JOURNAL OF CHEMICAL EDUCATION
Technology Report
Cite This: J. Chem. Educ. 2018, 95, 672−677
pubs.acs.org/jchemeduc

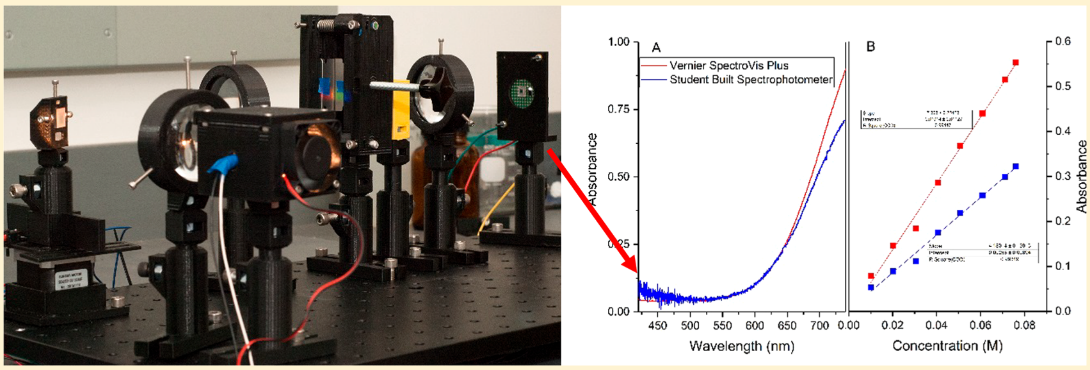
Using Open-Source, 3D Printable Optical Hardware To Enhance Student Learning in the Instrumental Analysis Laboratory

Eric J. Davis,*,† Michael Jones,† D. Alex Thiel,† and Steve Pauls‡

†Azusa Pacific University, Azusa, California 91702, United States

‡Fresno Pacific University, Fresno, California 93702, United States

Supporting Information



ABSTRACT: Additive manufacturing (3D printing) is a technology with near-unlimited potential for the chemical educator. However, its adoption into higher education has been limited by the dual requirements of expertise in 3D printing and 3D computer-aided design (CAD). Thus, its reported utilization in the chemistry curriculum has been within the creation of 3D models for the macroscopic visualization of molecular models and processes. With the commercialization of inexpensive 3D printers, we seek to provide a series of optical mounts and tools for use in chemical research or education by designing systems which may be mounted on a breadboard and used to construct chemical instrumentation. These designs include mounts for cylindrical lenses or mirrors with 0.5, 1, and 2 in. diameters, 0.5 in. diffraction gratings, an adjustable optical slit, cuvette holders, stepper motor (NEMA 17) adapters, and a modular, 3D printed breadboard. All designs were created using Solidworks CAD, and have been provided in Supporting Information and uploaded to https://github.com/EdavisAPU/Education-Optics in both Solidworks native format (*.SLDPRT) and a standard file exchange format for 3D objects (*.STL) format for use, modification, or collaboration. All files are released under the MIT Open-Source license (modified for Design). In comparison with commercially available products, the prototypes presented herein provide significant cost-savings, with many designs 1−2 orders of magnitude cheaper than commercial equivalents. In addition, these designs have been utilized in an upper division instrumental analysis course as students designed and constructed a visible spectrophotometer using these optical devices. Data from the resultant instrument is presented and compared with a commercially available spectrophotometer.

KEYWORDS: *General Public, Analytical Chemistry, Hands-On Learning/Manipulatives, Instrumental Methods, Spectroscopy*

INTRODUCTION

Additive manufacture (3D printing) is a technology in the early stages of adoption as an educational tool. The educational community has been slow to adopt 3D printing due to initial costs and the technological proficiency required to own and operate a printer. However, recent advances in technology have brought costs down to be approachable by educators of nearly every level. At the time of this writing, multiple printers are available to purchase commercially within the $300 price range, with filament costing $20−40 per kg of material. 3D printers are now being installed into university libraries for common usage by students, and this trend is only likely to continue as costs continue to decrease.[1,2] With this have come a multitude of approaches represented in the literature for the use of 3D printing as an educational and research tool.

Educational applications of 3D printing have been increasing over the past several years. Usage has ranged from laboratory tools to educational models for demonstration of chemical principles on a macroscopic scale. These include 3D models of atomic[3,4] and molecular[5,6] orbitals, phase diagrams,[7] crystallographic unit cells,[8] potential surfaces,[9] and the folding patterns of proteins.[10] These hands-on tools serve to aid students in their ability to visualize the quantum-mechanical realm.

The use of additive manufacturing in education has also benefitted those in analytical education by providing hands-on tools for demonstrating or using analytical instrumentation,

Received: July 1, 2017
Revised: January 19, 2018
Published: February 9, 2018

such as the prediction and demonstration of diffraction angles using 3D printed models.[11] Additional work has produced simple, yet effective, instrumentation for use in curriculum ranging from general chemistry to instrumental analysis. At the time of writing, 3D printed, smartphone visible spectrophotometers[12] and 3D printed filter fluorimeters[13] have been successfully fabricated, with unlimited potential for future work in simplified and cost-effective educational instrumentation. However, some educators have chosen to bypass the 3D printing movement, and spectrophotometers have been described using student construction with anything from PVC pipe to LEGO building blocks.[14−17]

This is contrasted with the historical methods of manufacturing in educational laboratories. The concept of constructing an instrument in an instrumental analysis course is not new and has been demonstrated in the literature on numerous occasions. These include simple absorption spectrophotometers[18] and flame atomic absorption spectrophotometers.[19] The use of 3D printing in education has not been limited to the chemical sciences. Its use in mechanical engineering is the most obvious application of 3D printing. However, it has been used in electrical engineering education as a method for providing electrical pathways through a part that would be impossible with traditional manufacturing methods.[20]

3D printing has also begun to aid in laboratory methodologies and lab-based education. Baden et al. demonstrate a series of laboratory equipment that may be manufactured using 3D printing technologies.[21] In their work, the authors demonstrated functioning micropipettors, micromanipulators, and links to multiple resources for open-source projects involving both 3D printing and the "maker movement" in general.[22] This has valuable applications in research by providing a rapid method for manufacturing simple parts that would have previously been too expensive to manufacture for a single experiment.[22−24] A database has been created where this laboratory equipment may be downloaded and printed for use.[25] The research utilization of 3D printing has evolved for manufacture of lenses for THz range spectroscopic analyses,[26,27] an imaging fluorescence microscope constructed using 3D printed objective mounts,[28] and an open-source nephalometer (water quality) meter designed for use in developing countries.[29]

Zhang et al.[23] have demonstrated a series of 3D printed optical mounts for use in both research and education. In their work, the authors focused on rail and magnet-mounted optical holders for lenses, filters, mirrors, fiber optics, and optical positioners, and the designs have been published and made available to the community. This is an excellent example of the power of 3D printing, the open-source mentality, and its applications to education and research. In this work, we seek to add to this database and fill a resource gap for those using 3D printers in chemical education. While the designs provided by Zhang et al. are excellent, they are designed for an optical rail system: a system very useful in physics and physics education, but limited in its utility for instrumental chemistry. Herein is presented a series of optical mounts, posts, holders, and other hardware intended to be used with a traditional optical breadboard, expanding the use of 3D printing into prototyping optical systems and analytical instrumentation. These designs are contrasted with commercially available products on a price comparison, and student use of them is demonstrated through the construction and evaluation of a visible spectrophotometer in an instrumental analysis laboratory.

MATERIALS AND METHODS

3D Printing

The mounts and devices pictured herein were produced using an HICTOP Prusa I3 desktop printer (www.hic3dprinter.com) purchased through Amazon (Seattle, WA). All demonstrated parts were printed using 1.75 mm polyacetic acid (PLA) plastic (various manufacturers) with a nozzle temperature of 195 °C, and a bed temperature of 70 °C, with a print speed of 45 mm/s, and a fill density of 35%. With these settings, most of the prints described herein require between 1 and 2 h to complete. The large parts described may take significantly longer (4−5 h to print both halves of one breadboard unit). PLA was chosen for its ease of use in 3D printing, thermal and mechanical stability, and its ready availability to the 3D printing community. It is cautioned that the use of different printers or plastics will require the reader to alter these settings. The settings provided herein are given as benchmarks that have produced successful, consistent results with the printer used in this work. While these settings should work for any properly tuned 3D printer, it is noted that 3D printing is an art which requires experience with a particular printer. Some failed prints in the early stages of utilizing a new printer should be expected.

Design

All parts were designed using Solidworks 2014 (Dassault Systèmes, Velizy, France). Both Solidworks native file format (*.SLDPRT) and file exchange format (*.STL) are made available for use or editing. All files are available on GitHub for future updates and are intended as an open-source collaboration made available to the community. Files may be found athttps://github.com/EdavisAPU/Education-Optics and within the Supporting Information of this paper. Solidworks is a CAD system common in the engineering community. It was chosen for its ease of use and extensive features not found in free software. However, the purchase of Solidworks is not required for utilizing this work in 3D printing, only for editing the raw files if desired.

Instrumental Analysis Course Application

All parts designed in this work were utilized in an upper division instrumental analysis laboratory course. During a portion of the laboratory semester, students were split into groups and tasked with the construction of a simple analytical instrument. Herein is detailed a simplified visible spectrophotometer constructed in this course. Optics provided included 60 and 150 mm focal length uncoated glass lenses and mirrors, a 600 lines/mm reflection grating (500 nm blaze), a 12 in. × 24 in. optical breadboard (Thorlabs, Newton, NJ), an amplified photodiode (Texas Instruments Opt101, Dallas, TX), a National Instruments USB-6001 (Austin, TX), instructor-written software, and the optical mounts and components described herein. Over the course of four 3 h laboratory sessions, students constructed and tested their visible spectrophotometer and compared their results to a Vernier SpectroVis Plus PDA spectrophotometer (Beaverton, OR). A Bill of Materials and the LabView-based software are made available in the Supporting Information. In this work, the students did not design the parts. The authors have attempted this previously, and it is not recommended for students with no prior CAD experience as the associated learning curve requires a significant expenditure of laboratory time for students to gain proficiency prior to designing usable prototypes.

DOI: 10.1021/acs.jchemed.7b00480
J. Chem. Educ. 2018, 95, 672−677

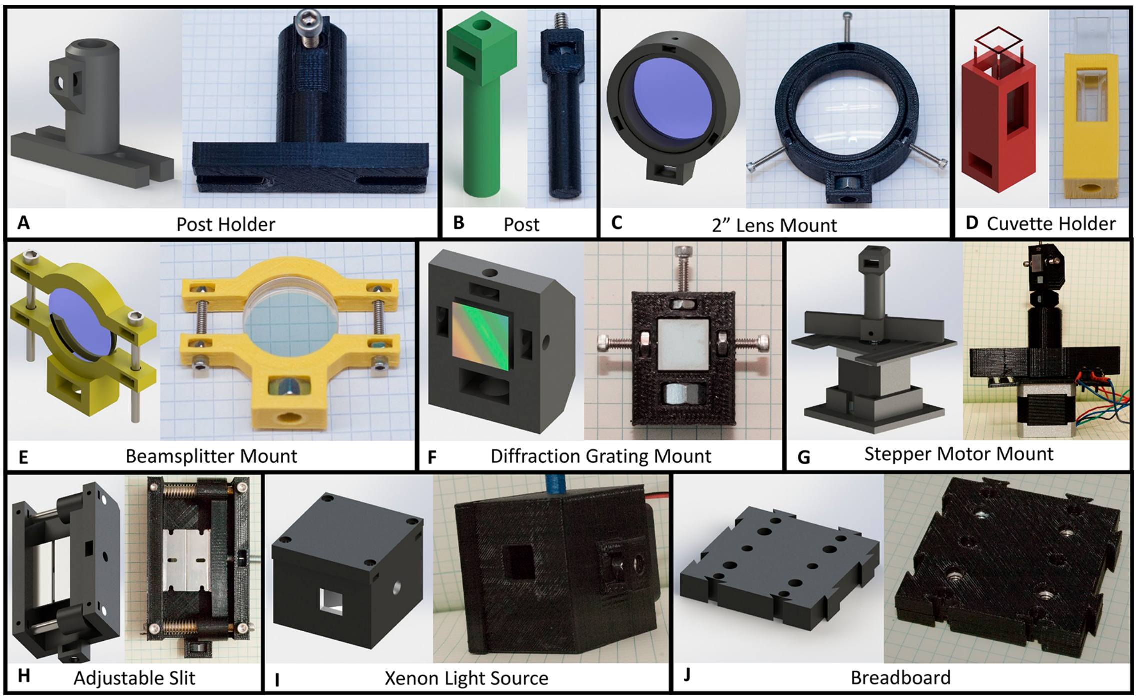


Figure 1. Optical components. Solidworks renderings and photographs of each 3D printed part outlined. Posts are available in 3, 4, and 5 in. heights (3 in. post represented); lens mounts provided in 1/2, 1, and 2 in. diameters (2 in. mount demonstrated). The breadboard is designed as a modular part which may be connected to provide the desired total breadboard area.

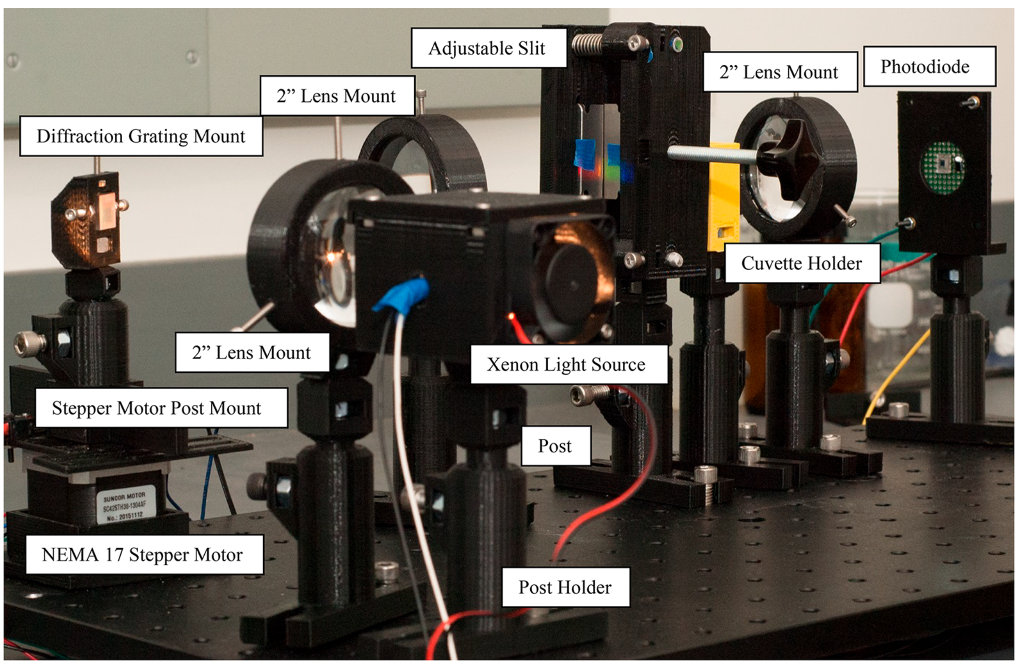


Figure 2. Student-built spectrophotometer. Using the optical components demonstrated herein, students in an upper division instrumental analysis course constructed a visible spectrophotometer. A 12 V xenon light bulb was used to illuminate a diffraction grating mounted to a computer-controlled NEMA 17 stepper motor. The resultant spectrum was passed through an adjustable optical slit before the selected wavelengths transmitted through a cuvette and onto a photodiode detector. Wavelength was calibrated through replacing the photodiode with a fiber optic cable connected to an OceanOptics USB 2000+.

■ RESULTS AND DISCUSSION

Optical Component Designs

Figure 1 demonstrates representative parts designed for this project. Included are post holders (Figure 1A) and posts (Figure 1B) (3 in. posts shown; designs uploaded to Supporting Information and GitHub repository for 4 and 5 in. posts) designed for mounting onto any standard optical breadboard. All mounting posts contain a slot for a 1/4 in. ANSI nut at the top for mating to the optical mount components using a 1/4 in. set screws. Posts have been designed in 3, 4, and 5 in. lengths, though modification to any

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Table 1. Cost Comparison of 3D Printed Parts[a]

Part	Image in Figure 1	Plastic Cost	Hardware Cost	Newport Research Part Number	Newport Research Cost	Difference
Post Holder	A	$0.72	$0.23	BPH-2	$10.00	($9.05)
3 in. Post	B	$0.70	$0.53	SPV-3	$7.00	($5.77)
2 in. Lens Mount	C	$0.47	$0.25	LH-2A	$27.00	($26.28)
Cuvette Holder	D	$0.17	$0.04	13950	$215.00	($214.79)
Beamsplitter Mount	E	$0.24	$0.18	U100-A	$87.00	($86.58)
Diffraction Grating Mount	F	$0.15	$0.18	DGA-25[b]	$140	($139.67)
Stepper Motor Mount	G	$1.25	$45.62	PR50PP	$1,607	($1,560.13)
Adjustable Slit	H	$7.51	$6.01	SV-0.5	$255.00	($241.48)
Xenon Light Source	I	$0.93	$7.76	60046	$84	($75.31)
2 in. × 2 in. Breadboard	J	$8.96	$2.84	SA2-04 × 06[b]	$42.00	($30.20)

[a]Costs of the printed parts are broken into the cost for the raw material (PLA plastic, $20 per kg) and the hardware required to assemble the device (see Supplementary Materials for a bill of materials). Equivalent parts commercially available through Newport Research are provided along with their respective cost at the time of publication. Total cost difference for each design is provided. [b]Indicates unavailability of a direct comparison to the provided design. The closest available approximation is provided.

length may be achieved through alteration of the provided files. The authors caution against the use of posts greater than 6 in. due to printing difficulty without modification of the design to allow additional support during the printing process. Post holders are designed with slots for attaching to an optical bench using 1/4 in. screws, and provide positioning of mounting posts via a slot and hole for 1/4 in. set screws through the side of the holders to lock the post at a desired height (pictured). It is cautioned that these post holders tended to bow at the base where the connection to the breadboard is intended. This is easily corrected through lightly sanding the bottom surface of the post holder to provide a level mount.

A series of optical mounts were created for various sized lenses, filters, mirrors, or gratings. These mounts were designed to mate onto commercially available mounting hardware (standardized to 1/4 in.-20 screws and nuts) or the 3D printed posts and post holders described above. Figure 1C demonstrates a model optical mount designed for this project with a 2 in. inner diameter. Optical mounts were designed for 0.5, 1, and 2 in. mirrors, lenses, or filters (only the 2 in. lens mount is demonstrated in Figure 1). For all closed lens mounts, an inner ring is held against the inside of the lens or mirror using three set screws mounted through the body of the lens mount. These set screws are threaded through nut slots into which an ANSI 4-40 nut is placed to provide threading for the fastener and avoid threading hardware directly into plastic parts. A slot at the base of the mounts provides access for a 1/4-20 nut intended for mating the optical holder to a mounting post. This nut allows interfacing onto printed posts or any ANSI Inch standard optical post using a set screw. All optics have been tested with appropriately sized lenses through multiple prints. No printed parts have yet to be found defective as a result of variability in the authors' printing setup. Nut slots and screw holes were designed with 0.1 mm clearance to compensate for any slight printing errors while allowing nuts to be firmly held within the plastic slot.

A beamsplitter mount (Figure 1E) is designed to pinch a 1 in. lens and allow full optical access to the edge of the optical component. A 1/2 in. square diffraction grating mount (Figure 1F) is designed to directly contact the sides of a diffraction grating with set screws for optical mounting. The mount would work for a diffraction grating (as demonstrated herein) or any square, reflective optical component. Both of these mounts are designed to mate with 1/4 in. standard mounting screws similar to the optical components described above.

A cuvette holder (Figure 1D) designed for 1 cm cuvettes in absorption mode (pictured) or 1 cm cuvettes in fluorescence mode (90° emission reading angle, available in Supporting Information and GitHub) is provided for spectroscopic applications of this work. Figure 2 demonstrates the use of this cuvette holder in a visible spectrophotometer application. An adjustable optical slit (Figure 1H) was designed which utilizes a pair of opposed flat razor blades for a sharp, straight slit. Turning a screw on the side of the slit opens or closes the slit as desired against the pressure of a pair of small springs incorporated into the design.

For optical illumination, a small box was designed to house a G4, 12 V xenon light bulb with a square opening at the front (Figure 1I). This box may be mounted to any commercially available mounting hardware or those described herein through the same 1/4 in. nut trap method described. A 2 in. computer fan (rated to 12 V) provides cooling of the light source and prevents softening of the plastic box through heat. A breadboard mount for a stepper motor, as well as mounts for pressure switches and a post designed to mate with a NEMA 17 stepper motor, is provided (combined, Figure 1G). This allows controlled rotation of optical components through 360°. In this work, this mount was utilized for the computer-aided control of a diffraction grating for wavelength selection through the adjustable slit in a visible spectrophotometer (Figure 2).

Finally, a modular 2 in. × 2 in. breadboard with 1.5 in. screw spacing was designed in two halves (assembled, Figure 1J). Each half contains traps for 1/4-20 ANSI inch nuts, with 4-40 screw holes spaced throughout to hold the halves together upon assembly. Dovetailed joints allow multiple units to be connected to create a breadboard of any size regardless of available print area with a specific model of 3D printer.

With these designs, each optical post has been utilized in both teaching and research laboratories. They have not allowed any noticeable optical drift from center through multiple weeks of use, though it is cautioned that care must be taken to ensure a tight fit of the lens trap. Figure 2 demonstrates an optical setup of a visible spectrophotometer constructed by students as a part of an instrumental analysis laboratory course. All optical components (with the exception of the breadboard, where a commercial version was utilized) in this design were 3D printed from the demonstrated designs and held optical alignment across multiple weeks of coursework, as evidenced through a consistent wavelength calibration over a period of several weeks.

DOI: 10.1021/acs.jchemed.7b00480
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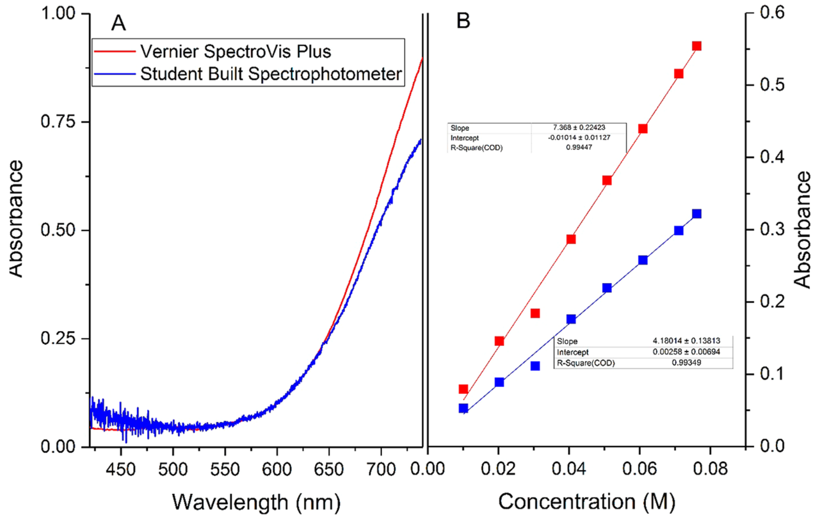

Figure 3. Student visible spectrophotometer data. (A) Visible spectrophotometry scan of 0.07 M copper(II) sulfate from 420 to 720 nm using the student-built spectrophotometer and a Vernier SpectroVis plus. Overall spectral shape matched the commercial instrument, though stray light resulted in an abnormally low absorbance at the higher wavelengths. (B) Calibration curve of copper(II) sulfate using the same two instruments at a wavelength of 700 nm. Decreased slope in the student-built instrument was likely due to stray light contaminating the detector.

Table 1 provides the printed cost of each optical mount and compares these to the closest relative commercial part available through Newport Research (Franklin, MA). Part numbers for these products are provided, as are the costs for these parts at the time of publication. Printed costs are divided into the cost of the plastic and the associated hardware. Plastic cost is calculated on the basis of an assumption of \$20.00 per roll of PLA plastic (an average value of 1.75 mm PLA plastic on Amazon at the time of publication), while hardware costs cover the nuts, bolts, and other hardware required to assemble a working lens holder (a bill of materials is provided in Supporting Information). As noted, the 3D printed optical mounts provide a substantial cost-savings over purchased items. While the parts are not identical in comparison with their commercial counterparts, they have proven sufficient in both teaching and research for high-tolerance optical mounting requirements.

Student-Built Instrumentation

As mentioned above, the described optical components were utilized in an instrumental analysis course intended for an upper division chemistry major. In this laboratory exercise, students were provided with a 12 in. × 24 in. optical breadboard (ThorLabs, Newton, NJ), a box containing several copies of each component described herein, a series of optics with either 60 mm or 150 mm focal lengths (both lenses and mirrors), a light source, photodiode detector, stepper motor, stepper motor controller, National Instruments USB-6001 Analog to Digital Converter, and an instructor-designed computer program (programmed using National Instruments LabView). In addition, each group was provided with a basic block diagram of the instrument to be constructed, as well as instruction in how to use the National Instruments hardware and software. From these, students were given four 3 h laboratory sessions to develop a working visible spectrophotometer in a project-based learning exercise. The image in Figure 2 demonstrates a student-designed visible spectrophotometer utilizing the hardware outlined herein.

This spectrophotometer had a wavelength range of 420−720 nm, calibrated against an OceanOptics USB-2000+ spectrophotometer connected via fiber optic cable in place of the photodiode detector. Due to the glass lenses used, UV spectroscopy was impossible, although with an increase in scan length, near IR spectra could be obtained. As a test of this device, the students made a solution of copper(II) sulfate at a known total concentration. Figure 3 demonstrates the data obtained from the pictured instrument (blue trace) compared with that obtained from a Vernier SpectroVis Plus visible spectrophotometer (red trace). Figure 3A shows the absorbance spectrum of the copper(II) ion, and it may be noted that the wavelength of maximal absorption matches that obtained by the commercial instrument, though the maximal absorption at this wavelength differed between the two instruments.

To further investigate this issue, Figure 3B demonstrates a calibration curve comparison of these two instruments at 700 nm. While both showed an error at 0.03 M (likely a dilution error on the part of the student), the calibration curve from the student instrument shows a significantly shallower slope than that of the commercial instrument. It is suspected that this is due to stray light as while this data was obtained in a near darkroom environment, the instrument was not enclosed and the detector was not shielded from the light source. This is reinforced through Figure 3A where deviation in absorbance is noted at higher wavelengths, where copper(II) absorbs more strongly. As absorption increased, stray light became more significant to the absorption reading.

■ CONCLUSION

Herein are demonstrated a series of 3D printable optical holders, posts, mounts, and associated functional parts for use in optical systems and analytical instrumentation. Presented devices include optical holders in 3 sizes, 0.5 in. diffraction grating mounts, mounting posts, post holders, cuvette holders, open lens holders, stepper motor mount components, an adjustable slit, and modular optical breadboard, all made available to the community under an open-source license. These designs have been demonstrated within an instrumental analysis course as students designed and constructed a working visible spectrophotometer using the mounts and devices

DOI: 10.1021/acs.jchemed.7b00480
J. Chem. Educ. 2018, 95, 672−677

designed in this work. All files have been made available at https://github.com/EdavisAPU/Education-Optics for modification, collaboration, and editing in future work. Readers are encouraged to upload modifications or additional designs based on these templates using this Web site. All designs have also been provided within Supporting Information.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.7b00480.

- 3D printed part designs (ZIP)
- UV–vis control software (ZIP)
- Bill of materials and assembly instructions for designed components (ZIP)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: edavis@apu.edu.

ORCID

Eric J. Davis: 0000-0001-9844-6243

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This material is based in part upon work supported by the National Science Foundation under Grant Number CHE-1507155. The authors would also like to thank the Azusa Pacific University Faculty Research Counsel for their support in this work.

■ REFERENCES

(1) Bharti, N.; Singh, S. Three-Dimensional (3D) Printers in Libraries: Perspective and Preliminary Safety Analysis. *J. Chem. Educ.* **2017**, *94* (7), 879–885.

(2) Pryor, S. W. Implementing a 3D printing service in an Academic Library. *Journal of LIbrary Administration* **2014**, *54* (1), 1–10.

(3) Griffith, K. M.; de Cataldo, R.; Fogarty, K. H. Do-It-Yourself: 3D Models of Hydrogenic Orbitals through 3D Printing. *J. Chem. Educ.* **2016**, *93*, 1586–1590.

(4) 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*, 1591–1594.

(5) Robertson, M. J.; Jorgensen, W. L. Illustrating Concepts in Physical Organic Chemistry with 3D Printed Orbitals. *J. Chem. Educ.* **2015**, *92*, 2113–2116.

(6) Rossi, S.; Benaglia, M.; Brenna, D.; Porta, R.; Orlandi, M. Three Dimensional (3D) Printing: A Straightforward, User-Friendly Protocol to Convert Virtual Chemical Models to Real-Life Objects. *J. Chem. Educ.* **2015**, *92*, 1398–1401.

(7) Striplin, D. R.; Blauch, D. N.; Carroll, F. A. Discovering Pressure-Volume-Temperature Phase Relationships with 3D Models. *Chemical Educator* **2015**, *20*, 271–275.

(8) 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*, 1960–1962.

(9) 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*, 2106–2112.

(10) Meyer, S. C. 3D Printing of Protein Models in an Undergraduate Laboratory: Leucine Zippers. *J. Chem. Educ.* **2015**, *92*, 2120–2125.

(11) Piunno, P. A. E. Teaching the Operating Principles of a Diffraction Grating Using a 3D Printable Demonstration Kit. *J. Chem. Educ.* **2017**, *94*, 615–620.

(12) Grasse, E. K.; Torcasio, M. H.; Smith, A. W. Teaching UV-VIS Spectroscopy with a 3D Printable Smartphone Spectrophotometer. *J. Chem. Educ.* **2016**, *93*, 146–151.

(13) Porter, L. A. J.; Chapman, C. A.; Alaniz, J. A. Simple and Inexpensive 3D Printed Filter Fluorometer Designs: User-Friendly Instrument Models for Laboratoyr Learning and Outreach Activities. *J. Chem. Educ.* **2017**, *94*, 105–111.

(14) Mueller, S.; Mohr, T.; Guenther, K.; Frohnhofen, J.; Baudisch, P. In *faBrickation: Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks*; SIGCHI Conference on Human Factors in Computing Systems, Toronto, Ontario, Canada, 2014.

(15) Knagge, K.; Raftery, D. Construction and Evaluation of a LEGO Spectrophotometer for Student Use. *Chem. Educ.* **2002**, *7* (6), 371–375.

(16) Wang, J. J.; Rodriguez Núñez, J. R.; Maxwell, E. J.; Algar, R. W. Build Your Own Photometer: A Guided-Inquiry Experiment to Introduce Analytical Instrumentation. *J. Chem. Educ.* **2016**, *93* (1), 166–171.

(17) Albert, D. R.; Todt, M. A.; Davis, H. F. A Low-Cost Quantitative Absorption Spectrophotometer. *J. Chem. Educ.* **2012**, *89* (11), 1432–1435.

(18) Tabbutt, F. Experiments and Equipment for Teaching Chemical Instrumentation. *J. Chem. Educ.* **1962**, *39* (12), 611–616.

(19) Ramaley, L.; Young, K.; Guy, R. D.; Stephens, R. Inexpensive Instrumental Analysis. *J. Chem. Educ.* **1994**, *71* (4), 353–357.

(20) Espalin, D.; Muse, D. W.; MacDonald, E.; Wicker, R. B. 3D Printing multifuncionality: structures with electronics. *International Journal of Advanced Manufacturing Technologies* **2014**, *72*, 963–978.

(21) Baden, T.; Chagas, A. M.; Gage, G.; Marzullo, T.; Prieto-Godino, L. L.; Euler, T. Open Labware: 3-D Printing Your Own Lab Equipment. *PLoS Biol.* **2015**, *13* (3), e1002086.

(22) Kitson, P. J.; Rosnes, M. H.; Sans, V.; Dragone, V.; Cronin, L. Configurable 3D-Printed millifluidic and microfluidic 'lab on a chip' reactionware devices. *Lab Chip* **2012**, *12*, 3267–3271.

(23) Zhang, C.; Anzalone, N. C.; Faria, R. P.; Pearce, J. M. Open-Source 3D-Printable Optics Equipment. *PLoS One* **2013**, *8* (3), e59840.

(24) Kosenkov, D.; Shaw, J.; Zuczek, J.; Kholod, Y. Transient-Absorption Spectroscopy of Cis-Trans Isomerization of N,N-Dimethyl-4–4′-azodianiline with 3D-Printed Temperature Controlled Sample Holder. *J. Chem. Educ.* **2016**, *93*, 1299–1304.

(25) Pearce, J. *Open-Source Scientific Tools*; https://www.thingiverse.com/jpearce/collections/open-source-scientific-tools/page:1 (accessed Jan 2018).

(26) Pandey, S.; Gupta, B.; Nahata, A. Terahertz plasmonic waveguides created via 3D printing. *Opt. Express* **2013**, *21* (21), 24422–24430.

(27) Busch, S. F.; Weidenbach, M.; Fey, M.; Schäfer, F.; Probst, T.; Koch, M. Optical Properties of 3D Printable Plastics in the THz Regime and their Application for 3D Printed THz Optics. *J. Infrared, Millimeter, Terahertz Waves* **2014**, *35* (12), 993–997.

(28) Stewart, C.; Giannini, J. Inexpensive, Open Source Epifluorescence Microscopes. *J. Chem. Educ.* **2016**, *93*, 1310–1315.

(29) Wijnen, B.; Anzalone, G. C.; Pearce, J. M. Open-source Mobile Water Quality Testing Platform. *J. Water, Sanit. Hyg. Dev.* **2014**, *4* (3), 532–537.

DOI: 10.1021/acs.jchemed.7b00480
J. Chem. Educ. 2018, 95, 672–677