CNSNE program to the two pandemic years, the specific recording equipment used to teach remotely advanced laboratory classes in quantum optics and nanometrology, our approaches, and lessons learned.

During the 2014–2017 period, this project was supported by a U.S. NSF grant "NUE: Development of Multidisciplinary Nanotechnology Undergraduate Education Program at UR Integrated Nanosystems Center (URnano)." In December 2021, UR provided updates at the NSF Nanoscale Engineering Grantees Conference.[23] Information about the CNSNE program and training quantum and nanotechnology workforce at UR is located on a specific website.[29]

In Secs. 1.1 and 1.2, pertinent background information is provided about the URnano at the UR and MCC.

1.1 *University of Rochester Integrated Nanosystems Center*

The URnano was created in 2011 through funding from various U.S. government agencies with grants totaling four million dollars. NY Congresswoman L. Slaughter aided in obtaining these grants. This center is truly interdisciplinary, involving faculty and students from the departments of optics, chemistry, physics, biomedical, chemical, mechanical, and electrical engineering and the UR Medical Center.

Currently, UR has a centralized 2000-square-foot, class-1000, clean-room nanofabrication facility linked with nanometrology instruments. URnano houses scanning electron (with a focused ion beam), transmission electron, atomic force, and optical microscopes; deposition and etching equipment; and devices capable of lithography at nanoscales. The real-world applications pursued at URnano include new fuel cells, new dialysis techniques, and new devices for detecting ultra-small quantities of biological materials. The URnano website is provided.[30] URnano also offers training to faculty, students, and outside researchers to become certified in the use of these tools.

1.2 *Monroe Community College (Rochester, New York)*

MCC's Engineering Science/Physics program is a rigorous academic curriculum designed to facilitate transfer into B.S. Engineering/Physics programs.[31] To date, the graduates of this program have transferred to over 30 four-year institutions in NY State and nationally, and the MCC has 2 + 2 dual admission agreements with UR biomedical, chemical, electrical, and mechanical engineering, and optics. In addition to STEM majors, non-STEM liberal arts majors benefited from collaboration with UR. About ~44% of MCC students are minorities, and 58.7% are women (data of fall 2020).

2 UR Program on Certificate in Nanoscience and Nanoengineering for Undergraduate Students

Since 2015, 45 undergraduate students from different UR departments (39 students from optics, three students from biomedical engineering, one student from chemical engineering, one student from the IDE program, and one foreign university student) completed the program on CNSNE by May 2022. Thirty-seven of them completed the program after ending the NSF grant. Before describing the details of the program, we present the results of our study on career paths after graduation. We followed the career paths of the 36 awardees as of May 2021. Figure 1 shows that 50% of the 36 awardees selected nanoscience/nanotechnology careers [the right data bar (orange color)], 50% of all awardees stayed in academia (graduate students), ~41.7% selected business, one student selected the US Navy, one student went to the National Laboratory, and one student had not graduated yet. From the awardees in academia, 60% are working on projects connected with nanoscience/nanotechnology, and 40% of awardees in business are working in nanotechnological companies.

Here is an excerpt from one student's letter to one of the organizers of this program after receiving the Certificate:

> "After taking the nano-metrology courses, I have decided to pursue a Ph.D. in photonics and nanoscale optical devices. I loved what I learned, and I want to continue doing this."

Currently, this student is working on a PhD thesis in École Polytechnique Fédérale de Lausanne, with a recent journal publication devoted to nano-emitting heterostructures.

The CNSNE program has the following requirements for completion (see Fig. 2):

1. A required four credit-hour laboratory course OPT 254/PHY 371 "Nanometrology Laboratory." This new course started in the spring of 2015 and was specifically prepared for this program.
2. The students' selection should contain two other courses with nanotechnology content (refer to the list of possible courses shown in Fig. 2).
3. A full-semester research or design project related to nanoscience or nanotechnology.

The Institute of Optics administration, the Dean's office of the Hajim School of Engineering and Applied Sciences, and the UR Laboratory for Laser Energetics financially supported this

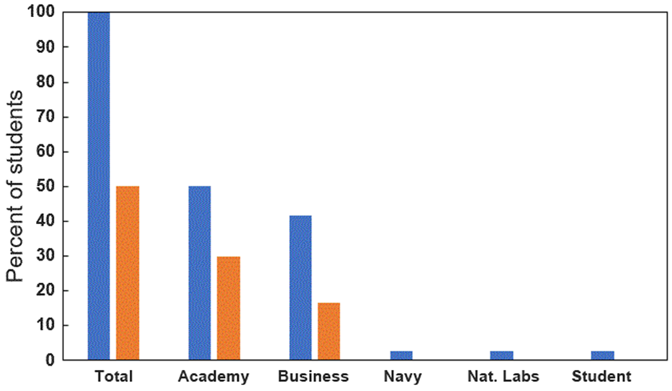


Fig. 1 Histogram showing career selection of the CNSNE awarded students (graduated by May 2021). The right bar (orange color) indicates a percent of students working in nanoscience/nanotechnology.

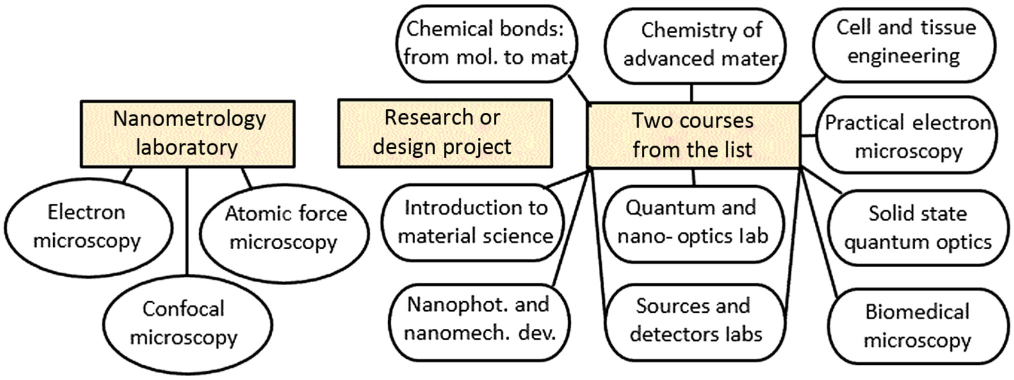


Fig. 2 Requirements for the program on the CNSNE.

program after ending the NSF grant (covering URnano fees, material costs, and adjunct instructors' salaries).

2.1 *Required Nanometrology Laboratory Class (OPT 254/PHY 371)*

The prerequisite class for the Certificate, Nanometrology Laboratory OPT 254/PHY 371, quickly became popular: the clean-room limited the maximum number of students from six to eight students. The instruction proceeds entirely through direct student-professor contact at all times. Three-course modules were taught by three instructors: (1) electron microscopy [scanning electron microscopy (SEM) and transmission electron microscopy (TEM)], McIntyre and Lukishova; (2) optical microscopy (wide-field and confocal fluorescence microscopy of single nanoemitters), nanoobjects/nanoengineering/quantum nanophotonics, Lukishova; and (3) atomic force microscopy (AFM) (started by Papernov and continued by Lukishova). The electron microscopy module consists of (1) six 1.5-h lectures and two 2 to 3-h labs (SEM and TEM), (2) the optical microscopy module includes five 1.5-h lectures and four 1.5-h labs, and (3) the AFM module contains two 1.5-h lectures and three 1.5-h labs.

Throughout the semester, students face three exams (in each module separately) and are required to submit individual lab reports for each module (during the pandemic years, students submitted an essay on electron microscopy instead of a lab report).

2.2 *Undergraduate Research and Design Projects*

The scientific direction of research topics for CNSNE depends on a specific department. UR is a top research university with professors leading cutting-edge projects; therefore, all students working toward their certificates are members of strong scientific groups. Design projects are created based on industry demands to solve technological problems of companies. For design projects, students working in groups of three to four have two advisors: a company representative (primary customer) and a UR faculty member. During the two-semester-project, students regularly communicate with primary customers, although the design projects are conducted at the UR. In addition, all design and senior thesis projects are discussed and graded in a separate class, OPT 320/321 Senior Design and Senior Thesis (Professor Knox), which includes more than CNSNE projects. After this class, students submit reports, deliver talks, and present posters on UR Senior Design Day. Table 1 gives the statistics of various stakeholders on the accomplished

Table 1 Stakeholders' statistics of completed research and design projects toward the CNSNE.

	Students	Professors	Companies
Research projects	37	40	—
Design projects	8	4	4

students' projects: 45 students (by May 2022); eight of them involved in the design, 37 in research projects, four companies, and 44 professors participated in advising students.

Some research projects advised by the UR professors are listed below:

1. development of a micro-arrayed, label-free biosensor using theoretical and experimental analysis of arrayed imaging reflectometry (Professor Miller's lab, Biomedical Engineering);
2. adaptive optics scanning light ophthalmoscope (nanoscale measurements) and how it can mitigate a disease called achromatopsia (Professor Merigan's lab, Center for Visual Science);
3. effects of nanoparticle-mediated siRNA delivery on human mesenchymal stem cell proliferation (Professor Benoit's lab, Biomedical Engineering);
4. radio frequency bias-assisted sputtering of silicon nitride thin films on silicon wafers (Professor Cardenas' lab, Optics);
5. silicon nitride waveguide polarization beam splitter based on a directional coupler (Professor Cardenas' lab, Optics);
6. polarization-sensitive atomically thin photodiode (Professor Vamivakas' lab, Optics);
7. quantum-enabled super-resolution microscopy (Professor Vamivakas Lab, Optics);
8. plasmonic nanoantenna array metasurfaces and colloidal nanoparticles for single-photon source applications (Professor Lukishova's lab, Optics); and
9. fabrication of optical microcavities (Professor Krauss' lab, Chemistry).

The stakeholders' companies in the students' design projects in CNSNE during these years were ASML [nanostructure antireflection coating (primary customer Dr. Kelkar, UR faculty advisor Professor Kruschwitz)], Harris Corp. [quantum key distribution (QKD) system design (primary customer Dr. Bucklew, UR faculty advisor Professor Lukishova)], Sydor Optics [nanoroughness scatterometer (primary customer Dr. Hobbs, faculty advisor Professor Knox)], Materion [design, fabrication, and testing of new types of mid-infrared wavelength optical filters using nanofabrication technology (primary customer Dr. Tatarek, faculty advisor Professor Vamivakas)].

2.3 *Elective Classes for the Certificate*

Among the elective classes for CNSNE, the most popular class is OPT 253 Quantum and Nano-Optics Laboratory.[25–28] This four-credit-hour class consists of four, 6- to 15-h laboratory experiments in quantum and nano-optics accompanied by lectures (see Ref. 28 of this issue in which this class is described in detail).

Because of the lack of space in the UR Curriculum for new classes, we modified a required class for optics and optical engineering majors, OPT 204 Sources and Detector Labs and Lab Lectures (Lukishova) by adding content on nanoscience, nanotechnology, and quantum nanophotonics. To satisfy Certificate program requirements, we included several new lab experiments: (1) with CdSe nanocrystal quantum dot (NQD) solutions as bright fluorescence sources and the calculation of their sizes from spectral measurements; (2) on measurements in a spectrophotometer, a reflectivity of liquid crystal photonic bandgap material showing photonic stop band; and (3) comparison of photon statistics from laser- and pseudothermal-light sources with a single-photon counting detector, which is widely used in nanoscience. In addition, in the two lecture workshops on lasers and nonclassical light sources, nanolasers and nanophotonic advances for antibunched photon sources and entangled and squeezed-photon sources are discussed. In Sec. 4, more details are described on the introduced mini-labs in nanophotonics (see also Ref. 28 of this issue for quantum optics experiments of this class).

2.4 *Undergraduate Students' Training Abroad During the Summer of 2016*

In the summer of 2016, nine UR optics undergraduate students took part in educational events in Moscow and St. Petersburg as part of the U.S.–Russian collaboration.[32–34] In Moscow, UR students were immersed for five days in cutting-edge research, technologies, and ideas on offers by

Russian, European, and U.S. scientists at the National Research Nuclear University MEPhI, International School on Optics and Laser Physics.[32,34] This experience also included tours of the MEPhI's Center on Nanotechnology with its clean-room facility for electronic components and nano-bioengineering laboratory. UR students also visited laboratories at the Lebedev Physical and General Physics Institutes of the Russian Academy of Sciences. These include facilities for the growth of diamond thin films and nanocrystals with single defect centers. The students also learned about cutting-edge research on NQDs. After one week in Moscow, students moved to St. Petersburg to participate in research projects on photonics, nanophotonics, and quantum information in the scientific laboratories of the International Institute of Photonics and Optical Information Technologies of ITMO University.[33,34] Two UR students had the opportunity to work directly with ITMO researchers on a QKD system. Before becoming quantum network operators, they learned about QKD through lectures and seminars. They performed a secure transfer of encrypted messages that contained the logos of both UR and ITMO between two ITMO buildings. After returning to Rochester, one of the students used the skills acquired in ITMO to set up an in-air orbital-angular-momentum QKD system between two UR buildings.[34] After the ITMO researches, each UR student delivered 15-min talks about their results and obtained the Certificates of this School on Photonics. These collaborations with Russian institutions were outlined in the magazine of the Optical Society OSA (Optica) Optics & Photonics News.[34] Some students' comments in their written interviews after their MEPhI visit were as follows:

1. …The lab tour I liked the most would be the tour of the laboratories of MEPhI scientific-educational center "Nanotechnologies." This was my first time attending a lab focusing on nanotechnology…
2. …Some of my favorite lectures were "Carbon Photonics" given by Professor Vitali I. Konov, "Organic Nanophotonics" given by Professor Alexei Vitukhnovsky, and "Laser printing of sensing plasmonic nanostructures" given by Dr. Yuri N. Kulchin. My favorite labs were laser and nanotechnologies centers' labs. I was fascinated by the two different lithography systems of laser lithography and electron beam lithography during my visit to the nanotechnology center in MEPhI…

Several students on this trip have already been awarded the UR CNSNE.

3 Training Local Monroe Community College Students at the UR

This section describes the joint efforts of UR and MCC in forging an exemplary model of collaboration between a research university with strong programs in science and technology and modern experimental facilities and a local two-year CC. One of the challenges faced by physics courses at CCs is the lack of student activities in modern experiments. A typical lab consists predominantly of replicating nearly 100-year-old experiments (photoelectric effect, hydrogen spectroscopy, etc.). The addition of state-of-the-art lab experience makes the course truly modern and provides a strong motivating force for future STEM studies. Experience at the URnano enhanced the laboratory portion of MCC's modern physics course, helping prepare MCC students for employment and making it easier for students enrolled in the $2 + 2$ transfer option. In addition, liberal arts students taking the MCC Physics for non-majors course enlivened a broader outreach.

The NSF NUE grant strengthened the UR–MCC collaboration that was supported earlier by two previous NSF (Course, Curriculum, and Laboratory Improvement programs) grants on quantum and nano-optics laboratories. From 2009 to 2013, 90 MCC students conducted two 3-h labs (single-photon interference, entangled photons, and Bell's inequalities) in two-week stints at the UR. During 2014–2015, another 52 MCC students with NSF NUE grant support conducted two labs at the UR described in this section. Professor P. D'Alessandris led the project for the MCC.

After completing the lab activities, the MCC students answered conceptual and quantitative questions about the experiments. The evaluation showed a high percentage of correct answers. The formative evaluation showed a positive MCC student response to this experience (refer to Sec. 5).

In the spring of 2014–2015, 52 MCC students were trained on a compact AFM, EasyScan 2, Nanosurf (Lukishova's laboratory). During a 3-h lab, they measured the topography of nanodiamonds.

In collaboration with the URnano (McIntyre), a 3-h lab on photolithography in a clean room was developed for MCC students. For example, several groups of MCC students prepared MCC and UR logos using photolithography and vacuum deposition of metal. Before the lab, students were trained in clean-room habits; therefore, they were approved in the facility admission quiz.

4 Mini-labs on Quantum Nanophotonics and Quantum Optics in Required UR Classes

This section describes examples of two mini-labs that were introduced in the required class OPT 204 "Sources and Detectors Labs and Lab Lectures" with ~40 students every spring semester (Lukishova). These 15-min labs can be easily introduced in any lab or lecture classes with demonstration experiments.

4.1 *Using Schrödinger Equation for Calculation of Sizes of Quantum Dots from Spectral Measurements*

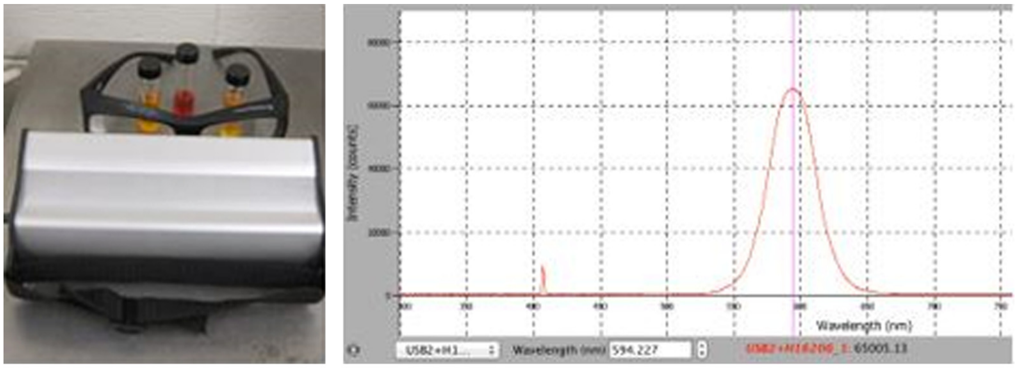
We adopted the idea of this mini-lab from the NanoSys Company, which offered some teaching materials for sale. The UR used NQDs with different fluorescence wavelengths from the UR Chemistry Department (Krauss).

The electronic and optical characteristics of NQDs are driven by their size and shape. For example, the bandgap of a semiconducting NQD is inversely proportional to its size. In fluorescence applications, the frequency of the emitted light shifts as the size of the quantum dot decreases.

For a semiconducting NQD to produce photoluminescence, an exciton (electron–hole pair) must be created. Photoluminescence results from the recombination of each pair. In this laboratory, excitons are created by the absorption of UV or blue light.

Solutions of colloidal NQDs in vials were excited by either the blue light of a laser pointer or a special UV source, as shown in Fig. 3(a). Students wore UV-protective goggles during the experiment. NQD fluorescence spectra were recorded using an Ocean Optics spectrometer [Fig. 3(b)].

To calculate the size of the NQDs from their fluorescence wavelength maximum, the NQDs were modeled as quantum particles in a box with discrete energy levels. From the solution of the time-independent Schrödinger equation for a particle in a box (infinite potential well) in a three-dimensional case, the dependence of energy E on the radius R is derived in the form



(a) (b)

Fig. 3 Nano-mini-lab #1 of the OPT 204 class sources and detectors. (a) Three solutions of NQDs and the UV source for excitation of NQD fluorescence. (b) A typical fluorescence spectrum of NQDs.

$$E = \frac{\hbar^2 \pi^2}{2m_e R^2} + \frac{\hbar^2 \pi^2}{2m_e R^2} + E_g. \tag{1}$$

Here, $E_g = 2.15 \times 10^{-19}$ J; $m_e = 7.29 \times 10^{-32}$ kg; $m_h = 5.47 \times 10^{-31}$ kg; E_g corresponds to the energy of the semiconductor bandgap; and m_e and m_h are the effective masses of the electrons and holes, respectively. From Eq. (1), the sizes of quantum dots from spectral measurements of their fluorescence can be calculated.

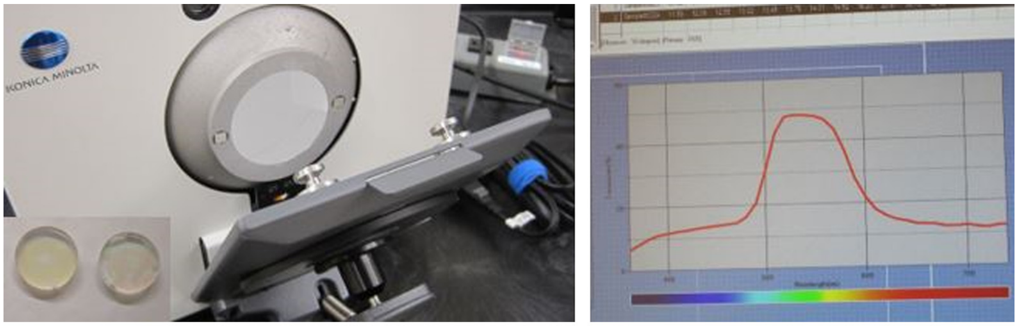
4.2 *Cholesteric Liquid Crystal Photonic Bandgap Structures and Their Application in Quantum Optics*

Planar-aligned cholesteric-liquid-crystal (CLC) structures exhibit one-dimensional (1D) photonic bandgaps (light at a certain frequency band is reflected) for the handedness of circularly polarized light, the electric field vector of which follows the rotation of the CLC molecular director. The stopband is centered at wavelength $\lambda_\text{o} = p(n_\text{e} + n_\text{o})/2$, where p is the pitch of the CLC spiral structure and n_e and n_o are the extraordinary and ordinary refractive indices of the molecules, respectively. The bandwidth of the transmission stopband is given by $\Delta\lambda = p(n_\text{e} - n_\text{o})$.

Planar alignment of CLC materials is among the simplest methods for the preparation of photonic bandgap structures. They can be prepared from a cholesteric oligomeric powder by heating the powder between two cover-glass slips on a hotplate (∼70°C to 100°C) to the liquid state. In the liquid state, the cholesteric material is sheared between substrates for planar alignment. Once cooled to a glassy (solid) state, the liquid crystal alignment remains preserved. Attractive colors appear from the initially uncolored powder oligomers, indicating photonic bandgap (selective reflection) structures. Using a monomeric (liquid form at room temperature) CLC, the preparation of a photonic bandgap requires only 1 min. A drop of a monomeric, cholesteric liquid crystal should be placed between two glass slips; after shearing, a uniform color from an initial milky liquid crystal appears.

This lab was very popular among middle and high school students and their parents during the Institute of Optics Family Day. OPT 204 students measured the reflectivity of the prepared CLC photonic bandgap structures during their lab on spectroscopy of different light sources and radiometry using a Konica Minolta CM-3700 A spectrophotometer with an integrating sphere [Fig. 4(a)]. The inset (left) shows samples of the photonic bandgap CLC structures. The spectral dependence of the reflectivity of a sample is shown in Fig. 4(b) (spectrophotometer user interface).

Liquid crystal examples were used in an OPT 204 lecture workshop on nonclassical light sources.[35,36] Entangled sources, indistinguishable photons, and a Hong-Ou-Mandel interferometer[37] were described, and examples of experiments with 1D photonic bandgap CLC structures in a Hong-Ou-Mandel interferometer at the Institute of Optics were discussed.[38–41] In addition, students learned about single-photon sources based on single-emitter fluorescence



(a)

(b)

Fig. 4 Nano-mini-lab #2 of the OPT 204 class Sources and Detectors. (a) Input port of an integrating sphere inside a spectrophotometer. CLC samples between two glass substrates are shown in the insert. (b) A selective reflection curve (spectral dependence of reflectivity) of the photonic bandgap CLC structure was obtained on this spectrophotometer.

in planar-aligned liquid crystal hosts and other micro- and nanostructures for tailoring the properties of the emitted single photons.[35,36]

5 Pedagogical Research on Students' Learning

How do we know whether students are learning? What did they learn? How well did they learn? What are the outcomes of their learning? To answer these questions, we used two evaluation-methodology approaches:

1. a qualitative approach (individual and group interviews, focus group technique, observations, end-of-course evaluations, student surveys, content analysis of student reports) and
2. a quantitative approach (grades and questionnaires).

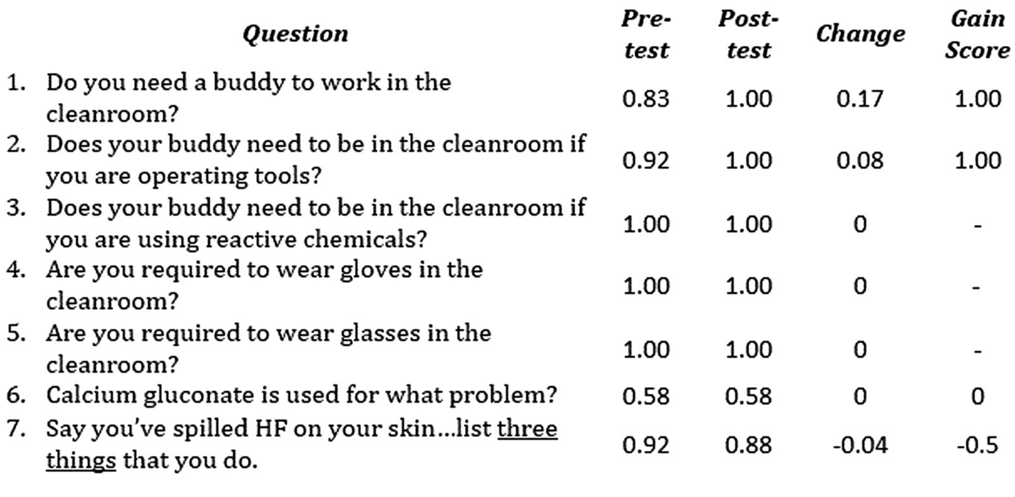
For pedagogical research, we collaborated with the external evaluator, J. Zawicki (State College at Buffalo). This section provides examples of evaluating the knowledge of student groups with different levels of experience and demonstrates progress in educational outcomes for nearly all students.

5.1 *Students of Monroe Community College*

The following is one example from the spring of 2015 involving MCC students. They completed both pre- and post-experience Cleanroom Access quizes. The pre-assessment was delivered prior to formal instruction and lab experience at the UR, although during lectures at MCC, all questions were discussed; post-assessment measures were administered following the labs. The questions of this quiz are shown in Fig. 5, which also includes the pre- and post-test item scores, pre-test/post-test changes, and normalized gain scores. Gain scores were calculated as follows:

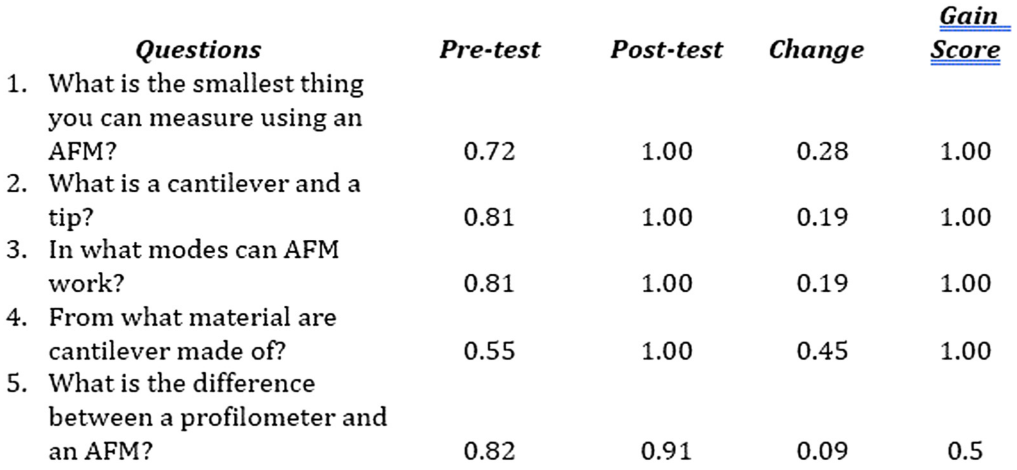
$$\text{Gain} = \frac{(\text{Post} - \text{Pre})}{(1.00 - \text{Pre})}. \tag{2}$$

Students were generally able to answer the five questions, addressing general working procedures, at the mastery level (>83%) even on the pre-test. Students were able to respond to the need for gloves and glasses, as well as for a buddy. The two questions addressing the use of calcium gluconate and the proper response to skin contact with hydrofluoric acid were the most difficult for students. Only 58% of students correctly answered questions about calcium gluconate in a pre-test and post-test quiz. Selecting three correct options of what to do in a case of skin contact with hydrofluoric acid from six options, most students answered unsatisfactorily,



Question	*Pre-test*	*Post-test*	*Change*	*Gain Score*
1. Do you need a buddy to work in the cleanroom?	0.83	1.00	0.17	1.00
2. Does your buddy need to be in the cleanroom if you are operating tools?	0.92	1.00	0.08	1.00
3. Does your buddy need to be in the cleanroom if you are using reactive chemicals?	1.00	1.00	0	-
4. Are you required to wear gloves in the cleanroom?	1.00	1.00	0	-
5. Are you required to wear glasses in the cleanroom?	1.00	1.00	0	-
6. Calcium gluconate is used for what problem?	0.58	0.58	0	0
7. Say you've spilled HF on your skin…list <u>three things</u> that you do.	0.92	0.88	-0.04	-0.5

Fig. 5 Evaluation of knowledge of MCC students (provided by Professor Zawicki): A Cleanroom Access quiz (maximum pre-test and post-test value equal to 1 corresponds to 100% of students correctly answering this particular question).



Questions	Pre-test	Post-test	Change	Gain Score
1. What is the smallest thing you can measure using an AFM?	0.72	1.00	0.28	1.00
2. What is a cantilever and a tip?	0.81	1.00	0.19	1.00
3. In what modes can AFM work?	0.81	1.00	0.19	1.00
4. From what material are cantilever made of?	0.55	1.00	0.45	1.00
5. What is the difference between a profilometer and an AFM?	0.82	0.91	0.09	0.5

Fig. 6 Evaluation of knowledge of OPT 253 students (provided by Professor Zawicki): An AFM quiz (maximum pre-test and post-test value equal to 1 corresponds to 100% of students correctly answering this particular question). Later an AFM lab was transferred to the OPT 254 class.

even with negative gain scores. The instructors should find better ways to explain to students these important safety issues in a photolithography laboratory. However, most of the data provided evidence that MCC students were benefiting from the laboratory experiences at the UR.

5.2 *Technical Elective OPT 253 Class Quantum and Nano-Optics Laboratory (Sophomores-Seniors)*

UR students of this advanced lab class (Sec. 2.3) were also evaluated with the help of Professor Zawicki. OPT 253 was taught as a technical elective class with a maximum of twenty students in the class. In fall 2015, eleven students completed both pre- and post-assessments on an AFM quiz. The questions and the assessment data (item difficulties both pre- and post-experience, the change in item difficulties, and the normalized item gain scores) are shown in Fig. 6.

All five questions, which addressed the operation and significance of AFM, were initially tested and ranged from 0.55 to 0.82 difficulty level. The post-test scores for these items ranged from 0.91 to 1. Gain scores ranged from 0.5 (what is the difference between a profilometer and an AFM?) to 1 (all other questions). The data provides substantial evidence of student learning.

Success in bringing advanced quantum photonics and nano-photonics concepts to undergraduate students was evaluated by a written survey of these eleven undergraduate students with the following questions:

1. Did the labs help you to understand some concepts of quantum physics?
2. Did the labs help you understand some concepts of nanooptics?
3. Did the lab increase your interest in quantum mechanics, nanotechnology, or optics?
4. Was it helpful to include an AFM lab for topography measurements of nanoemitters that you used for fluorescence excitation?

All students answered "yes" to these questions. One typical example of students' answers follows:

> "After completing these labs, I have gained a better appreciation for the field of quantum mechanics and nanotechnology. Going forward, I would like to continue taking courses in this field to expand my knowledge even further."

5.3 *OPT 254/PHY 371 Nanometrology Laboratory Class, Required for CNSNE (Sophomores-Seniors)*

The survey was conducted in the spring of 2022 with five highly motivated students after finishing this advanced Nanometrology Laboratory class (see Sec. 2.1). Practically all students taking this class are working toward the CNSNE, and their grades, both for lab reports and quizzes, sometimes exceed the maximum 100 points for each assignment. We conducted a study on the self-efficacy of these students. According to Refs. 42 and 43 and a definition of Ref. 44, self-efficacy is a set of beliefs about an individual's own capacity that impacts an individual's choices and the effort that they put forth to complete a task and accomplish goals. For this study, two questions were included in the survey:

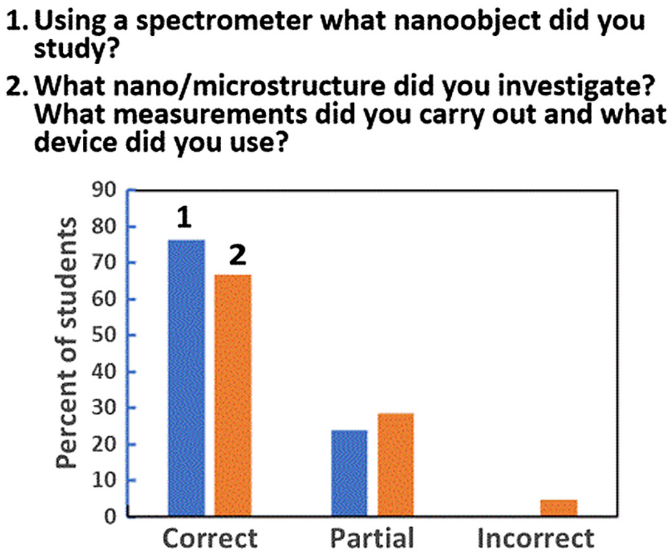
1. Will you be able to work in a company with applications in nanotechnology or select your career in an academy or government laboratory in this field?
2. Are you confident that you will succeed in working in nanotechnology/nanoscience applications?

All of the students answered yes to both questions. For instance, one student answered that she is more confident now after taking this class.

Another survey asked about the work environment in nanotechnology and what they would do on a daily basis if they chose this career path. All students preferred a lab environment over modeling, for instance "making samples, preparing experiments, testing new methods." Answering a multiple-choice questionnaire about future careers after college, all students selected "science/engineering/medicine." One student also added education/teaching, one added patent law, but nobody selected business.

5.4 *OPT 204 Sources and Detectors Labs and Lecture Class (Juniors-Seniors) with Nano-mini-labs*

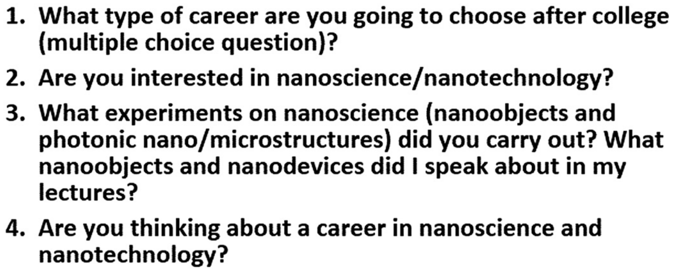
The 15-mins "nano-mini-labs" introduced to OPT 204 are described in Sec. 4. In spring 2022, we conducted two pedagogical research surveys in this class: (1) on students' understanding of nanoobjects and nanostructures and (2) on students' attitudes toward working in nanotechnology, including their self-efficacy. Figure 7 shows two questions and a histogram from a final "Big" quiz of the percent of 42 students answering correctly these questions on nanoobjects and nanostructures that they investigated in their lab on spectroscopy of different light sources and materials. Almost all students answered either correctly (76.2/66.67%) or partially (23.8/28.57%) to these questions. Partially means that these students did not describe experiments with nanoobjects/nanostructures although they identified both NQDs and CLCs photonic bandgap



1. Using a spectrometer what nanoobject did you study?

2. What nano/microstructure did you investigate? What measurements did you carry out and what device did you use?

Fig. 7 Evaluation of knowledge of OPT 204 students from the final "Big" quiz. TOP: two questions on nanotechnology; BOTTOM: a histogram of the percent of students answering correctly, partially, and incorrectly these two questions.



1. **What type of career are you going to choose after college (multiple choice question)?**
2. **Are you interested in nanoscience/nanotechnology?**
3. **What experiments on nanoscience (nanoobjects and photonic nano/microstructures) did you carry out? What nanoobjects and nanodevices did I speak about in my lectures?**
4. **Are you thinking about a career in nanoscience and nanotechnology?**

Fig. 8 Survey # 1 of OPT 204 students: a list of questions (Q) (see also Fig. 9).

structures. Only two students (4.76%) were unable to identify cholesteric liquid crystal photonic bandgap nano/microstructures characterized in a spectrophotometer.

Two surveys were conducted at the end of the semester on students' attitudes toward nanoscience and nanotechnology. The questions of the first survey are listed in Fig. 8. Figure 9 shows four histograms of a percent from 34 students answering these questions. Although 87.9% of students are interested in nanotechnology, only 33% of them are thinking about a career in this field. Question #3 in Figs. 8 and 9 was practically the same as the two questions together in Fig. 7, but the survey of Fig. 8 was done shortly after the last lab ended and students answered this question without preparation, in contrast with the Fig. 7 questions of a graded "Big" quiz. Interestingly, almost the same percentage of students (72.7%) answered correctly question #3 in Fig. 8 as in the "Big" quiz, but 27.3% did not know the answer at all. At least partially, these students answered questions after preparing for the "Big" quiz (Fig. 7).

The second survey, with 23 students, was devoted to self-efficacy and students' expectations of the work environment in the field of nanotechnology. The results of this class with only two 15-mins nano-mini-labs are different from those of the Nanometrology Laboratory class. Two questions from this survey are shown in Fig. 10. From this survey, only 52.2% of students are confident that they will succeed. Some of them suggested further learning in this field. 39.1% are not confident, and 8.7% suggested that to be confident they will need to take more classes on

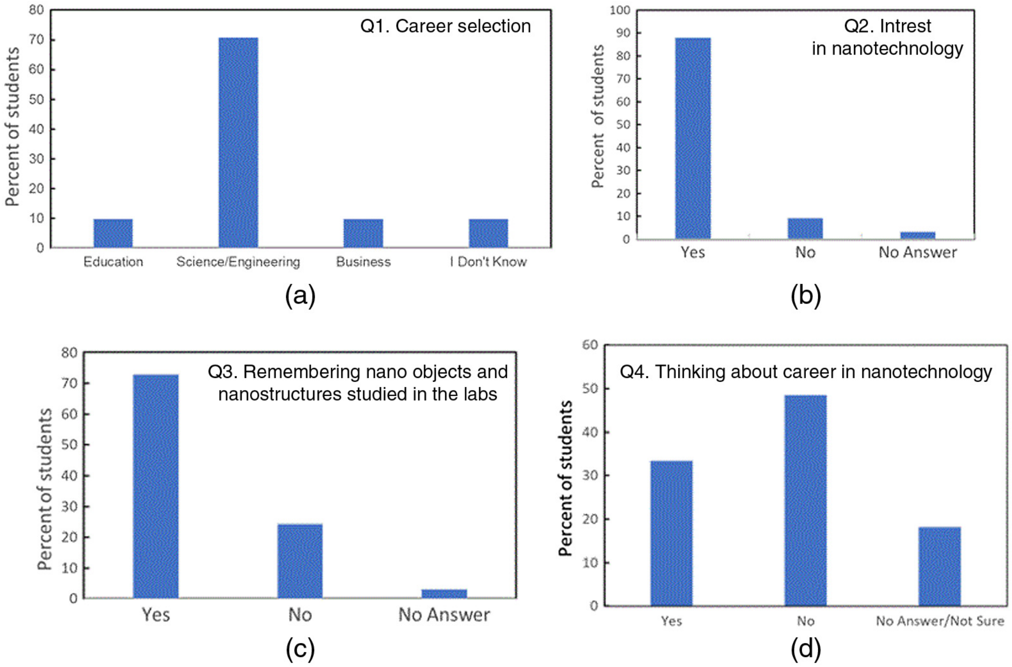


Fig. 9 Survey # 1 of OPT 204 students. Four histograms of percent of students answering each of four questions of Fig. 8: (a) Q1. Selection of a future career; (b) Q2. Interest in nanotechnology; (c) Q3. Remembering nanoobjects and nanodevices from the labs; and (d) Q4. Thinking about a career in nanoscience/nanotechnology.

1. **With your experience are you confident that you will be able to work in a company with applications in nanotechnology or select your career in academy or government laboratory in this field? Are you confident that you will succeed working in nanotechnology/nanoscience applications?**
2. **If you choose a career in nanotechnology, what will be your work environment, what will you do on daily basis? Whether it will be a laboratory work or modeling?**

Fig. 10 Survey #2 of OPT 204 students: a list of questions. The results of this survey are discussed in the text of this paper.

nanotechnology. Answering the second question about the work environment, 30.4% of students prefer a lab environment, 2% modeling, 2% both laboratory and modeling, and 52.2% of them are not sure what their work environment will be. The results of the Fig. 10 survey show the necessity for including information about real-world industrial and research environments in the field of nanotechnology within this class format on optical sources and detectors. Yet, the format of this class with four labs and seven lectures and its assignments is accepted by the students. For instance, here is an excerpt from an e-mail of a recent student:

> "The format of the labs and lab reports has greatly increased the amount I feel like I have learned during this course."

6 Hybrid Teaching of Advanced Labs and Their Lecture Classes during a Pandemic

The 2020-2021 COVID-19 pandemic has caused enormous damage to the economy.[45,46] Education with the concentration of students in universities and schools has become one of the most vulnerable areas,[47] especially in connection with the lockdown and the sudden transition to distance learning occurring only within a few days. Multiple universities' accommodations to this critical situation are described in multiple recent publications; see, for instance, Refs. 44 and 48–57. Considering a well-organized website, many experts' ideas and resources of research-based pedagogical principles for teaching labs online during lockdown are discussed.[48]

The UR program on CNSNE that required advanced, upper-division lab classes faced challenges. During a week before a lockdown in the middle of March 2020, when the semester was halfway in progress and the students had performed half of the lab experiments, four lab videos were prepared and edited by TAs, with a professor carrying out the rest of the semester's lab measurements and providing students with all data files. In fall 2020, a lockdown was over, but a social distance of 1.5 m became a mandatory requirement; therefore, in the small lab rooms, only a TA and one student from a group were permitted to work simultaneously. In addition, some students did not come back from their native countries, enrolling in all classes remotely. Hybrid teaching of the three following advanced labs and lecture classes both through the Zoom conference managing software and in-person continued until the summer of 2021:

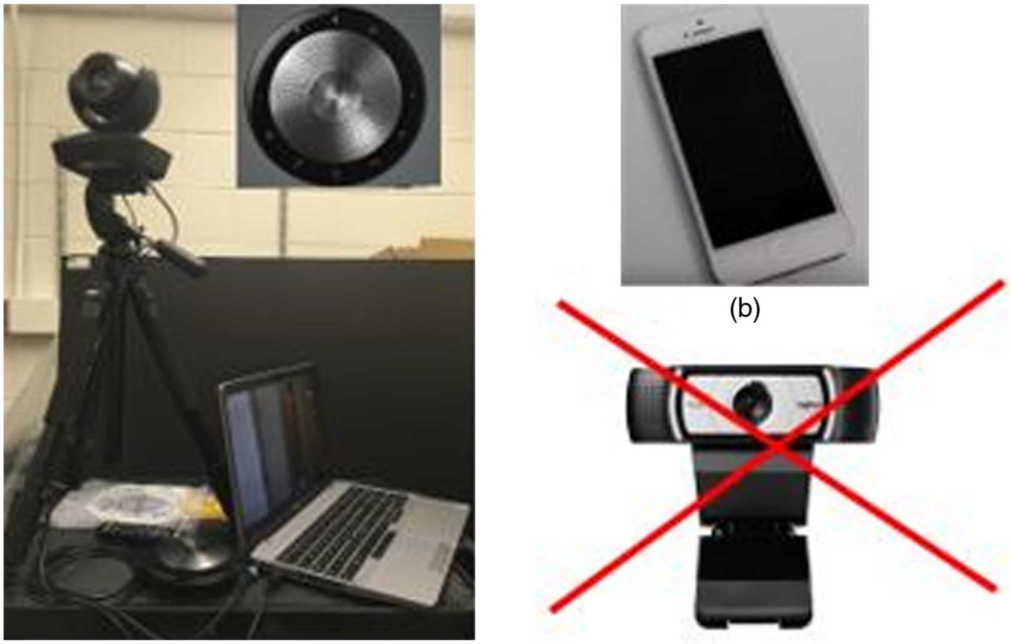
1. OPT 204 Sources and Detectors Labs (11 totally remote students, and 22 "in person" in the spring of 2021) comprised the following experiments: spectral measurements of several optical sources, spectrophotometry, mode-locked Er-doped fiber laser; fiber stripping, cleaving, and fusion splicing; photon statistics measurements of a laser and a pseudothermal source; and single-photon interference with a CMOS camera.
2. OPT 254/PHY 371 Nanometrology Laboratory (1 totally remote student, five "in person" in the spring of 2021) contained three modules on AFM, SEM/TEM, and single-nanoemitter confocal fluorescence microscopy and spectroscopy.
3. Undergraduate OPT 253 and graduate OPT 453/PHY 434 Quantum and Nano-Optics Laboratory (11 students "in person" in the fall of 2020) contained the following experiments: entanglement and Bell's inequalities; single-photon interference with an EM-CCD; and single (antibunched) photon source (confocal fluorescence microscopy and spectroscopy of single nanoemitters and a Hanbury Brown and Twiss correlator).

The main experiments of all three lab courses are devoted to quantum nanophotonics and photon quantum mechanics. Photon counting instrumentation is widely used in these courses, but single-photon counting detectors require darkness in a classroom. This section describes our experience in teaching advanced, upper-division, and research level labs in real time via Zoom, see also Ref. 57 with similar experience at Colgate University. According to Ref. 49, during the pandemic, some universities delayed challenging, upper-division lab courses, requiring that students get their "hands on the equipment." The novelty of our approach is in reducing the limitations in acquiring "hands on the equipment" and "hands-on" experience in remote lab classes using high-quality, affordable recording tools controlled by Zoom and our teaching methods. These teaching methods, which allow for keeping the level of on-site quality, as well as outcomes with advantages in students' performance with available recorded materials, students' involvement in the remote lab sessions, and lessons learned, are discussed in this section.

6.1 *Hybrid Teaching in Small Lab Rooms: High-Quality Zoom Recording of Upper-Division Labs*

The requirement of a 1.5-m social distance permitted only one student and a TA to be in one laboratory room simultaneously, even with personal protective equipment. Recent research showed that, upon exhalation, a coronavirus may survive in the air in aerosols[58,59] for up to 9 h.[58] This is why in fall 2021 and the spring of 2022, an air purifier (Blue Pure 211*) with a HEPA particle filter for ~500 sq. ft room was used during all advanced lab courses. Three "in-person" scheduled lab attendants worked 1/3 of each lab time (usually 3 h) in the lab and 2/3 of each lab time remotely through Zoom.

The quality of video recording was very important, especially because one-half of two lab classes and the entire third lab class required darkness during measurements. The dynamic range of the Marshall Electronics CV610-UB video camera with remote control [see Fig. 11(a)] permitted us to show all details of the lab experiments in darkness to remote students and to record videos of each lab session. The Jabra Speak 710 microphone is shown in an insert of this figure. Remote control of the Marshall camera permits not only showing the whole setup but also


(a)

(b)

(c)

Fig. 11 (a) The Marshall Electronics CV610-UB video camera with remote control with a Jabra Speak 710 microphone; (b) an iPhone is widely used to record small details of the experiments; and (c) a webcam video camera does not provide the required quality of Zoom videos of lab experiments, especially right after turning off the lights in the room.

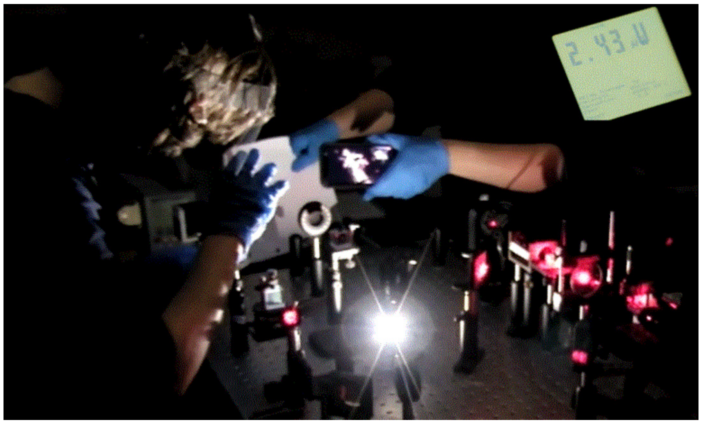


Fig. 12 (From a recorded Zoom video by a Marshall video camera). A single-photon interference lab experiment recorded in the darkness. An inset shows the power meter readings immediately after the lights were turned off.

focusing on its particular component. In many cases, an iPhone was used for Zoom recording even smaller details [Fig. 11(b)]. Usual webcam cameras [Fig. 11(c)] have no required quality of video and a necessary dynamic range for Zoom video recording, especially in darkness. Figure 12 from a recorded Zoom video by the Marshall camera shows all details of single-photon interference experiments in spite of darkness in a laboratory.

All lab sessions were recorded, as was communication with remote students during the labs, and all videos were uploaded to Blackboard through Panopto. Blackboard is a virtual hub for student services that provides access to online course materials, grades, organizations, accounts, and many other academic and campus services. Panopto is a software that provides lecture recording, screencasting, video streaming, and video content management. All pictures of the experiments in this section are screenshots from Panopto of recorded Zoom movies uploaded to Panopto.

An option for "screen sharing" in the Zoom software facilitates participating in the experiments of remote students. See, for instance, Fig. 13 from Panopto of AFM imaging of the topography of a plasmonic nanoantenna array metasurface. In addition, a Zoom insert at the right top corner of this screenshot shows (from top to bottom) a compact AFM with a controller, a student in the lab (with a mask and a protective plastic shield), and two other students taking the lab remotely and waiting for their time in the lab.

The most challenging labs during the pandemic years were project-oriented labs with the purpose of students' immersion in discovery-oriented environments, in which the results of their work are initially unknown to both the students and the instructor but are of interest to

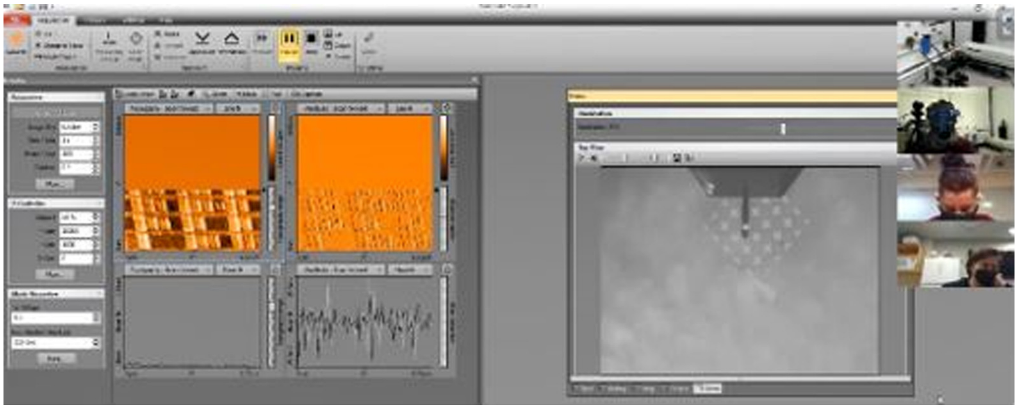


Fig. 13 (From a recorded Zoom video with screen sharing). A user interface of an AFM Easyscan 2 (Nanosurf). An insert from a Zoom software shows an AFM, a student in the lab, and two remote students.

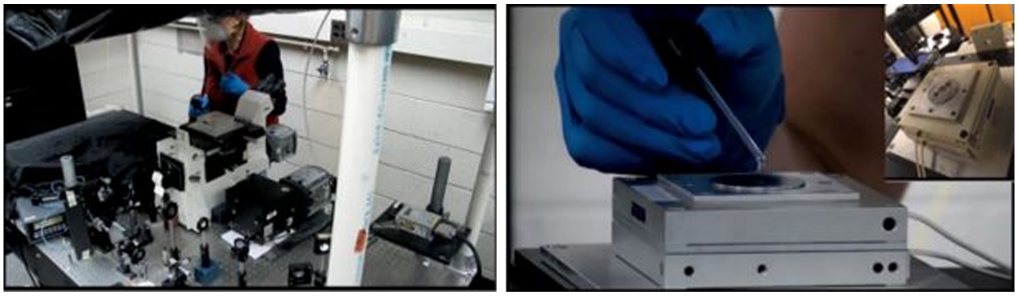

(a) (b)

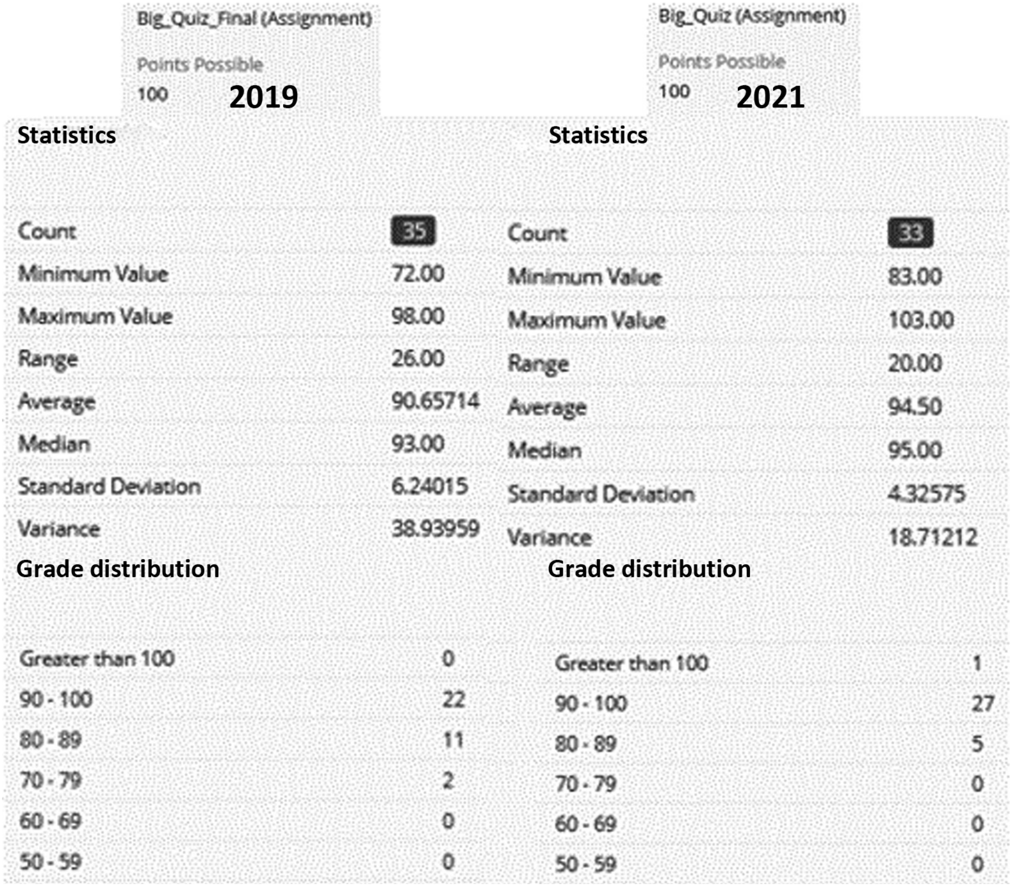
Fig. 14 (From a recorded Zoom video by a Marshall video camera). Remote teaching of the research-oriented lab at the single (antibunched) photon generation and characterization unit. (a) A confocal fluorescence microscope for single-emitter fluorescence and a Hanbury Brown and Twiss correlator (taught by Lukishova). (b) Dropping an index-matching oil on a microscope objective. An insert from a Zoom video frame recorded by an iPhone shows the same sample table with a different view.

stakeholders in the broad scientific community[52,53] (labs of the OPT253/OPT 453/PHY434 and OPT 254 classes in the author's research laboratory with complex equipment). These 1.5 to 3 h/week "open-end"[52,53] projects last 4 to 5 weeks for each of several groups of three students, with the discussion of results in weekly lectures with all students in the class. Switching to hybrid teaching, in the pandemic, in the labs with the single (antibunched) photon source generation and characterization unit (see Fig. 14), five different monitors were used simultaneously in Zoom in a lab room with switching monitors using a "pin" option, for Zoom video online in real time with the recording. A host computer for Zoom, an iPhone, and a Marshall camera, as well as two lab computers connected with devices for sharing their screens with data (single-emitter fluorescence imaging/antibunching correlation measurements) and an EM-CCD camera for spectral measurements, were used during this lab. Owing to the Marshall camera dynamic focus, either the whole setup [Fig. 14(a)] or an oil drop on the microscope objective can be viewed in close-up [Fig. 14(b)]. The insert shows a recording by an iPhone at some position not accessible by the Marshall camera. Demonstrating research experiments in real time while directing the regime of the video production, wearing a respirator, and constantly speaking with the students through the Jabra microphone to increase students' engagement constitutes a less than the optimal form of professional growth. However, real-time and instant-feedback communication with remote students through Zoom is a reward to be cherished. One of the students took this research-level lab while residing in Vietnam, and another logged in from Pakistan; however, all of these students were immersed in a real research environment, learning what it means to do research with unknown results but with the possibility of discovery.

Some advanced labs were held at the URnano facility's TEM and SEM. URnano computers cannot be used for Zoom—not all screens can be shared. In this case, we used either the Marshall camera or an iPhone to record the URnano computer monitors during a scheduled class time.

6.2 *Evaluation of Students' Knowledge via Zoom and Lessons Learned*

One of the main problems in online instruction is how to administer exams while suppressing cheating, minimizing students' anxiety, and preserving their privacy.[49] In the Physics Today paper,[49] several examples of remote exam practice are outlined. In the three lab classes mentioned in the preface to the current Sec. 6, in the pre-pandemic years, every group of three students scheduled for their lab was required to answer individually several questions of a graded 10-min-written quiz in the presence of a TA as their proctor. In the middle and at the end of a semester, one to three other "Big" written quizzes with up to 25 questions were included with proctoring. Trying to find the best solution for the remote exams in a pandemic, we declined as unpractical any proctoring software described in Ref. 49 and selected a practice similar to that of Carl Wieman of Stanford University:[49] open book route. To understand if the students really learned the course, additional, graded 15 to 20 min oral "Big" quizzes with the students divided into several groups between TAs and a professor were scheduled (at a definite time for each



Big_Quiz_Final (Assignment)
Points Possible
100 **2019**

Statistics

Count	35
Minimum Value	72.00
Maximum Value	98.00
Range	26.00
Average	90.65714
Median	93.00
Standard Deviation	6.24015
Variance	38.93959

Grade distribution

Greater than 100	0
90 - 100	22
80 - 89	11
70 - 79	2
60 - 69	0
50 - 59	0

Big_Quiz (Assignment)
Points Possible
100 **2021**

Statistics

Count	33
Minimum Value	83.00
Maximum Value	103.00
Range	20.00
Average	94.50
Median	95.00
Standard Deviation	4.32575
Variance	18.71212

Grade distribution

Greater than 100	1
90 - 100	27
80 - 89	5
70 - 79	0
60 - 69	0
50 - 59	0

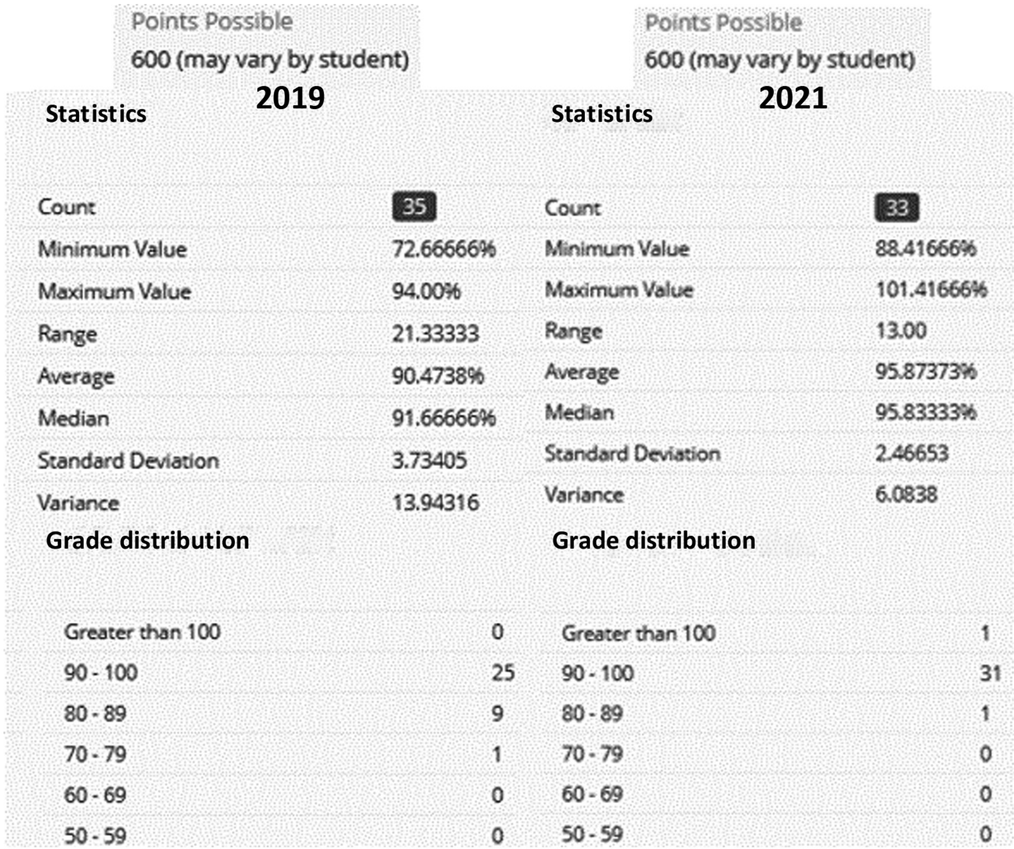
(a) (b)

Fig. 15 (From Blackboard). Statistics of the OPT 204 class grades for a final "Big" quiz (maximum 100 points). (a) For a pre-pandemic year (2019) and (b) for a pandemic year (2021).

student) after their written "Big" quiz. The short quizzes before each lab also became "open book," and the students were required to upload their answers before the labs, but during the online lab sessions, TAs asked each student the quiz questions, and in the case of failing to answer, the grade for the written quiz was reduced. A very important lesson that we learned from this successful practice for avoiding cheating is that a combination of both written and oral exams works, and we continue to use this practice since all classes at the UR returned to the "all students in-person" requirement. We only replaced open book written exams with proctoring. Cheating becomes evident during the oral exams, even with fewer questions and a shorter time. Surprisingly, our practice shows an interesting observation: sometimes students demonstrate much better knowledge in their oral exams than in open book written exams.

Learning outcomes from our experience in pandemic with advanced, upper-division lab classes demonstrated that a hybrid format of recording real-time lab sessions and communicating with students via Zoom has advantages in students' assignment preparation. Grading of all lab reports and quizzes showed higher grades of assignments and final grades in comparison with the pre-pandemic years when Zoom recorded videos of lectures and lab sessions had not yet been used. For instance, we compared an average "Big" quiz grade in 2019 (90.66 points) and 2021 (94.5 points) (see Fig. 15) and average final grades in 2019 (90.47%) and 2021 (95.9%) (see Fig. 16) for OPT 204 with 35 students in 2019 and 33 students in 2021. The impact of the online videos on students' learning was thoroughly investigated in Ref. 60:

> "Compared with the students who saw the live demos, the students who watched the online videos learned more, and their self-reported enjoyment was just as high… videos could provide students with an equally effective learning experience when live demos are unavailable. Even when live demonstrations are available, it may be beneficial to supplement them with online presentations."



Points Possible
600 (may vary by student)

Statistics 2019

Count	35
Minimum Value	72.66666%
Maximum Value	94.00%
Range	21.33333
Average	90.4738%
Median	91.66666%
Standard Deviation	3.73405
Variance	13.94316

Grade distribution

Greater than 100	0
90 - 100	25
80 - 89	9
70 - 79	1
60 - 69	0
50 - 59	0

(a)

Points Possible
600 (may vary by student)

Statistics 2021

Count	33
Minimum Value	88.41666%
Maximum Value	101.41666%
Range	13.00
Average	95.87373%
Median	95.83333%
Standard Deviation	2.46653
Variance	6.0838

Grade distribution

Greater than 100	1
90 - 100	31
80 - 89	1
70 - 79	0
60 - 69	0
50 - 59	0

(b)

Fig. 16 (From Blackboard). Statistics of the OPT 204 class final grades (maximum 600 points, 100%). (a) For a pre-pandemic year (2019) and (b) for a pandemic year (2021).

We would like to add that, despite a lack of "hands-on" experience for remote students, for instance, in fusion splicing of the optical fibers, showing online struggles of "in-person" students with detailed, high-quality real-time videos (see Fig. 17 from a video screenshot) permitted them to learn more about this procedure in comparison with pre-pandemic years students of this class. In addition, following the needs of remote students, a separate educational video was prepared in the optics teaching labs, so remote students' learning needs forced us to significantly improve course materials.

Fig. 17 (From a recorded Zoom video by an iPhone camera.) Fusion splicing of the optical fibers during a remote lab. A Marshall camera positioned on a cart in a small room did not permit recording of this delicate procedure in detail.

Another lesson learned was the importance of socialization for remote students, even through Zoom: students with up to a 13-h time shift voluntarily attended the labs at a local night time and refused any offer to watch the recorded lab sessions without real-time feedback and communication with other students.

7 Conclusion

The primary goal of the described project supported by the NSF educational grant (2014–2017) was to implement the multidisciplinary nanotechnology/nanoscience undergraduate educational program at the UR with the involvement of the local MCC. The main outcomes of this project based on the Institute of Optics and the URNano facilities are as follows:

1. creating a coherent educational program at the UR culminating in the CNSNE being issued to 45 students
2. creating an exemplary model of collaboration in nanotechnology between a university with state-of-the-art, expensive experimental facilities and a nearby, two-year CC, with 52 MCC students who carried out two 3-hour labs on nanotechnology at the UR
3. developing universally accessible "hands-on" experiments ("mini-labs") on nanophotonics, learning materials, and pedagogical methods that were introduced in some Institute of Optics classes from freshman to senior levels. The two inexpensive "mini-labs" described in this paper can be adopted in small colleges
4. adapting to the pandemic by developing remote teaching methods in real time through Zoom for laboratory classes, as well as a written open-book plus short oral exam strategy to avoid cheating. Our remote teaching methods with high-quality recording tools successfully worked in the upper-division research-level open-ended laboratory projects on the complex equipment with measurements requiring darkness in a laboratory.

Assessment results for classes with different levels of students' knowledge demonstrated progress in educational outcomes for nearly all students. Success in bringing advanced quantum photonics and nanophotonics concepts to undergraduate students through the labs was also confirmed by written surveys: the labs helped students to understand some concepts of quantum physics and nanooptics and increased their interest in quantum mechanics, nanotechnology, and optics.

The main lessons learned include confirmation that our strategy in teaching nanotechnology by students' laboratory experience (learning by doing)[61] is working, although the results of surveys showed that students need more interactions with real-world nanotechnology. Some of our CNSNE students directly communicated with companies-customers in their design projects, but the majority of our students did not have this valuable experience. Another lesson for us is the relatively low percent (52.2%) of students in regular classes with self-efficacy toward their success in the field of nanotechnology. The main lesson from remote lab teaching in a pandemic is surprising: a significant increase in students' learning outcomes in comparison with pre-pandemic years despite students' preference for in-person classes. It shows that recorded course materials, which students can watch several times individually, enhance their learning. Returning to in-person teaching, we should not forget our valuable experience of distance learning.

Most of these results have been presented at the International Conferences on Training and Education in Optics and Photonics (2017 and 2021).[21,22,26,27]

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References

1. L.E. Friedersdorf, "Developing the workforce of the future: how the national nanotechnology initiative has supported nanoscale science and engineering education in the United States," *IEEE Nanotechnol. Mag.* **14**(4), 13–20 (2020).
2. M. Roco, "The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years," *J. Nanopart. Res.* **13**, 427–445 (2011).
3. J. B. Spicer, "The landscape of nanotechnology education," *IEEE Nanotechnol. Mag.* **14**(4), 12 (2020).
4. R. P. Tan et al., "Practical works on nanotechnology: middle school to undergraduate students," *IEEE Nanotechnol. Mag.* **14**(4), 21–28 (2020).
5. R. Kamali-Sarvestani et al., "Virtual reality to improve nanotechnology education: development methods and example applications," *IEEE Nanotechnol. Mag.* **14**(4), 29–38 (2020).
6. M. G. Jones et al., "Nanotechnology and nanoscale science: educational challenges," *Int. J. Sci. Educ.* **35** (9), 1490–1512 (2013).
7. J. A. Jackman et al., "Nanotechnology education for the global world: training the leaders of tomorrow," *ACS Nano* **10**(6), 5595–5599 (2016).
8. A. Greenberg, "Integrating nanoscience into the classroom: perspectives on nanoscience education projects," *ACS Nano* **3**(4), 762–769 (2009).
9. J. Bauer, "Teaching nanotechnology through research proposals," *J. Chem. Educ.* **98**(7), 2347–2355 (2021).
10. E. J. Park, "Nanotechnology course designed for non-science majors to promote critical thinking and integrative learning skills," *J. Chem. Educ.* **96**(6), 1278–1282 (2019).
11. S. Mekid, "Dedicated instruments for nano-engineering education: Integrated nano-manipulation and micro-nanomachining," *Int. J. Mech. Eng. Educ.* **49**(1) 60–71 (2021).
12. F. Xia et al., "A modular low-cost atomic force microscope for precision mechatronics education," *Mechatronics* **76**, 102550 (2021).
13. L. Chrostowski and H. Shoman, "Online training in the design-fabricate-test of silicon photonic circuits," in *Educ. and Training in Opt. & Photonics (ETOP) Conf.*, 8–10 September, Optica Publishing Group, Washington, DC, United States, p. F2B.3 (2021).
14. O. Awadelkarim, "Nanotechnology professional development partnership: A web-based, live-streaming approach for optimizing impact, effectiveness, and cost," NSF Award Abstract, # 1700630. See also, O. Awadelkarim, "Nanotechnology applications and career knowledge resource center, NSF Award Abstract, # 2000725.
15. L. Mao, "NUE: UNITE – Undergraduate nanotechnology inquiry, training, and experimentation at the University of Georgia (UGA)," NSF Award Abstract, # 1242030.
16. Z. Leseman, "NUE: an integrated multidisciplinary nanotechnology undergraduate education program at the University of New Mexico," NSF Award Abstract, # 1042062.
17. R. Shabani et al., "Classroom modules for nanotechnology undergraduate education: development, implementation, and evaluation" *Eur. J. Eng. Educ.* **36**, 199 (2011).
18. P. J. Hill et al., "Multidisciplinary undergraduate nanotechnology education at Mississippi State University," *J. Nano Educ.* **5**(2), 124–134 (2013).
19. P. J. Hill et al., "A multidisciplinary undergraduate nanotechnology education program with integrated laboratory experience," in *120 ASEE Annu. Conf. Exposition*, Seattle, Washington, p. 12686 (2015).
20. S. Serna et al., "A modular laboratory curriculum for teaching integrated photonics to students with diverse backgrounds," *Proc. SPIE* **11143**, 111431C (2019).

21. S. G. Lukishova, N. P. Bigelow, and P. D'Alessandris, "Development of multidisciplinary nanotechnology undergraduate education program at the University of Rochester Integrated Nanosystems Center," *Proc. SPIE* **10452**, 1045210 (2017).
22. S. G. Lukishova, "Undergraduate program in nanoscience and nanoengineering: 5 YEARS after the NSF Grant," in *Educ. and Training in Opt. & Photonics (ETOP) Conf.*, 8–10 September, Optica Publishing Group, Washington, DC, United States, p. F1A.6 (2021).
23. S. G. Lukishova and N. P. Bigelow, "Undergraduate program in nanoscience and nanoengineering: 5 years after the NSF Grant," in *NSF Nanoscale Sci. and Eng. Grantees Conf.*, 7–8 December (2021). https://www.nseresearch.org/2021/posters/11%20SL%20Lukishova_Bigelow_poster_NSF_2021_new.pdf (accessed 5 July 2022).
24. Nanowerk, "Nanotechnology degree programs," https://www.nanowerk.com/nanotechnology/nanotechnology_degrees.php (accessed 4 July 2022).
25. S. G. Lukishova, "Quantum optics laboratory," in *A Jewel in the Crown II: Essays in Honor of the 90th Anniversary of the Institute of Optics*, G. Kern and C. R. Stroud Jr., Eds., pp. 65–68, Meliora Press, University of Rochester (2020).
26. S. G. Lukishova, "Quantum optics and nano-optics teaching laboratory for the undergraduate curriculum: teaching quantum mechanics and nano-physics with photon counting instrumentation," *Proc. SPIE* **10452**, 104522I (2017).
27. S. G. Lukishova, "15 years of quantum optics educational facility at the Institute of Optics, University of Rochester," in *Educ. and Training in Opt. & Photonics (ETOP) Conf.*, Optica Publishing Group, Washington, DC, United States, p. W2B.3 (2021).
28. S. G. Lukishova, "Fifteen years of quantum optics educational facility at the Institute of Optics, University of Rochester," *Opt. Eng.* **61**(8) (2022).
29. S. G. Lukishova, "Quantum Optics, Quantum Information and Nano-Optics Laboratory," http://www2.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/ (accessed 4 July 2022).
30. Integrated Nanosystems Center, https://www.rochester.edu/urnano/ (accessed 4 July 2022).
31. Engineering Science & Physics, https://www.monroecc.edu/depts/engineering-science-and-physics/ (accessed 4 July 2022).
32. S. G. Lukishova et al., "Launching partnership in optics and photonics education between University of Rochester and Moscow Engineering Physics Institute NRNU MEPhI," *Proc. SPIE* **10452**, 1045226 (2017).
33. E. Buyanovskaya et al., "Research summer camp in photonics," *Proc. SPIE* **10452**, 104523H (2017).
34. S. G. Lukishova, S. A. Kozlov, and I. N. Zavestovskaya, "A Rochester–Russia collaboration," Opt. Photonics News, November, 20–21 (2016).
35. S. G. Lukishova et al., "Single-photon source for quantum information based on single dye molecule fluorescence in liquid crystal host," *Mol. Cryst. Liq. Cryst.* **454**, 403–416 (2006).
36. S. G. Lukishova and L. J. Bissell, "Nanophotonic advances for room-temperature single-photon sources," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, R. W. Boyd, S. G. Lukishova, and V. N. Zadkov, Eds., Springer Series in Optical Sciences, Vol. 217, pp. 103–178, Springer Nature Switzerland AG (2019).
37. C. K. Hong, Z. Y. Ou, and L. Mandel, "Measurement of subpicosecond time intervals between two photons by interference," *Phys. Rev. Lett.* **59** (18), 2044–2046 (1987).
38. G. M. Gehring et al., "Time-domain measurements of reflection delay in frustrated total internal reflection," *Phys. Rev. Lett.* **111**, 030404 (2013).
39. S. G. Lukishova et al., "Single-photon experiments with liquid crystals for quantum science and quantum engineering applications," *Liq. Cryst. Rev.* **2** (2) 111–129 (2014).
40. A. C. Liapis et al., "Time-domain measurements of single photon tunneling phenomena," in *Tenth Rochester Conf. Coherence and Quantum Opt. (CQO-X)*, June 17–20, Technical Digest on CD, Rochester NY, p. G-M6.51 (2013).
41. A. C. Liapis et al., "Temporal reshaping of single photon wave packets using cholesteric liquid crystals," in *Front. in Opt./Laser Sci. Conf.*, 14–18 October, Rochester NY, p. LTu4J.7 (2012).

42. A. Bandura, "Self-efficacy: toward a unifying theory of behavioral change," *Psychol. Rev.* **84**, 191 (1977).
43. A. Bandura, "Social cognitive theory: an agentic perspective," *Annu. Rev. Psychol.* **52**, 1 (2001).
44. D. Zohrabi Alaee, M. K. Campbell, and B. M. Zwickl, "Impact of virtual research experience for undergraduates experiences on students' psychosocial gains during the COVID-19 pandemic," *Phys. Rev. Educ. Res.* **18**, 010101 (2022).
45. E. Dorn et al., *COVID-19 and Student Learning in the United States: The Hurt Could Last a Lifetime*, McKinsey & Company (2020).
46. R. Chetty et al., "How did COVID-19 and stabilization policies affect spending and employment? A new real-time economic tracker based on private sector data," The Opportunity Insights Team (2020). https://www.nber.org/system/files/working_papers/w27431/w27431.pdf (accessed 5 July 2022).
47. J. M. Kuhfeld et al., "Projecting the potential impact of COVID-19 school closures on academic achievement," *Educ. Res.* **49**, 549 (2020).
48. L. Strubbe and S. McKagan, "I suddenly have to move my lab course online! What should I do?" PhysPort, https://www.physport.org/recommendations/Entry.cfm?ID=119927 (accessed 4 July 2022).
49. T. Feder, "Universities overcome bumps in transition to online teaching," *Phys. Today* **73**(6), 22 (2020).
50. M. F. J. Fox et al., "Teaching labs during a pandemic: Lessons from Spring 2020 and an outlook for the future," arXiv200701271. https://arxiv.org/abs/2007.01271 (accessed 5 July 2022).
51. M. F. J. Fox et al., "Lab instruction during the COVID-19 pandemic: effects on student views about experimental physics in comparison with previous years," *Phys. Rev. Phys. Educ. Res.* **17**, 010148 (2021).
52. J. R. Hoehn et al., "Remote advanced lab course: a case study analysis of open-ended projects," *Phys. Rev. Phys. Educ. Res.* **17**, 020111 (2021).
53. A. Werth, C. G. West, and H. J. Lewandowski, "Impacts on student learning, confidence, and affect in a remote, large-enrollment, course-based undergraduate research experience in physics," *Phys. Rev. Phys. Educ. Res.* **18**, 010129 (2022).
54. D. J. Rosen and A. M. Kelly, "Working together or alone, near, or far: social connections and communities of practice in in-person and remote physics laboratories," *Phys. Rev. Phys. Educ. Res.* **18**, 010105 (2022).
55. T. Delgado, S.-J. Bhark, and J. Donahue, "Pandemic teaching: Creating and teaching cell biology labs online during COVID-19," *Biochem. Mol. Biol. Educ.* **49**, 32–37 (2021).
56. S. G. Lukishova et al., "Hybrid teaching during a pandemic of advanced labs and their lecture classes," in *Educ. and Training in Opt. & Photonics (ETOP) Conf.*, 8-10 September, Optica Publishing Group, Washington, DC, United States, p. F2B.5 (2021).
57. E. J. Galvez, "Remote quantum optics labs," *Proc. SPIE* **11701**, 1170106 (2021).
58. S. Ding et al., "Aerosols from speaking can linger in the air for up to nine hours," *Build. Environ.* **205**, 108239 (2021).
59. K. K. Coleman et al., "Viral load of severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2) in respiratory aerosols emitted by patients with coronavirus disease 2019 (COVID-19) while breathing, talking, and singing," *Clin. Infect. Diseases* **74** (10), 1722–1728 (2022).
60. G. Kestin et al., "Comparing the effectiveness of online versus live lecture demonstrations," *Phys. Rev. Phys. Educ. Res.* **16** (1), 013101 (2020).
61. T. Feder, "College-level project-based learning gains popularity," *Phys. Today* **70** (6), 28 (2017).

Svetlana G. Lukishova is currently a group leader at the Institute of Optics, University of Rochester, where she has worked for more than 20 years. Her research interests include quantum nanophotonics, liquid crystals, and nonlinear optics with more than 250 publications. She served as topical editor of *Optics Letters* for six years. She created and directs the University of Rochester undergraduate program on the Certificate in Nanoscience and Nanoengineering based on Quantum Optics and Nano-Optics laboratory facility.

Nicholas P. Bigelow joined the university in 1992 and is a group leader and the Lee A. DuBridge professor at the Department of Physics and Astronomy and Optics, University of Rochester. He is the director of the Integrated Nanosystems Center (URNano). He has served as the director of Undergraduate Studies in the Department of Physics and Astronomy (1998–2004) and as department chair (2007–2013). His research interests are in the areas of quantum optics and quantum physics.