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Low-Cost 3D-Printed Polarimeter

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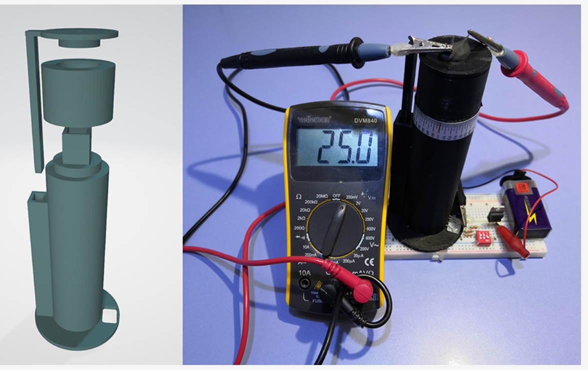
ABSTRACT: 3D printing and simple electronics were used to create a polarimeter suitable for a variety of chemistry courses. This device allows instructors to demonstrate optical activity but is also easy to use and low cost enough to be widely available for student use, as well. The instrument uses an LED light source and detector housed in a 3D-printed base. By rotating the top piece, users can visually detect changes in brightness or measure this directly with a multimeter.



KEYWORDS: *High School, Introductory Chemistry Student-Centered Learning Hands-On Learning, Manipulatives Laboratory Equipment, Apparatus*

INTRODUCTION

Development of 3D printing technology and the rise of affordable, commercial 3D printers has created a wealth of new opportunities for science teachers. This has led to the ability to produce personalized models[1,2] of everything from hybridization,[1,3−6] crystal unit cells,[7−10] nanostructures,[11] complex orbitals,[6,12,13] steric interactions[14,15] and even models of potential energy surfaces.[16,17] In addition, 3D-printed educational tools can be low cost and easily personalized for use as colorimeters,[18] fluorimeters,[19] UV−vis spectrophotometers,[20] reactors,[21,22] and elements of more complex hardware.[23−25] Unfortunately, until now, no 3D-printable polarimeter designs are on the market.

A polarimeter is a device that allows the user to measure the angle of rotation of polarized light after passing through a sample of an optically active substance/solution.[26−30] Basically, a polarimeter consists of a source of monochromatic light, sample chamber, and two polarizing filters, one before and one behind the sample.[31] The second filter is rotatable, allowing it to be adjusted to the angle of rotated light after passing through a sample to minimize or maximize the transmitted light (see Figure 1).

Typically, the optical activity of substances is only demonstrated by the teacher/instructor[32−34] at the high school level and during introductory chemistry college courses. The demonstration usually involves overhead projection technology.[35−38] There is an example of a zero-cost polarimeter[39] that is based on a mobile phone and sunglasses. Those approaches let the teacher present the phenomena but are not as useful for students' experiments. Student laboratory exercises classically

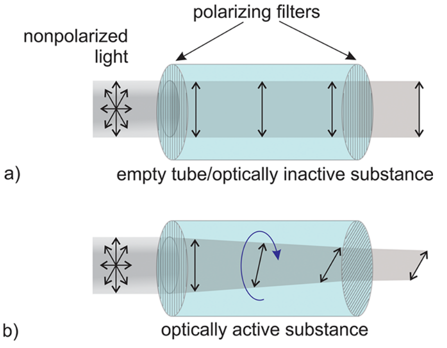


Figure 1. Schematic of a basic polarimeter and its working theory.

use Laurent's half-shade polarimeter, a biquartz polarimeter, or, during instrumental analysis classes, a fully automatic device. Unfortunately, the price of even classical measuring devices can be a limiting factor to run hands-on measurements in a school laboratory or during large-scale academic laboratory courses. There were attempts to design a low-cost polarimeter,[40−46] such as using a shoebox[47] or PVC pipes,[46] but the quality of these tools depends strongly on personal crafting skills, and product durability can often be an issue. Therefore, the use of

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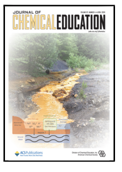

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3D printing technology is a perfect solution. The body of a polarimeter can be printed in a reasonable time; the price of the plastic and electronics is low, and the actual assembly of the elements is relatively simple.

■ CONSTRUCTION OF THE 3D-PRINTED POLARIMETER

The general construction of a polarimeter is presented in Figure 2. There are several variants of the tool. First, the device can use a test tube or a 3D-printed cuvette. Next, the detection can be visual or more precise using a photodiode (tracking the voltage changes with a multimeter).

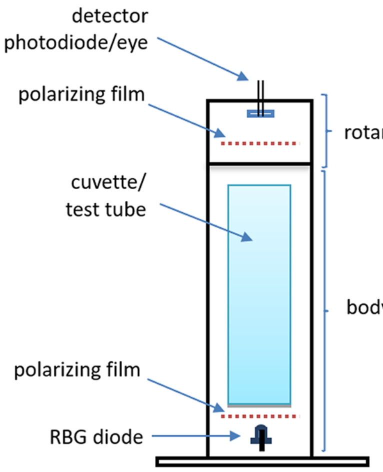

Figure 2. Schematic of the 3D-printed polarimeter.

These polarimeter models are compatible with commercially available LEDs that are low-voltage, long-lived, and inexpensive light sources. The RBG diode can be plugged directly into a 5 V (or 4.5 V) battery, or a simple circuit with a standard 9 V battery can be used,[48] as shown in Figure 3.

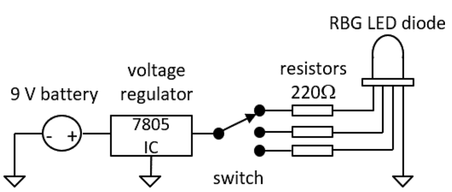

Figure 3. Schematic of a 9 V power supply circuit.

In the construction, two layers of polarizing filters (polarizing film) are used. It is a low-cost, commercially available material, used for the construction of 3D glasses among other things. Our experience shows that it is easier to identify the lowest (rather than highest) intensity of the light passing through the sample; therefore, we advise arranging two layers of polarizing film rotated by 90°. In such a setup at neutral position (0° angle) without a sample, or with a sample of optically nonactive substance, it is dark, showing the lowest light intensity. The detection can be based on visual observation, but such a measurement is limited by the observer's subjective reading. Alternatively, detection based on the voltage produced by a photodiode can be used; it is advised to use a photodiode with low IR radiation sensitivity. The construction of the device using a test tube as a sample container is simpler but also more problematic in use. The bottom of a test tube scatters the light. Usually, the center of the light spot is darker, but there is an unpolarized light ring around it (see Figure 4c). Such reading is acceptable for eye detection but problematic for photodiode readings as there is not complete blackout at the minimum light point. Using a 3D-printed container with a flat bottom solves this problem. It should be noted that the scattering effect also depends on the sample. Stable readings require the body of the device to be printed with a dark (preferably black) filament.

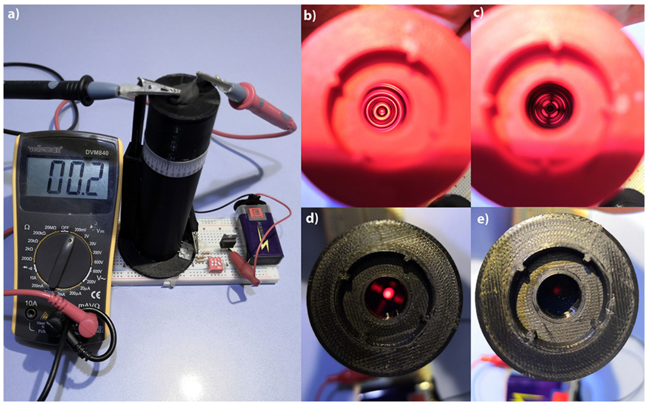

Figure 4. (a) Operating the 3D-printed cuvette polarimeter with a photodiode detector at zero position (minimum signal), (b) operating the 3D-printed test tube polarimeter at the max signal, (c) operating the 3D-printed test tube polarimeter at the minimum signal, (d) operating the 3D-printed cuvette polarimeter at the max signal, (e) operating the 3D-printed cuvette polarimeter at the minimum signal.

The polarimeter body elements are not very complex; therefore, printing does not require special materials or techniques. The elements used in this study were made of acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) filaments, with a nozzle size of 0.4 mm. Our tests showed that the best results for printing the main body and rotary cup are achieved using a dual extruder printer and water-soluble supports (PVA − poly(vinyl alcohol)); those prints are regular, with a smooth surface and tight holes for wires. Prints from single-extruder printers are also usable, however, because support leftovers may require some grinding or drilling of wire holes. Stable readings require total blackout in the measurement chamber; therefore, it is advised to use black filament. Good results can also be achieved also using dark filaments and/or painting prints with black paint spray.

■ ASSEMBLY AND OPERATION

The ready-to-use device is best suited for high school and introductory chemistry students. Students making measurements follow simple instructions (see Supporting Information). Taking measurements is quick and simple: students change samples and adjust a cap rotation in less than 1 min. However, students need to be informed about which way to rotate the instrument for a particular substance because the device gives the same readings in both directions (90° = −270°). It is also advised to adjust the concentration of the sample solution and path length so that the readings are in the range of the provided rotation scale (from −180° to +180°). Using measured rotation and simple mathematical relations, students can calculate a substance's specific rotation. Taking measurements was tested with 50 high school students (K11) in an extended chemistry program in Poland, and 15 organic

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chemistry university students in the U.S. During ordinary classes, they were acquainted with polarimetry principles and device schema and ran several measurements. They were working in 2−3 person groups. Students ran measurements first with pure liquids and then with aqueous solutions. The studied substances were (*R*)-limonene, fructose, and sucrose. Students were asked to run initial measurements using both methods of detection. For aqueous solutions, they made measurements for a given sample and after dilatation (4 up to 6 measurements depending on the group). Thanks to the fact that the device uses RBG diode as a light source, they could also take measurements with three various colors (wavelengths). The results were a starting point for a discussion on optical rotatory dispersion phenomena. Calculating the specific rotation of the substances was homework, verified by the teacher during subsequent classes. Exemplary samples and results are provided below and in the Supporting Information.

Another option is to have students assemble the devices themselves. As L. Porter noticed working with his 3D-printed colorimeter,[18] assembling other chemistry devices themselves assists learners in discovering the technology and fundamental principles of analysis, and the measurements are no longer run in a "black box". Kits containing all of the materials including the 3D-printed body, polarizing film sheet, circuit components (e.g., breadboard, resistors, LED source, photodiode, batteries, alligator clip leads), a digital multimeter, and basic tools and supplies (tweezers, diagonal pliers, black plasticine, sanitary silicone, double-sided adhesive tape, hot glue gun) were prepared by instructors. Constructing the device was tested by 16 preservice teachers, chemistry majors, during a Chemistry Education course in Poland, and by four undergraduate students in the U.S. The subject of the classes was not introduced in advance, so at first, a cautious and suspicious approach of students to the task was evident. Nevertheless, after getting acquainted with the guidelines and provided materials, they started work enthusiastically. Students did not have previous experience in constructing measuring devices nor using breadboards. The design does not require soldering diodes and wires, but it was optional. They worked in pairs following detailed instructions (see Supporting Information) with instructor assistance. All groups constructed operational devices (the version with the photodiode detector). Assembly took approximately 45−60 min. Students were very satisfied and proud with effects of their work and claimed that it was great fun to learn how circuits can be built on a breadboard and how simple it is to build a polarimeter. After assembly, students ran test measurements. The devices built were used later by other students.

■ HAZARDS AND DISPOSALS

During 3D printing, harmful vapors may be emitted;[49] therefore, the PLA filament should be used whenever possible and the printer should be used in a well-ventilated room. The plastic leftovers should be collected and recycled into a new filament or properly disposed of.

Working with the 3D-printed cuvette requires special attention. The tightness of the cuvette should be tested before use. Leaks might be caused by slits between the printed body of the cuvette and glued transparent piece of glass/plastic, and they also might be an effect from low-quality printing (under-extrusion) and gaps between layers of printed plastic. Finally, some organic solvents may dissolve or react with plastic; therefore, filament resistance for a particular solvent should be checked before use, and substance should be removed from the cuvette right after measurement.

(*R*)-Limonene (CAS 5989-27-5) is irritating, flammable, and toxic to aquatic life. It should be handled with care and kept away from heat, hot surfaces, sparks, open flames, and other ignition sources. Standard personal protective equipment, such as safety gloves and goggles, should be worn at all times. Working under a fumehood is advised. After the experiments, the substance should be recycled or properly disposed of.

■ PERFORMANCE

Using the measured rotation and eq 1 or 2, students can calculate a substance's specific rotation.[29] The measured angle of rotation depends on path length, concentration, specific rotation of the molecule, wavelength of light, and temperature. For pure liquids, the specific rotation is given by

$$[\alpha]_\lambda^T = \frac{\alpha}{l \cdot \rho} \quad (1)$$

where l is the path length in decimeters, ρ is the density in grams per milliliter, and α is the measured rotation in degrees. It is quoted at a specific temperature and wavelength. If the measurement is made for a solution, the specific rotation can be calculated using the following equation:

$$[\alpha]_\lambda^T = \frac{\alpha}{l \cdot c} \quad (2)$$

where c is the concentration in grams per milliliter.

Exemplary results of single measurements for limonene are presented in Table 1. Measurements were run with two types of 3D-printed polarimeters operating with various detection modes, and compared to data obtained from a commercial, fully automatic digital polarimeter using a sodium lamp at 589 nm.

Table 1. Measured and Specific Rotation for (*R*)-Limonene and Results of Single Measurements

polarimeter	path length (dm)	density ($g \cdot mL^{-1}$)	light	measured rotation (deg)	specific rotation (deg)
3D-printed cuvette photodiode detection	0.5	0.842	red	45	107
	0.5	0.842	green	65	154
	0.5	0.842	blue	95	226
3D-printed test tube eye detection	0.5	0.842	red	45	107
	0.5	0.842	green	60	143
	0.5	0.842	blue	85	202
commercial	0.5	0.842	sodium lamp	52.6	124.9

In Figure 5, exemplary results for aqueous solutions of sucrose are presented. In this case, a 3D-printed test tube polarimeter with eye detection was used. On the plot, average results for 10 independent measurements are presented. Error bars represent the standard deviation of results. For a commercial polarimeter, error bars were skipped because of negligible error values (SD < 0.01).

■ CONCLUSION

The 3D-printed polarimeter is a low-cost, simple device that can be constructed by students. Using 3D printing makes construction very simple and independent from user crafting skills. Measurement results are repeatable and consistent with commercial, digital, fully automatic devices. The 3D-printed

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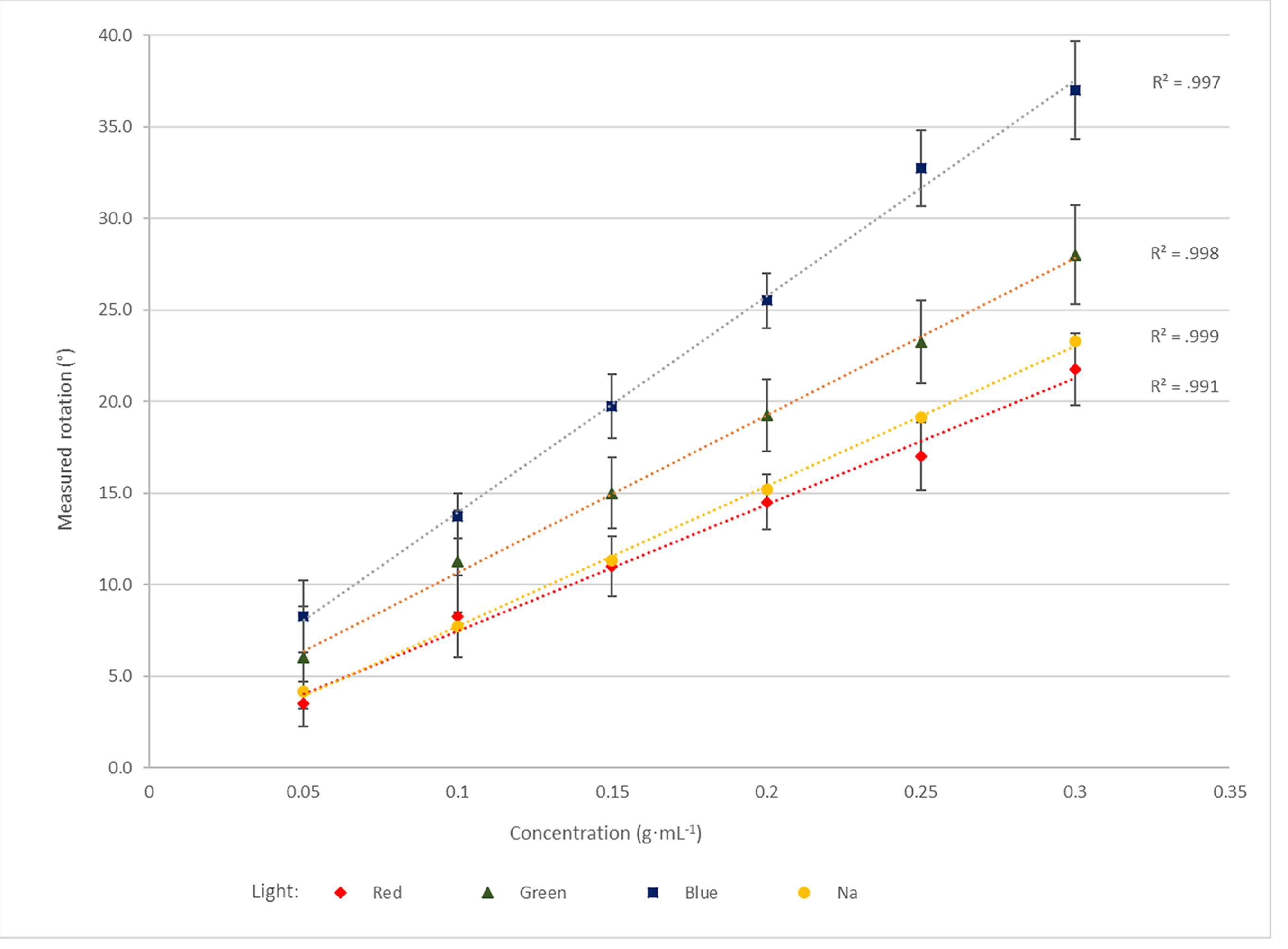

Figure 5. Measured rotation for aqueous solutions of sucrose in the concentration range of 0.05−0.35 g·mL, a series for various colors of light (red, green, blue) measured with a 3D-printed polarimeter, and accompanied by results from commercial polarimeter with a sodium lamp 589 nm.

polarimeters can be used not only to demonstrate the optical activity phenomena but also to be used by students. That fact provides teachers/instructors with a possibility of using those devices not only during basic measurement laboratory exercises but also during independent student inquiry activities. The presented construction is a significant step forward from the previous shoebox and PVC pipe designs.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.9b01083.

Polarimeter construction manual, cost breakdown, measurement instructions, and exemplary results (DOCX, PDF)

3D printer build files (ZIP)

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Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Jones, O. A. H.; Spencer, M. J. S. A Simplified Method for the 3D Printing of Molecular Models for Chemical Education. *J. Chem. Educ.* **2018**, *95* (1), 88−96.

(2) Bernard, P.; Mendez, J. D. Drawing in 3D: Using 3D Printer Pens to Draw Chemical Models. *Biochem. Mol. Biol. Educ.* **2020**, DOI: 10.1002/bmb.21334.

(3) Smiar, K.; Mendez, J. D. Creating and Using Interactive, 3D-Printed Models to Improve Student Comprehension of the Bohr Model of the Atom, Bond Polarity, and Hybridization. *J. Chem. Educ.* **2016**, *93* (9), 1591−1594.

(4) Van Wieren, K.; Tailor, H. N.; Scalfani, V. F.; Merbouh, N. Rapid Access to Multicolor Three-Dimensional Printed Chemistry and Biochemistry Models Using Visualization and Three-Dimensional Printing Software Programs. *J. Chem. Educ.* **2017**, *94* (7), 964−969.

(5) Violante, L. E. H.; Nunez, D. A.; Ryan, S. M.; Grubbs, W. T. 3D Printing in the Chemistry Curriculum: Inspiring Millennial Students To Be Creative Innovators. In *Addressing the Millennial Student in Undergraduate Chemistry*; ACS Symposium Series; American Chemical Society: Washington, DC, 2014; Vol. *1180*, pp 125−146.
(6) Griffith, K. M.; Cataldo, R. de; Fogarty, K. H. Do-It-Yourself: 3D Models of Hydrogenic Orbitals through 3D Printing. *J. Chem. Educ.* **2016**, *93* (9), 1586−1590.
(7) Rodenbough, P. P.; Vanti, W. B.; Chan, S.-W. 3D-Printing Crystallographic Unit Cells for Learning Materials Science and Engineering. *J. Chem. Educ.* **2015**, *92* (11), 1960−1962.
(8) Scalfani, V. F.; Williams, A. J.; Tkachenko, V.; Karapetyan, K.; Pshenichnov, A.; Hanson, R. M.; Liddie, J. M.; Bara, J. E. Programmatic Conversion of Crystal Structures into 3D Printable Files Using Jmol. *J. Cheminf.* **2016**, *8*, 66.
(9) Scalfani, V. F.; Vaid, T. P. 3D Printed Molecules and Extended Solid Models for Teaching Symmetry and Point Groups. *J. Chem. Educ.* **2014**, *91* (8), 1174−1180.
(10) Paukstelis, P. J. MolPrint3D: Enhanced 3D Printing of Ball-and-Stick Molecular Models. *J. Chem. Educ.* **2018**, *95* (1), 169−172.
(11) Scalfani, V. F.; Turner, C. H.; Rupar, P. A.; Jenkins, A. H.; Bara, J. E. 3D Printed Block Copolymer Nanostructures. *J. Chem. Educ.* **2015**, *92* (11), 1866−1870.
(12) Robertson, M. J.; Jorgensen, W. L. Illustrating Concepts in Physical Organic Chemistry with 3D Printed Orbitals. *J. Chem. Educ.* **2015**, *92* (12), 2113−2116.
(13) Carroll, F. A.; Blauch, D. N. 3D Printing of Molecular Models with Calculated Geometries and p Orbital Isosurfaces. *J. Chem. Educ.* **2017**, *94* (7), 886−891.
(14) Diaz-Allen, C.; Sibbald, P. A. Using 3D Printing to Model Steric Interactions. *Chem. Educ.* **2016**, *21*, 10−12.
(15) Carroll, F. A.; Blauch, D. N. Using the Force: Three-Dimensional Printing a π-Bonding Model with Embedded Magnets. *J. Chem. Educ.* **2018**, *95* (9), 1607−1611.
(16) Lolur, P.; Dawes, R. 3D Printing of Molecular Potential Energy Surface Models. *J. Chem. Educ.* **2014**, *91* (8), 1181−1184.
(17) Kaliakin, D. S.; Zaari, R. R.; Varganov, S. A. 3D Printed Potential and Free Energy Surfaces for Teaching Fundamental Concepts in Physical Chemistry. *J. Chem. Educ.* **2015**, *92* (12), 2106−2112.
(18) Porter, L. A.; Washer, B. M.; Hakim, M. H.; Dallinger, R. F. User-Friendly 3D Printed Colorimeter Models for Student Exploration of Instrument Design and Performance. *J. Chem. Educ.* **2016**, *93* (7), 1305−1309.
(19) Porter, L. A.; Chapman, C. A.; Alaniz, J. A. Simple and Inexpensive 3D Printed Filter Fluorometer Designs: User-Friendly Instrument Models for Laboratory Learning and Outreach Activities. *J. Chem. Educ.* **2017**, *94* (1), 105−111.
(20) Grasse, E. K.; Torcasio, M. H.; Smith, A. W. Teaching UV−Vis Spectroscopy with a 3D-Printable Smartphone Spectrophotometer. *J. Chem. Educ.* **2016**, *93* (1), 146−151.
(21) Stefanov, B. I.; Lebrun, D.; Mattsson, A.; Granqvist, C. G.; Österlund, L. Demonstrating Online Monitoring of Air Pollutant Photodegradation in a 3D Printed Gas-Phase Photocatalysis Reactor. *J. Chem. Educ.* **2015**, *92* (4), 678−682.
(22) Tabassum, T.; Iloska, M.; Scuereb, D.; Taira, N.; Jin, C.; Zaitsev, V.; Afshar, F.; Kim, T. Development and Application of 3D Printed Mesoreactors in Chemical Engineering Education. *J. Chem. Educ.* **2018**, *95* (5), 783−790.
(23) Lu, Y.; Santino, L. M.; Acharya, S.; Anandarajah, H.; D'Arcy, J. M. Studying Electrical Conductivity Using a 3D Printed Four-Point Probe Station. *J. Chem. Educ.* **2017**, *94* (7), 950−955.
(24) Pinger, C. W.; Castiaux, A.; Speed, S.; Spence, D. M. Plate Reader Compatible 3D-Printed Device for Teaching Equilibrium Dialysis Binding Assays. *J. Chem. Educ.* **2018**, *95* (9), 1662−1667.
(25) Davis, E. J.; Jones, M.; Thiel, D. A.; Pauls, S. Using Open-Source, 3D Printable Optical Hardware To Enhance Student Learning in the Instrumental Analysis Laboratory. *J. Chem. Educ.* **2018**, *95* (4), 672−677.
(26) Eichlin, C. G. The Polarimeter (Saunders, Vivian T.). *J. Chem. Educ.* **1927**, *4* (8), 1067.
(27) Kiplinger, C. C. An Improvised Polarimeter. *J. Chem. Educ.* **1930**, *7* (9), 2174.
(28) Evans, J. O. M.; Tietze, H. R. Optical Rotation. *J. Chem. Educ.* **1964**, *41* (12), A973.
(29) Mickey, C. D. Optical Activity. *J. Chem. Educ.* **1980**, *57* (6), 442.
(30) Knauer, B. A Demonstration of the Optical Activity of a Pair of Enantiomers. *J. Chem. Educ.* **1989**, *66* (12), 1033.
(31) Kapauan, A. F. A Simple Split-Field Polarimeter. *J. Chem. Educ.* **1973**, *50* (5), 376.
(32) Burkett, H. A Demonstration Polarimeter. *J. Chem. Educ.* **1949**, *26* (5), 273.
(33) Spear, C. S. A Demonstration Polarimeter. *J. Chem. Educ.* **1960**, *37* (4), 203.
(34) Hambly, G. F. Optical Activity: An Improved Demonstration. *J. Chem. Educ.* **1988**, *65* (7), 623.
(35) Frank, F. J.; Kidwell, S. M. Polarimeter for an Overhead Projector. *J. Chem. Educ.* **1969**, *46* (1), 58.
(36) Dorn, H. C.; Bell, H.; Birkett, T. A Simple Polarimeter and Experiments Utilizing an Overhead Projector. *J. Chem. Educ.* **1984**, *61* (12), 1106.
(37) Hill, J. W. An Overhead Projection Demonstration of Optical Activity. *J. Chem. Educ.* **1973**, *50* (8), 574.
(38) Kolb, D. Introduction to Overhead Projector Demonstrations. *J. Chem. Educ.* **1987**, *64* (4), 348.
(39) Thomson, P. I. T. Is That a Polarimeter in Your Pocket? A Zero-Cost, Technology-Enabled Demonstration of Optical Rotation. *J. Chem. Educ.* **2018**, *95* (5), 837−841.
(40) Nechamkin, H. A Student Polarimeter. *J. Chem. Educ.* **1954**, *31* (11), 579.
(41) Shaw, W. H. R. A Mailing-Tube Polarimeter. *J. Chem. Educ.* **1955**, *32* (1), 10.
(42) Garvin, J. E. Inexpensive Polarimeter for Demonstrations and Student Use. *J. Chem. Educ.* **1960**, *37* (10), 515.
(43) Vennos, M. S. Construction and Uses of an Inexpensive Polarimeter. *J. Chem. Educ.* **1969**, *46* (7), 459.
(44) Stary, F. E.; Woldow, N. Build a Simple Polarimeter. *J. Chem. Educ.* **2001**, *78* (5), 644.
(45) Lisboa, P.; Sotomayor, J.; Ribeiro, P. A New Cost-Effective Diode Laser Polarimeter Apparatus Constructed by Undergraduate Students. *J. Chem. Educ.* **2010**, *87* (12), 1408−1410.
(46) Breton, G. W. An Inexpensive Homemade Polarimeter for Demonstration Use in the Classroom. *J. Lab. Chem. Educ.* **2015**, *3* (1), 7−11.
(47) Mehta, A.; Greenbowe, T. J. A Shoebox Polarimeter: An Inexpensive Analytical Tool for Teachers and Students. *J. Chem. Educ.* **2011**, *88* (8), 1194−1197.
(48) Bergantin, J. H.; Sevilla, F., III *Low-Cost Microscale Colorimeter*; International Conference on Chemical Education, Taipei, Taiwan, Aug 8−13, 2010.
(49) Stabile, L.; Scungio, M.; Buonanno, G.; Arpino, F.; Ficco, G. Airborne Particle Emission of a Commercial 3D Printer: The Effect of Filament Material and Printing Temperature. *Indoor Air* **2017**, *27* (2), 398−408.