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Review of Student-Built Spectroscopy Instrumentation Projects

Michelle L. Kovarik
Trinity College Hartford

Julia R. Clapis
Trinity College Hartford

K. Ana Romano-Pringle
STEMCivics Charter School

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Michelle L. Kovarik,* Julia R. Clapis, and K. Ana Romano-Pringle

Cite This: *J. Chem. Educ.* 2020, 97, 2185–2195

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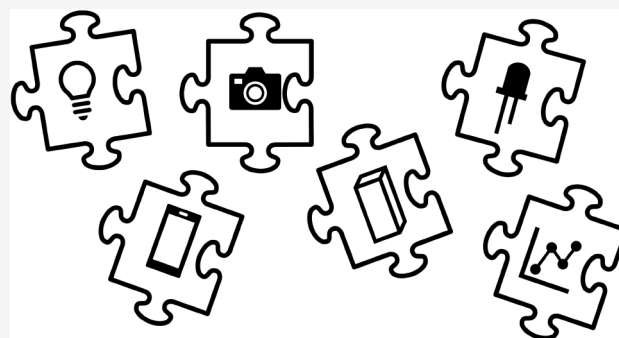
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ABSTRACT: One challenge of teaching chemical analysis is the proliferation of sophisticated, but often impenetrable, instrumentation in the modern laboratory. Complex instruments, and the software that runs them, distance students from the physical and chemical processes that generate the analytical signal. A solution to this challenge is the introduction of a student-driven instrument-building project. Visible absorbance spectroscopy is well-suited to such a project due to its relative simplicity and the ubiquity of absorbance measurements. This Article reviews simple instructor- and student-built instruments for spectroscopy, providing an overview of common designs, components, and applications. This comprehensive summary includes options that are suitable for in-person or remote learning with K–12 students and undergraduates in general chemistry, analytical chemistry, instrumental analysis, and electronics courses.

KEYWORDS: High School/Introductory Chemistry, First-Year Undergraduate, Upper-Division Undergraduate, Analytical Chemistry, Laboratory Instruction, Inquiry-Based/Discovery Learning, Spectroscopy, UV–Vis Spectroscopy, Atomic Spectroscopy



UV–vis absorbance spectroscopy is a workhorse measurement in industrial and academic laboratories. As a fundamental chemical measurement technique, it is often the earliest instrumental method introduced to students. However, even when students make their own measurements on modern UV–vis instruments, the measurement itself remains obscured inside the instrument case. One way to address this is to guide students in building their own spectroscopic instruments.

Most student-built photometers perform single-wavelength absorbance measurements, but others collect full absorbance spectra, fluorescence, or IR data. The majority of these instruments are constructed by undergraduates, but some projects are designed specifically for K–12 students.^{1–10} Instructors who undertake these activities have a variety of goals: to help students connect the abstraction of a block diagram with the reality of commercial instrumentation; to provide access to low-cost instrumentation when research-grade instruments are unavailable, including in remote learning situations; to develop students' understanding of Beer's law, including the effects of stray light and polychromatic light; and/or to promote active, authentic learning by allowing students to design, build and troubleshoot their own instruments.

In this review, we examine the existing literature on various low-cost, home-built spectroscopy devices (Box 1), including a review of construction materials, light sources, wavelength selectors, and detectors. While most activities have been tested with students, the extent of student involvement varies. Some instructors construct the instruments and provide them to students. In other cases, students build instruments from a kit or

Box 1. Device Definitions

Photometer: a device for measuring light intensity

Spectroscope: a device for viewing the spectrum of a light source (see Figure 1a)

Colorimeter: a device for measuring absorbance of a certain color of light with wavelength discrimination achieved by filters or wavelength-selective detectors (e.g., RGB channels of a digital camera) (see Figures 2a and 3a)

Spectrophotometer: a device for measuring light intensity across wavelength range with discrete measurements for each wavelength (see Figure 4a)

a set of components. In the most open-ended activities, students design devices independently, requesting components or selecting them from a variety of available items. We include this entire range of papers, including those on instructor-built instruments, since students are likely capable of building these given sufficient time and guidance. To aid instructors in selecting an appropriate project, Table 1 summarizes the main instrument

Received: April 28, 2020

Revised: June 14, 2020

Published: July 20, 2020

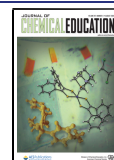


Table 1. Summary of Potential Spectroscopy Instrumentation Building Projects

instrument	suitable student audiences	time required for instrument construction	approximate cost	readily adapted to remote learning?
spectroscopes for viewing emission spectra	K–12, general chemistry	≤1 h	\$1–10	yes
colorimetry with cell phones, digital cameras, and scanners	K–12, general chemistry	3–6 h	\$1–20	yes
multicomponent colorimeters	introductory analytical, instrumental analysis	9–12 h	\$5–50	possibly
visible absorbance spectrophotometers	instrumental analysis	12–20+ h	\$10–200	no
fluorimeters and atomic emission instruments	instrumental analysis, graduate education	12–20+ h	\$30–500+	no

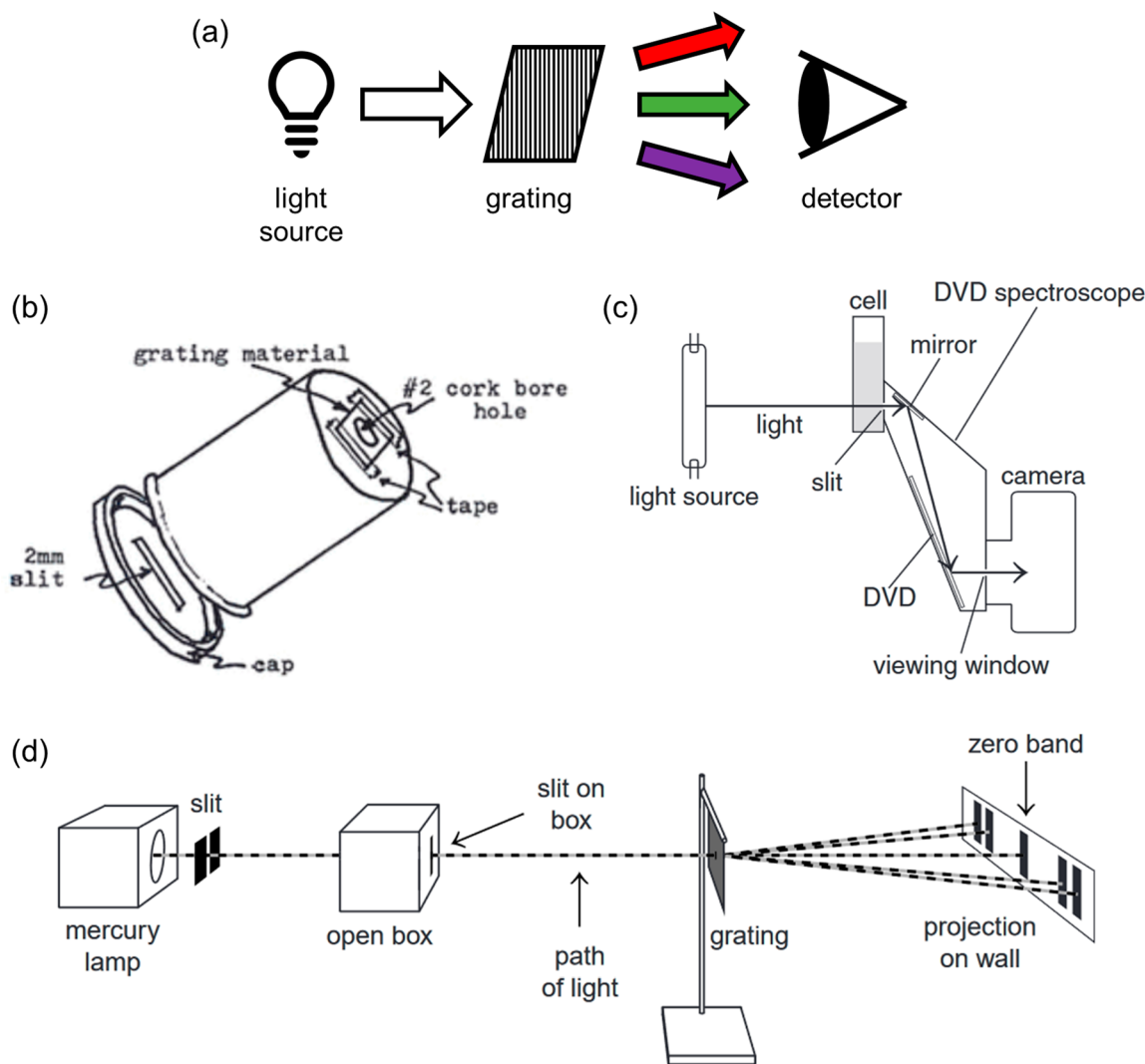


Figure 1. (a) Basic design of spectroscopes for viewing emission lines. (b) Simple spectroscope consisting of a film canister and grating for viewing emission lines by eye. Reproduced from ref 16, with the permission of the American Association of Physics Teachers. (c) Periscope-style spectroscope that accommodates a camera and collection of sample absorbance spectra. Reproduced from ref 19. Copyright 2008 American Chemical Society. (d) Setup for projecting emission lines onto a wall for class viewing. Reproduced from ref 24. Copyright 2005 American Chemical Society.

types and their approximate cost and time requirements, suitability for various student groups, and compatibility with remote learning.

■ SPECTROSCOPES FOR VIEWING EMISSION SPECTRA

The earliest reports of home-built spectroscopes are simple boxes equipped with a diffraction grating for viewing atomic emission lines from lamps, flames, or the solar spectrum

(Fraunhofer lines). These devices do not require a separate light source or sample holder since the “samples” are emission sources; students simply point the device at the light and observe the resulting spectral lines (Figure 1a). Most devices are constructed using a cardboard box,^{2,11–14} but PVC pipe¹⁵ and film canisters^{16,17} are sturdier options (Figure 1b). (Although 35 mm film is not commonly used today, empty canisters are available online.) For whole class viewing, the design may be modified to record spectra using a camera (Figure 1c)^{18–22} or to project spectra onto a screen (Figure 1d).^{23,24} Using a digital

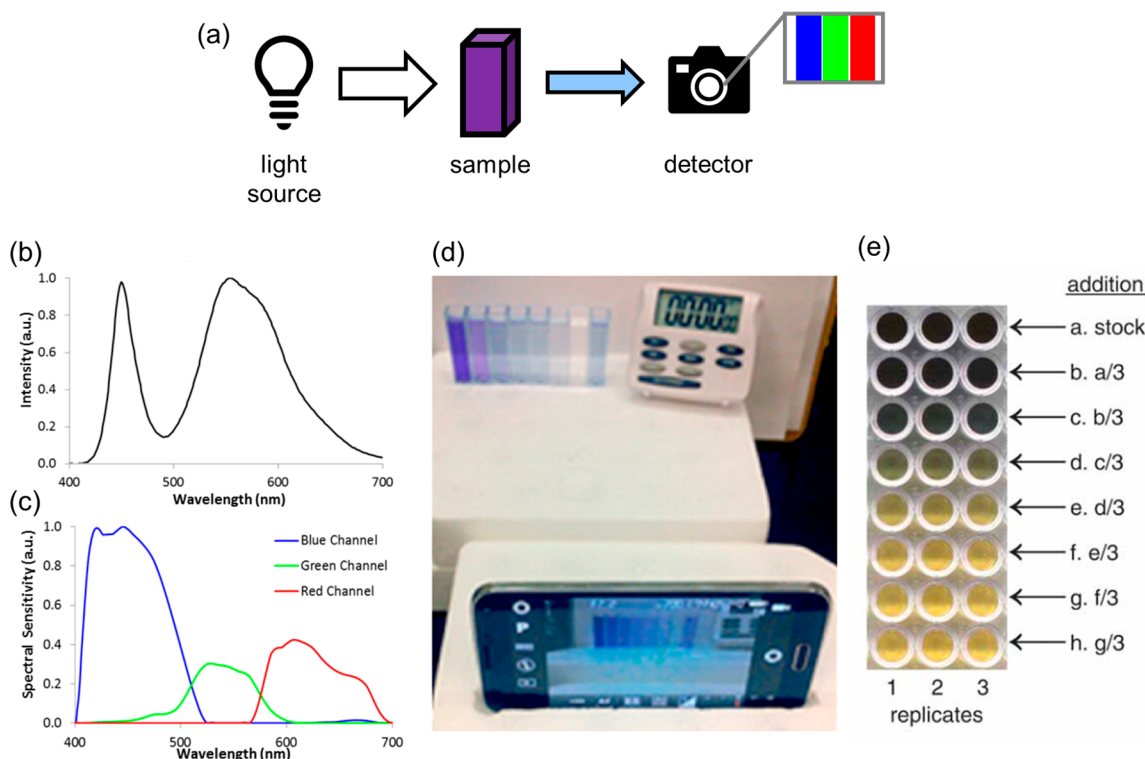


Figure 2. (a) Basic design of colorimetric measurements made using RGB channels of digital cameras or scanners. (b) Output spectrum of a white LED on a flatbed scanner. (c) Sensitivity of the three RGB color channels on a digital camera. (b, c) Reproduced from ref 28. Copyright 2015 American Chemical Society. (d) Example setup for a kinetics experiment using cellphone colorimetry. Reproduced from ref 38. Copyright 2015 American Chemical Society. (e) Sample image for iodide determination using scanner colorimetry. Reproduced from ref 46. Copyright 2004 American Chemical Society.

camera, students can extract quantitative data using freely available software, such as ImageJ.²² Emissions from a mercury lamp may be used to calibrate the wavelength scale.^{12,20,21} Inexpensive gratings are available from online sources, including vendors of optical components. Alternatively, small sections of a CD^{13,22} or DVD^{14,19,21} may be used; DVDs generally produce higher resolution spectra than CDs due to their finer grooves (1350 versus 625 lines/mm).¹⁴ These devices can even be used as simple spectrophotometers by viewing a sample backlit with white light (e.g., Figure 1c).^{13,19} Because of their simplicity, these spectroscopes have been constructed by high school or college students in under an hour, making them an excellent choice for a short classroom activity or a remote lab experience.

COLORIMETRY WITH CELL PHONES, DIGITAL CAMERAS, AND SCANNERS

Several authors report methods that use ambient light,^{25,26} a commercial or homemade light box,^{7,27–29} an LCD screen,^{8,30–32} or other white LED illumination (Figure 2a,b) to illuminate samples and a digital camera to record their absorbances. Color digital cameras collect data in three color channels [red, green, and blue (RGB)], corresponding to pixels that are sensitive to light at wavelengths of approximately 620, 550, and 450 nm, respectively (Figure 2c).²⁸ The ubiquity of cell phone cameras makes them a popular tool for this form of colorimetry (Figure 2d),^{7,8,26,28,29,31–37} and free apps provide greater control over image acquisition and processing.^{36,38} Other image processing software, including freeware such as ColorX,³⁶ ImageJ,³⁹ GIMP,⁴⁰ and/or R,⁴¹ extracts pixel intensity data from the most relevant color channel. Using a cell phone camera and food dye samples, students could conduct these

experiments remotely without purchasing any additional supplies, or more complex experiments are possible in-person. Students may investigate how their choice of color channel influences the sensitivity of the method, leading to the insight that molecules absorb light complementary in color to the light they transmit. Optimal results are obtained when the absorbance maximum of the analyte is close to the maximum sensitivity wavelength for one of the color channels, but even in these cases the sensitivity is lower than that obtained using a commercial spectrophotometer due to polychromatic light.²⁸ Despite this limitation, accurate quantitative data may be obtained, including analyte concentrations,^{7,8,27,28,32,34–37} binding stoichiometries,²⁶ diffusion coefficients,³¹ and rate constants.^{29,30,33,38} Many analytes have been tested, including complexed and free metal ions,^{7,26,32–34,36} organic dyes,^{7,27,30,37,38} gold nanoparticles,³⁸ and biochemical samples such as proteins, enzymes, and ELISA kits.^{8,28,29,36} In addition to their simplicity and low cost, these methods are compatible with solid samples, such as paper-based microfluidics⁴² or fluorimetry,^{43,44} and avoid interference from scattering due to particulates.^{29,45}

Color desktop scanners are used in a similar fashion for high-throughput readouts of samples in microwell plates (Figure 2e). This method is particularly useful for large sample sets for calibration curves in quantitative analyses,^{46–49} photometric titration curves,⁵⁰ or kinetic analyses.⁴⁵ Possible assays include measurements of starch in potatoes,⁴⁶ ionic species in water,⁴⁷ acetylsalicylic acid in aspirin tablets,⁴⁸ phenols in beer,⁴⁹ titratable acidity in wine,⁵⁰ and amylase activity in saliva.⁴⁵ The best results are obtained when the scanner is in transmission mode, rather than reflectance mode, since this mode maximizes pixel uniformity.²⁸ The ImageJ plug-in ReadPlate greatly

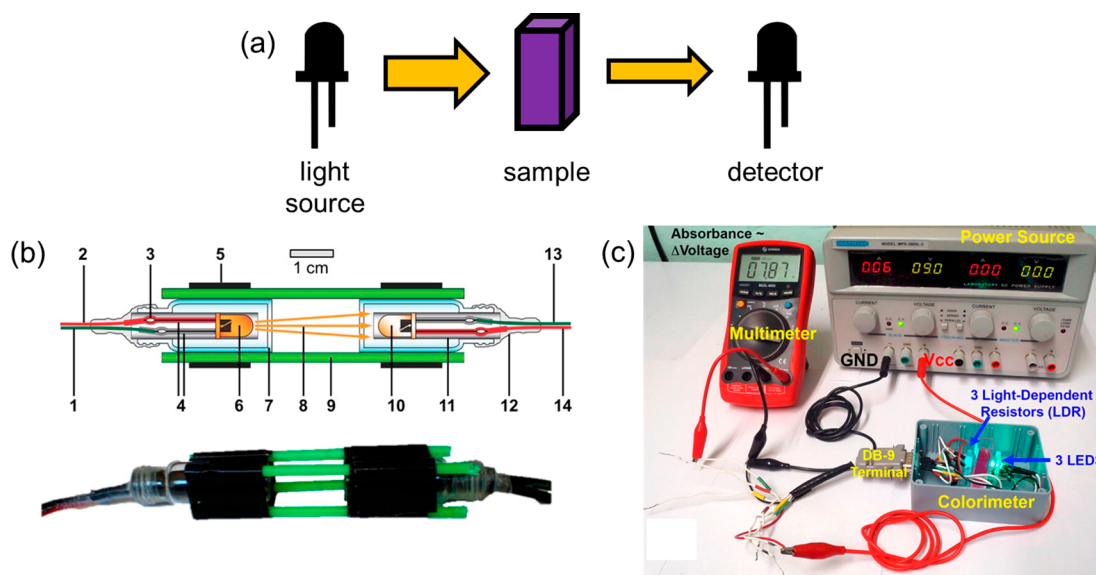


Figure 3. (a) Basic design of a single-wavelength colorimeter. (b, c) Examples of student-built colorimeters of this type. (b) Submersible colorimeter for titrations. Labels: 1–3 and 13–14, electrical connections; 4, heat shrink tubing; 5, electrical tape; 6, LED light source; 7, glass vial lens; 8, 2 cm path length; 9, plastic cotton swab; 10, LED detector; 11, plastic straw; 12, parafilm. Reproduced from ref 59. Copyright 2016 American Chemical Society. (c) Colorimeter with choice of three wavelengths. Reproduced from ref 56. Copyright 2014 American Chemical Society.

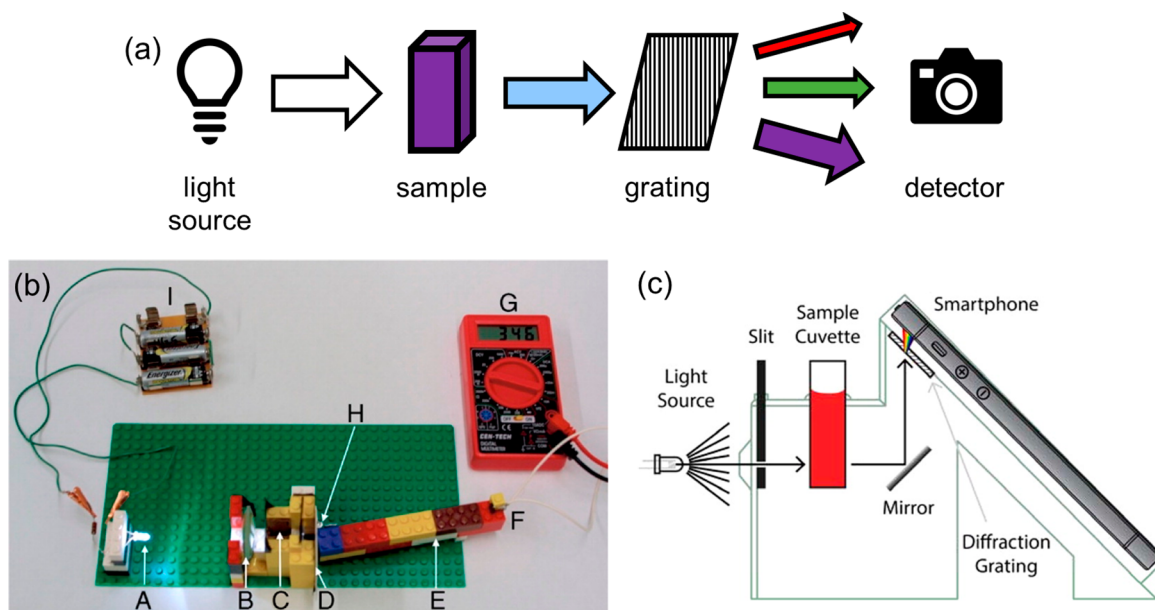


Figure 4. (a) Basic design of student-built spectrophotometers. If a point detector is used instead of a camera, an optional slit may be added after the grating. (b, c) Examples of student-built spectrophotometers. (b) LEGO spectrophotometer. Labels A–G indicate the LED light source, lens, cuvette holder, grating, rotatable detector arm, photodiode, digital multimeter, hinge, and power supply, respectively. Reproduced from ref 6. Copyright 2012 American Chemical Society. (c) 3D-printed spectrophotometer with smartphone camera detection. Reproduced from ref 66. Copyright 2016 American Chemical Society.

expedites data analyses for scanner-based colorimetry in microwell plates, allowing students to collect large data sets efficiently.^{48–51}

MULTICOMPONENT COLORIMETERS

More complex projects produce actual colorimeters from individual components that include single-wavelength light sources matched to sample absorbance, a sample holder, and a separate detector (Figure 3a). These instruments vary widely in complexity. Most instruments are single-beam and measure absorbance for a single color (Figure 3b), but double-beam

designs^{37,52,53} and instruments with multiple LEDs or filters^{1,54–57} to accommodate varying absorbance maxima (Figure 3c) have been published. One device that included seven LEDs could even approximate the absorbance spectra of analytes.⁵⁸ Single-wavelength designs are straightforward to construct and potentially compatible with remote learning, but they are limited to analytes that absorb at the selected wavelength. Multiwavelength devices are more flexible in application, but they require additional time and more direct instructor input.

VISIBLE ABSORBANCE SPECTROPHOTOMETERS

Home-built spectrophotometers that include a wavelength selection component are capable of collecting true absorbance spectra (Figure 4a). These instruments are significantly more complex than even multicomponent colorimeters, require careful alignment and wavelength calibration, and are best constructed in stages over several weeks by more advanced students in analytical chemistry or instrumental analysis.^{60,61} These more sophisticated instruments allow students to explore factors that affect instrument performance (e.g., slit width and resolution) in addition to investigating Beer's law. An early example of a spectrophotometer constructed for pedagogical purposes was published in 1953, but the instrument was quite complex.⁶² More recently, modular, commercial spectroscopic components have permitted students to build and compare UV-vis absorbance, fluorescence, and Raman instrumentation, but high quality components made this exercise expensive (\$1800–8650).⁶³ Lower-cost commercial kits are available for \$9–120,^{64,65} but materials for self-designed instruments are also readily available. Most publications use off-the-shelf parts, and the complete devices are usually relatively inexpensive (\$10–100). Below, we discuss options for individual components for multicomponent colorimeters and spectrophotometers, including housings, light sources, wavelength selectors, detectors, electronics, software, and commonly used samples.

Construction Materials

Many low-cost devices are constructed from cardstock or cardboard boxes,^{19–21,24,32,67–71} but other options include plastic,^{5,56,72–75} or aluminum housings,^{1,57,76} wood,^{77–80} PVC pipe,⁸¹ or professional optical mounts.^{60,82} A unique device using a graduated cylinder permitted careful investigation of the effect of path length on absorbance.⁸³ More recently, LEGO blocks (Figure 4b)^{6,10,61,84–92} and 3D printing (Figure 4c)^{37,66,93–99} have become popular. While commercial optical mounts are fairly expensive, designs for 3D-printed lens mounts, posts, gratings, cuvette holders, and a breadboard are freely available,⁹⁸ and some common optical components may be constructed from LEGOs.⁸⁴ Because one purpose of the housing is to minimize stray light, the addition of black felt, paint, or fabric is helpful. Beyond this, the housing plays a minimal role in performance, so students and instructors may choose materials based on availability, cost, and convenience.

Light Sources

Although some photometers use lamps,^{54,60,62,63,66,69,75,76,85,98} or even a flashlight³ or laser pointer,⁷⁰ LEDs are by far the most popular light source due to their low cost and ease of use. LEDs are readily powered by coin batteries or alkaline batteries (e.g., AA or 9 V) or, for more stable output, a wall outlet and a power converter. (Students should avoid exceeding the rated voltage of the LED and bias it correctly.) Single color LEDs have spectral bandwidths of 10–70 nm, which may lead to deviation from Beer's law due to polychromatic light;¹⁰⁰ however, their performance is typically acceptable if their maximum emission wavelength is well-matched to the maximum absorbance of the analyte. White light LEDs have also improved over the past decade, providing full coverage of the visible spectrum, albeit with variable intensity (Figure 2b). For this reason, data collection for an appropriate blank is critical. UV LEDs are also available for 265–400 nm. LEDs with emission maxima of 355–375 nm have been used for UV absorbance measurements,^{88–90} but availability decreases and cost increases for shorter wavelengths.¹⁰¹

Wavelength Selection

Because most multicomponent colorimeters use a narrow band source, such as a laser pointer or LED, no wavelength selection mechanism is required (although some colorimeters may include a white light source coupled with one or more filters).⁵⁴ However, a diffraction grating is needed for true spectrophotometers. As noted above, CDs or DVDs make inexpensive reflection gratings, or low-cost gratings are available online. Once white light is dispersed, the entire spectrum can be simultaneously captured using a digital camera.^{66,69,80,82,86,102,103} Alternatively, the grating may be coupled with one or more lenses and/or slits to produce a monochromator. The addition of lenses improves performance but increases cost, but one or more slits can be added without great expense. A pair of razor blades or a caliper mounted to the housing provides a simple, effective slit with controllable width.^{20,24,60,75,80,98} Alternatively, slits have been prepared by 3D-printing⁶⁶ or from heavy paper.⁹¹ When slits are included, students can make a systematic study of the effect of slit width on wavelength resolution.⁶⁶ However, alignment of the grating relative to other components is challenging, so these devices require significantly more time than a colorimeter or a spectrophotometer using a camera as an array detector. (If time is limited, separate investigations of an isolated grating are possible.²³) Additionally, spectrophotometers typically require wavelength calibration. Students at Doane College compared a holmium oxide reference cell, solutions with varying absorbance maxima, and various colors of LEDs or laser pointers. The best results were obtained using sample solutions of different colors.⁶¹ Alternatively, RSpec or ImageJ software may be used for wavelength calibration.^{66,69,80,104}

Detectors

Four main types of low-cost, solid state light detectors are available: LEDs,^{59,87–90,92,94,105} photodiodes,^{5,6,61,91,98,106–111} light dependent resistors (LDRs, also known as photocells or photoresistors),^{3,4,52,54,56,61,62,71,73,74,77,83,97,110,112–116} and phototransistors.^{72,117} The first option, an LED, is commonly used as a light source in the emission mode; however, forward biased LEDs can be repurposed as detectors for light of slightly higher energy than the light they emit (Figure 3b).^{118–120} When such light strikes the LED, a photocurrent is generated.¹²⁰ This effect is useful to detect a narrow band of wavelengths since the LED responds only to wavelengths just below its emission maximum.¹¹⁸ The second option, photodiode detectors, may be operated in photovoltaic or photoconductive mode. In photovoltaic mode, no voltage is applied, and photons generate a voltage difference across a resistor. In photoconductive mode, a reverse bias is applied, and photocurrent is measured. In general, photovoltaic mode is recommended because it is simpler and has better signal-to-noise ratios for low light; however, response times are slower compared to photoconductive mode.¹²¹ The third option, a LDR, decreases in resistance when photons excite electrons into the conduction band (Figure 3c). One advantage of LDRs is that their resistance is directly proportional to analyte concentration, which makes an intuitive readout for novice users;⁷⁴ however, the response to light intensity is not linear over the entire working range, so correction may be needed for quantitative applications.⁷¹ Finally, a phototransistor functions similarly to a photodiode but generates intrinsic signal amplification. For even higher sensitivity, a photodarlington, which consists of a pair of transistors, may be used.^{121,122}

Instructors or students have several considerations when choosing the best detector for their application. In general, LEDs have lower cost than photodiodes do but are also less precise and less sensitive.^{118,123} LDRs are generally even more sensitive in the visible range than photodiodes,⁶¹ and phototransistors are more sensitive still.⁹⁶ Student comparisons of a photodiode, LDR, and photodarlington suggest that the LDR produces the most accurate results.⁶⁷ If possible, students should evaluate multiple detector options (experimentally or through reading and research) and justify their choice based on the need for sensitivity, precision, and accuracy.

Finally, for simultaneous multicolor detection, array detectors are available, including photodiode arrays^{1,57} and digital cameras, which detect the entire spectrum in a single image (Figure 4c).^{66,69,80,82,86,102,103} This option is the simplest and fastest for the collection of full absorbance spectra since cell phone cameras are ubiquitous and the alignment requirements are less stringent than those with point detectors. For higher resolution, the larger sensor area of a SLR digital camera improves the performance compared to a cell phone or webcam,⁸² and in even more sophisticated instruments a linear CCD may replace the digital camera.^{60,75}

Electronics

Students may also explore the role of electronics in instrument design. For example, a multiweek laboratory allows students to build circuitry for high- and low-pass filters, an oscillator, a current-to-voltage converter, and a microcontroller interfaced with a photometer.¹¹⁰ Similarly, students can build a lock-in amplifier from a published design for <\$100.¹²⁴ While most home-built instrumentation uses a multimeter to record voltage or resistance, fully integrated devices using the open-source electronics platform Arduino^{93,97,110} and a low cost Raspberry Pi computer⁹¹ are possible. Alternatively, LabView programming can run home-built instrumentation,^{59,60,98,111} or students can develop their own apps.⁸⁶ These tools give students programming experience and lead to devices that report absorbance values directly, like a commercial instrument, rather than requiring further calculations to convert voltage or resistance to absorbance value. For instructors and students who are still mastering these tools, several references provide sample code and instructions.^{91,97,110}

Common Samples and Experiments

Absorbance spectroscopy is a widely used technique that is applicable to many analytes, but popular samples for visible absorbance measurements include brightly colored metal salts (such as Co(II), Cu(II), and Ni(II), which form colored complexes in aqueous solution) and strongly absorbing organic indicators and dyes (Table 2), including common food colorings (such as Red 40, Yellow 5, and Blue 1) that are compatible with remote instruction. Simple experiments ask students to develop the Beer's law relationship showing the linear relationship between absorbance and concentration or path length.^{7,31,32,83,87,96} More involved experiments may require students to perform a kinetic analysis,^{10,38,56,79,97} complete a photometric titration,^{59,108,117} detect analytes in eluent using a flow cell,⁹⁷ or compare their devices to commercial instrumentation. Many student-built systems are suitable for quantitative analysis and produce results that compare favorably with those from more expensive instruments. For example, several studies report relative errors $\leq 10\%$ compared to a commercial instrument^{8,34,67,70,88,109} and relative standard deviations $\leq 2\%$.^{117,125} Limits of detection (LODs) vary widely depending on

Table 2. Common Analytes for Student-Built Photometers^a

name	absorbance maximum (nm)	molar absorptivity (cm ⁻¹ M ⁻¹)	ref
folic acid	259	32,359	127
	368	7413	
cinnamaldehyde	281		127
quinine	332		127
Yellow 5 (tartrazine)	428		9
fluorescein	499	101,700	127
Red 40 (Allura Red AC)	502		9
methyl red	521	57,544	127
potassium permanganate (KMnO ₄)	545	26,600	128
Methylene blue	605	50,119	127
	660	50,119	
bromothymol blue	616	35,000	129
Blue 1 (Brilliant Blue FCF)	630		9
chlorophyll <i>a</i>	670	100,000	127

^aNote that absorbance maxima and molar absorptivity values are solvent dependent.

instruments and analytes with student-designed instrumentation yielding LODs that are 3–200× higher, or occasionally comparable to, those of commercial instruments.^{28,60,105,129}

■ FLUORESCENCE AND ATOMIC EMISSION INSTRUMENTS

More complex instrumentation for other spectroscopic methods provides excellent projects for instrumental analysis students, or potentially graduate students. Because they are similar in design to absorbance instruments, fluorimeters are a good option; however, fluorescence measurements pose additional challenges. First, fluorescence is proportional to the intensity of the excitation light.¹³⁰ Consequently, the first instructor-built example used a nitrogen laser, resulting in high cost (>\$3000) and safety considerations.¹²⁶ Newer systems using a red diode laser¹⁰⁶ or UV lamp^{43,73} address these concerns. More recently, higher intensity LEDs have become available, permitting visible^{95,107,111} or UV^{5,89,90} LED excitation. For highly fluorescent analytes, such as fluorescein or highlighter inks, it is even possible to excite detectable signals using the blue output from a LCD screen⁴⁴ or a flashlight covered with a cellophane filter.⁶⁸ A second challenge to student-built fluorescence instrumentation is the increased need for wavelength selection. A traditional spectrofluorimeter includes two monochromators to select excitation and emission wavelengths.¹³⁰ Simpler and lower cost wavelength selection is achieved by using narrow band excitation sources (such as lasers or LEDs), filters,^{5,106,107,111} detectors with wavelength selectivity (including LEDs),^{89,90,95} and/or RGB image analysis (Figure 5a).^{43,44} The most common analytes are quinine,^{5,73,89,90,95,126} which requires UV excitation, or fluorescein.^{43,44,107,111,126} Both are compatible with real-world samples (tonic water⁵ or antifreeze,¹⁰⁷ respectively) and are quenched by halide ions, allowing students to construct Stern–Volmer plots.^{43,44,73,89,90,111} Other potentially interesting analytes include riboflavin and salicylic acid,¹²⁶ chlorophyll,¹⁰⁷ whitening agents in paper, and vitamin B1 (after oxidation by mercuric chloride).⁵ For a slightly higher cost, a fluorescence microscope with 2× magnification may be used to view Lawson-stained fingerprints (Figure 5b).⁸¹

At the next level of complexity, low-cost flame atomic emission instruments can detect alkali metals,^{25,109,115,125,131,132}

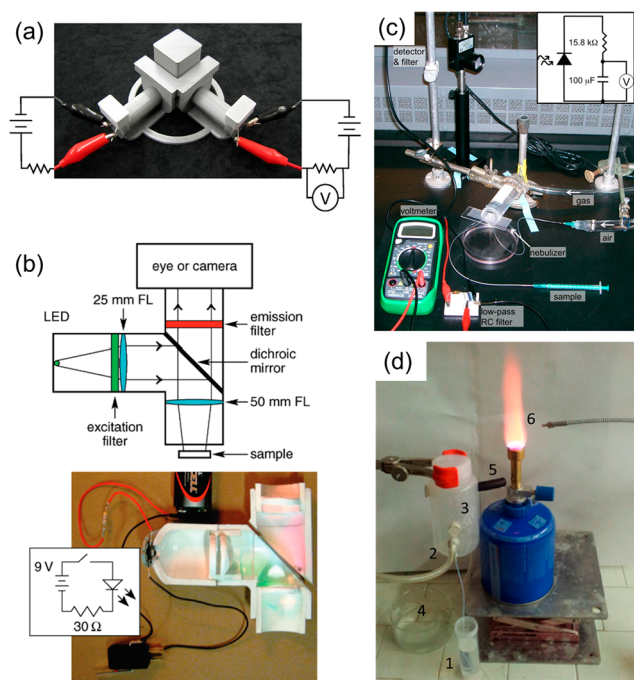


Figure 5. Home-built instrumentation for fluorescence and atomic emission spectroscopy. (a) 3D-printed filter fluorimeter. Reproduced from ref 95. Copyright 2017 American Chemical Society. (b) LED-based fluorescence microscope with 2X magnification. Reproduced from ref 81. Copyright 2010 American Chemical Society. (c) Bunsen burner flame atomic emission setup with a homemade nebulizer. Reproduced from ref 109. Copyright 2013 American Chemical Society. (d) Camping burner flame atomic emission setup. Reproduced from ref 125. Copyright 2014 American Chemical Society. Labels 1–6 correspond to the sample, nebulizer, spray chamber, waste, burner, and optical fiber, respectively.

since these elements are excited at relatively low temperatures.¹³⁰ Home-built instruments have been used to quantify potassium in beer,¹³¹ sodium in sports drinks,¹⁰⁹ seawater and coconut water,²⁵ and standard salt solutions.^{115,125,132} A sample nebulizer may be scavenged from a commercial instrument, constructed from common laboratory glassware (Figure 5c)¹³¹ or plasticware,¹⁰⁹ 3D-printed,¹²⁵ or replaced with a perfume atomizer.²⁵ Excitation occurs via a Bunsen burner,^{25,109,131} a propane camp burner (Figure 5d),¹²⁵ or a salvaged slot burner.¹³² Because a hotter flame yields more intense emission, a propane camp burner (2250 K) produces more signal than a Bunsen burner (1400 K) does, and an acetylene flame (2700–3300 K) should result in even higher emission.¹²⁵ Wavelength selection is required to reject stray light from the flame. To this end, students can extract the most relevant RGB color channel from cellphone videos,²⁵ place a filter between the flame and a point detector, such as a photoresistor or photodiode,^{109,115} or include a monochromator or commercial spectrometer (cost-permitting).^{125,131,132}

Beyond fluorescence and atomic emission instrumentation, several other student-built spectroscopic instruments have been demonstrated, including scattering measurements,^{99,116} polarimetry,⁵² and UV^{88–90} and IR^{113,124,133} absorbance spectroscopy. Home-built IR instruments have been applied to greenhouse gases,¹³³ ammonia,¹²⁴ and kerosene-adulterated gasoline (Figure 4a),¹¹³ and important principles of FT-IR, such as Fourier transformation and interferometry, have been demonstrated using visible light and LEGO blocks.⁸⁴ For advanced

students, instructors could imagine a broad range of spectroscopic instrument building projects.

RECOMMENDATIONS AND CONCLUSIONS

Few papers on student-built spectrophotometers formally assess student learning outcomes, and most of these focus on student surveys, which generally show that students believe these activities improve their understanding of spectroscopy and take pride in their instruments. For example, surveys suggested that digital imaging of fluorescence in well plates improved understanding of fluorescence generally and quenching specifically.⁴³ Wang et al. reported that students were proud of their photometers and valued the experience.⁵⁹ Diawati et al.'s student questionnaires and interviews showed that students found photometer construction to be challenging but interesting and were more confident in their understanding after the project.⁷⁰ Similarly, second-year students in analytical chemistry reported that a photometer-building project enhanced their understanding of solution preparation, spectrophotometry, and Beer's law.⁷¹ However, these studies are limited in that they include only students' self-reported outcomes. Wilson and Wilson studied a multiweek, open-ended project in which students built spectroscopic instruments from their own designs. In addition to positive affective changes, these authors also observed a 28% increase in post-test scores relative to pretest scores, with particular improvement on questions related to instrument design and troubleshooting,⁶¹ suggesting that students' self-evaluations of their learning may be accurate. Depending on project design, students may develop their understanding of Beer's law, the relationships between transmittance and absorbance, and/or the operating principles of spectroscopic instrumentation, including electronics and data processing. Nevertheless, future studies must examine how learning outcomes vary with the duration, complexity, and structure of these activities in order to guide practitioners implementing instrument-building activities.

In the meantime, instructors have a wide range of instruments and project structures from which to choose. This flexibility means that instrument-building may be incorporated into the curriculum at several points, from K–12 and general chemistry to advanced instrumentation and electronics coursework. Additionally, projects may be tailored to the time available, from simple spectrometers for viewing atomic emission during a lecture period to open-ended, multiweek projects that include optimization, characterization, and application. This review points to useful resources for instructors interested in adopting or adapting published examples to their own classrooms and laboratories. More detailed information regarding individual publications may be found in the annotated bibliography in the Supporting Information.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemeduc.0c00404>.

Annotated bibliography summarizing references cited in this paper (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Michelle L. Kovarik — Department of Chemistry, Trinity College, Hartford, Connecticut 06106, United States; orcid.org/0000-0001-8225-2487; Email: michelle.kovarik@trincoll.edu

Authors

Julia R. Clapis — Department of Chemistry, Trinity College, Hartford, Connecticut 06106, United States

K. Ana Romano-Pringle — STEMCivics Charter School, Ewing, New Jersey 08146, United States

Complete contact information is available at:

<https://pubs.acs.org/10.1021/acs.jchemed.0c00404>

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by Trinity College and by a Cottrell Scholar Award to M.L.K. from Research Corporation for Science Advancement.

■ REFERENCES

- (1) Hughes, B. Assembly and Validation of a Colorimeter. *Technol. Eng. Teach.* **2013**, 72 (6), 32–36.
- (2) Thompson, K. An Easy-to-Build Spectroscope. *Phys. Educ.* **1996**, 31 (6), 382–385.
- (3) Lema, M. A.; Aljinovic, E. M.; Lozano, M. E. Using a Homemade Spectrophotometer in Teaching Biosciences. *Biochem. Mol. Biol. Educ.* **2002**, 30 (2), 106–110.
- (4) Tavener, S. J. Build your own spectrophotometer. *Education in Chemistry*; Royal Society of Chemistry, 2007. <https://eic.rsc.org/feature/build-your-own-spectrophotometer/2020107.article> (accessed 2020-06-14).
- (5) Wigton, B. T.; Chohan, B. S.; McDonald, C.; Johnson, M.; Schunk, D.; Kreuter, R.; Sykes, D. A Portable, Low-Cost, LED Fluorimeter for Middle School, High School, and Undergraduate Chemistry Labs. *J. Chem. Educ.* **2011**, 88 (8), 1182–1187.
- (6) Albert, D. R.; Todt, M. A.; Davis, H. F. A Low-Cost Quantitative Absorption Spectrophotometer. *J. Chem. Educ.* **2012**, 89 (11), 1432–1435.
- (7) Kehoe, E.; Penn, R. L. Introducing Colorimetric Analysis with Camera Phones and Digital Cameras: An Activity for High School or General Chemistry. *J. Chem. Educ.* **2013**, 90 (9), 1191–1195.
- (8) Gee, C. T.; Kehoe, E.; Pomerantz, W. C. K.; Penn, R. L. Quantifying Protein Concentrations Using Smartphone Colorimetry: A New Method for an Established Test. *J. Chem. Educ.* **2017**, 94 (7), 941–945.
- (9) Rowland, T.; Bonham, A. See the Light by Making a Cell Phone Spectrophotometer | Science Project. *Science Buddies*. https://www.sciencebuddies.org/science-fair-projects/project-ideas/Chem_p100/chemistry/make-a-cell-phone-spectrophotometer (accessed 2020-06-14).
- (10) Irving, D. Building a Visible Light Spectrophotometer; Polytechnic Institute of NYU. http://engineering.nyu.edu/gk12/amps-cbri/pdf/visible_light_spectrophotometer.pdf (accessed 2020-06-14).
- (11) Edwards, R. K.; Brandt, W. W.; Companion, A. L. A Simple and Inexpensive Student Spectroscope. *J. Chem. Educ.* **1962**, 39 (3), 147.
- (12) Cortel, A.; Fernandez, L. A Simple Diffraction Grating Spectroscope: Its Construction and Uses. *J. Chem. Educ.* **1986**, 63 (4), 348.
- (13) Wakabayashi, F.; Hamada, K.; Sone, K. CD-ROM Spectroscope: A Simple and Inexpensive Tool for Classroom Demonstrations on Chemical Spectroscopy. *J. Chem. Educ.* **1998**, 75 (12), 1569.
- (14) Wakabayashi, F.; Hamada, K. A DVD Spectroscope: A Simple, High-Resolution Classroom Spectroscope. *J. Chem. Educ.* **2006**, 83 (1), 56.
- (15) Hughes, E. Suitable Light Sources and Spectroscopes for Student Observation of Emission Spectra in Lecture Halls. *J. Chem. Educ.* **1984**, 61 (10), 908.
- (16) Heideman, E. P. Apparatus: For Teaching Physics. *Phys. Teach.* **1990**, 28 (5), 343–343.
- (17) Katz, D. A. Build a Spectroscope. <http://www.chymist.com/Make%20a%20Spectroscope.pdf> (accessed 2020-06-14).
- (18) Kolb, K. B. Apparatus for Teaching Physics: Instant Spectrograph. *Phys. Teach.* **1966**, 4 (6), 285–286.
- (19) Wakabayashi, F. Resolving Spectral Lines with a Periscope-Type DVD Spectroscope. *J. Chem. Educ.* **2008**, 85 (6), 849.
- (20) Wahab, M. F. Estimating the Wavelength of Sodium Emission in Flame — The Easy Way. *Phys. Teach.* **2009**, 47 (6), 367–369.
- (21) Widiatmoko, E.; Widayani, Budiman, M.; Abdullah, M.; Khairurrijal. A Simple Spectrophotometer Using Common Materials and a Digital Camera. *Phys. Educ.* **2011**, 46 (3), 332–339.
- (22) Garrido-González, J. J.; Trillo-Alcalá, M.; Sánchez-Arroyo, A. J. Lights, Camera, Spectroscope! The Basics of Spectroscopy Disclosed Using a Computer Screen. *J. Chem. Educ.* **2018**, 95 (5), 903–907.
- (23) Kruglyak, H. The Compact Disc as a Diffraction Grating. *Phys. Educ.* **1991**, 26 (4), 255–256.
- (24) Diaz, L.; Smith, C. A. Investigating the Photoelectric Effect Using LEDs and a Modular Spectroscope. *J. Chem. Educ.* **2005**, 82 (6), 906.
- (25) Moraes, E. P.; da Silva, N. S. A.; de Moraes, C. de L. M.; Neves, L. S. d.; Lima, K. M. G. de. Low-Cost Method for Quantifying Sodium in Coconut Water and Seawater for the Undergraduate Analytical Chemistry Laboratory: Flame Test, a Mobile Phone Camera, and Image Processing. *J. Chem. Educ.* **2014**, 91 (11), 1958–1960.
- (26) de Moraes, C. de L. M.; Silva, S. R. B.; Vieira, D. S.; Lima, K. M. G. Integrating a Smartphone and Molecular Modeling for Determining the Binding Constant and Stoichiometry Ratio of the Iron(II)–Phenanthroline Complex: An Activity for Analytical and Physical Chemistry Laboratories. *J. Chem. Educ.* **2016**, 93 (10), 1760–1765.
- (27) Kohl, S. K.; Landmark, J. D.; Stickle, D. F. Demonstration of Absorbance Using Digital Color Image Analysis and Colored Solutions. *J. Chem. Educ.* **2006**, 83 (4), 644.
- (28) Christodouleas, D. C.; Nemiroski, A.; Kumar, A. A.; Whitesides, G. M. Broadly Available Imaging Devices Enable High-Quality Low-Cost Photometry. *Anal. Chem.* **2015**, 87 (18), 9170–9178.
- (29) Dangkulwanich, M.; Kongnithigarn, K.; Aurnoppakhun, N. Colorimetric Measurements of Amylase Activity: Improved Accuracy and Efficiency with a Smartphone. *J. Chem. Educ.* **2018**, 95 (1), 141–145.
- (30) Quagliano, J. M.; Marks, C. A. Demystifying Spectroscopy with Secondary Students: Designing and Using a Custom-Built Spectrometer. *J. Chem. Educ.* **2013**, 90 (10), 1409–1410.
- (31) Rice, N. P.; de Beer, M. P.; Williamson, M. E. A Simple Educational Method for the Measurement of Liquid Binary Diffusivities. *J. Chem. Educ.* **2014**, 91 (8), 1185–1190.
- (32) Kuntzleman, T. S.; Jacobson, E. C. Teaching Beer's Law and Absorption Spectrophotometry with a Smart Phone: A Substantially Simplified Protocol. *J. Chem. Educ.* **2016**, 93 (7), 1249–1252.
- (33) Moraes, E. P.; Confessor, M. R.; Gasparotto, L. H. S. Integrating Mobile Phones into Science Teaching To Help Students Develop a Procedure To Evaluate the Corrosion Rate of Iron in Simulated Seawater. *J. Chem. Educ.* **2015**, 92 (10), 1696–1699.
- (34) Montangero, M. Determining the Amount of Copper(II) Ions in a Solution Using a Smartphone. *J. Chem. Educ.* **2015**, 92 (10), 1759–1762.
- (35) Campos, A. R.; Knutson, C. M.; Knutson, T. R.; Mozzetti, A. R.; Haynes, C. L.; Penn, R. L. Quantifying Gold Nanoparticle Concentration in a Dietary Supplement Using Smartphone Colorimetry and Google Applications. *J. Chem. Educ.* **2016**, 93 (2), 318–321.
- (36) Šafranko, S.; Živković, P.; Stanković, A.; Medvidović-Kosanović, M.; Széchenyi, A.; Jokić, S. Designing ColorX, Image Processing Software for Colorimetric Determination of Concentration, To

Facilitate Students' Investigation of Analytical Chemistry Concepts Using Digital Imaging Technology. *J. Chem. Educ.* **2019**, *96* (9), 1928–1937.

(37) Bogucki, R.; Greggila, M.; Mallory, P.; Feng, J.; Siman, K.; Khakipoor, B.; King, H.; Smith, A. W. A 3D-Printable Dual Beam Spectrophotometer with Multiplatform Smartphone Adaptor. *J. Chem. Educ.* **2019**, *96* (7), 1527–1531.

(38) Knutson, T. R.; Knutson, C. M.; Mozzetti, A. R.; Campos, A. R.; Haynes, C. L.; Penn, R. L. A Fresh Look at the Crystal Violet Lab with Handheld Camera Colorimetry. *J. Chem. Educ.* **2015**, *92* (10), 1692–1695.

(39) Rasband, W. S., *ImageJ*; U.S. National Institutes of Health, Bethesda, MD, 1997–2018. <https://imagej.nih.gov/ij/>.

(40) The GIMP Team. *GIMP*. <https://www.gimp.org/> (accessed 2020-06-14).

(41) The R Foundation. *R: The R Project for Statistical Computing*. <https://www.r-project.org/> (accessed 2020-06-14).

(42) Koesdjojo, M. T.; Pengpumiak, S.; Wu, Y.; Boonloed, A.; Huynh, D.; Remcho, T. P.; Remcho, V. T. Cost Effective Paper-Based Colorimetric Microfluidic Devices and Mobile Phone Camera Readers for the Classroom. *J. Chem. Educ.* **2015**, *92* (4), 737–741.

(43) Cumberbatch, T.; Hanley, Q. S. Quantitative Imaging in the Laboratory: Fast Kinetics and Fluorescence Quenching. *J. Chem. Educ.* **2007**, *84* (8), 1319.

(44) Koenig, M. H.; Yi, E. P.; Sandridge, M. J.; Mathew, A. S.; Demas, J. N. "Open-Box" Approach to Measuring Fluorescence Quenching Using an iPad Screen and Digital SLR Camera. *J. Chem. Educ.* **2015**, *92* (2), 310–316.

(45) Cochran, B.; Lunday, D.; Miskevich, F. Kinetic Analysis of Amylase Using Quantitative Benedict's and Iodine Starch Reagents. *J. Chem. Educ.* **2008**, *85* (3), 401.

(46) Mathews, K. R.; Landmark, J. D.; Stickle, D. F. Quantitative Assay for Starch by Colorimetry Using a Desktop Scanner. *J. Chem. Educ.* **2004**, *81* (5), 702.

(47) Soldat, D. J.; Barak, P.; Lepore, B. J. Microscale Colorimetric Analysis Using a Desktop Scanner and Automated Digital Image Analysis. *J. Chem. Educ.* **2009**, *86* (5), 617.

(48) da Silva, R. S.; Borges, E. M. Quantitative Analysis Using a Flatbed Scanner: Aspirin Quantification in Pharmaceutical Tablets. *J. Chem. Educ.* **2019**, *96* (7), 1519–1526.

(49) Ledesma, C. M.; Krepsky, L. M.; Borges, E. M. Using a Flatbed Scanner and Automated Digital Image Analysis To Determine the Total Phenolic Content in Beer. *J. Chem. Educ.* **2019**, *96* (10), 2315–2321.

(50) Volmer, D. A.; Curbani, L.; Parker, T. A.; Garcia, J.; Schultz, L. D.; Borges, E. M. Determination of Titratable Acidity in Wine Using Potentiometric, Conductometric, and Photometric Methods. *J. Chem. Educ.* **2017**, *94* (9), 1296–1302.

(51) Delfino, J. M. *ReadPlate*. <https://imagej.nih.gov/ij/plugins/readplate/index.html> (accessed 2020-06-14).

(52) Isaacs, N. S. Two Readily-Constructed Instruments for the Teaching Laboratory. *J. Chem. Educ.* **1983**, *60* (7), 607.

(53) Hamilton, J. R.; White, J. S.; Nakhleh, M. B. Development of a Low-Cost Four-Color LED Photometer. *J. Chem. Educ.* **1996**, *73* (11), 1052.

(54) Jaffar, M.; Zahid, Q. Low-Cost Precision Colorimeter. *J. Chem. Educ.* **1988**, *65* (12), 1099.

(55) Visconti, P.; Primiceri, P.; De Fazio, R.; Ekuakille, A. L. A Solar-Powered White LED-Based UV-Vis Spectrophotometric System Managed by PC for Air Pollution Detection in Faraway and Unfriendly Locations. *Int. J. Smart Sens. Intell. Syst.* **2017**, *10* (1), 18–48.

(56) Delgado, J.; Quintero-Ortega, I. A.; Vega-Gonzalez, A. From Voltage to Absorbance and Chemical Kinetics Using a Homemade Colorimeter. *J. Chem. Educ.* **2014**, *91* (12), 2158–2162.

(57) Clippard, C. M.; Hughes, W.; Chohan, B. S.; Sykes, D. G. Construction and Characterization of a Compact, Portable, Low-Cost Colorimeter for the Chemistry Lab. *J. Chem. Educ.* **2016**, *93* (7), 1241–1248.

(58) Yeh, T.-S.; Tseng, S.-S. A Low Cost LED Based Spectrometer. *J. Chin. Chem. Soc.* **2006**, *53* (5), 1067–1072.

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

(60) Grove, T. T.; Masters, M. F. A Student Assembled Spectrograph with a CCD Detector to Assist with Students' Understanding of Spectrometry. *Eur. J. Phys.* **2007**, *28* (4), 747–753.

(61) Wilson, M. V.; Wilson, E. Authentic Performance in the Instrumental Analysis Laboratory: Building a Visible Spectrophotometer Prototype. *J. Chem. Educ.* **2017**, *94* (1), 44–51.

(62) Safford, H. W.; Westneat, D. F. An Inexpensive, Easily Constructed Spectrophotometer. *J. Chem. Educ.* **1953**, *30* (7), 343.

(63) Patterson, B. M.; Danielson, N. D.; Lorigan, G. A.; Sommer, A. J. Analytical Spectroscopy Using Modular Systems. *J. Chem. Educ.* **2003**, *80* (12), 1460.

(64) IO Rodeo. Educational Colorimeter Kit; *IORodeo Smart Lab Technology*. <https://iorodeo.com/products/educational-colorimeter-kit> (accessed 2020-06-14).

(65) Public Lab. Desktop Spectrometry Kit; *Public Lab*. <https://publiclab.org/wiki/dsk3> (accessed 2020-06-14).

(66) 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.

(67) Thal, M. A.; Samide, M. J. Applied Electronics: Construction of a Simple Spectrophotometer. *J. Chem. Educ.* **2001**, *78* (11), 1510.

(68) Wahab, M. F. Fluorescence Spectroscopy in a Shoebox. *J. Chem. Educ.* **2007**, *84* (8), 1308.

(69) Björn, L. O. The Amateur Scientist's Spectrophotometer. In *Photobiology: The Science of Life and Light*; Björn, L. O., Ed.; Springer: New York, 2008; pp 647–658.

(70) Diawati, C.; Liliyasi, S.; Setiabudi, A.; Buchari. Using Project-Based Learning To Design, Build, and Test Student-Made Photometer by Measuring the Unknown Concentration of Colored Substances. *J. Chem. Educ.* **2018**, *95* (3), 468–475.

(71) Adams-McNichol, A. L.; Shiell, R. C.; Ellis, D. A. Accurate, Photoresistor-Based, Student-Built Photometer and Its Application to the Forensic Analysis of Dyes. *J. Chem. Educ.* **2019**, *96* (6), 1143–1151.

(72) Wendlandt, W. W. Inexpensive LED Student Colorimeter. *J. Chem. Educ.* **1976**, *53*, 134.

(73) Delorenzi, N. J.; Araujo, C.; Palazzolo, G.; Gatti, C. A. A Simple Device to Demonstrate the Principles of Fluorometry. *J. Chem. Educ.* **1999**, *76* (9), 1265.

(74) O'Donoghue, J. Simplified Low-Cost Colorimetry for Education and Public Engagement. *J. Chem. Educ.* **2019**, *96* (6), 1136–1142.

(75) Domenic, F. *Design and Construction of a Digital CCD Spectrometer*. Semester project report, Czech Technical University, Prague, 2010.

(76) Matsuo, T.; Muromatsu, A.; Katayama, K.; Mori, M. Construction of a Photoelectric Colorimeter and Application to Students' Experiments. *J. Chem. Educ.* **1989**, *66* (4), 329.

(77) Crump, J.; Sandwick, R. K. A Simple Microwell Colorimeter for Use in an Introductory Chemistry Lab. *J. Chem. Educ.* **1994**, *71* (8), A199.

(78) Gordon, J.; Tye, S. A LED Microtiter Plate Reader. *J. Chem. Educ.* **2005**, *82* (6), 903.

(79) Kennepohl, D.; Connors, M. An Inexpensive Mini-Colorimeter for Undergraduate Science Laboratories. *Aust. J. Ed. Chem.* **2009**, *70*, 38–41.

(80) Vanderveen, J. R.; Martin, B.; Ooms, K. J. Developing Tools for Undergraduate Spectroscopy: An Inexpensive Visible Light Spectrometer. *J. Chem. Educ.* **2013**, *90* (7), 894–899.

(81) LaFratta, C. N.; Huh, S. P.; Mallillin, A. C.; Riviello, P. J.; Walt, D. R. Visualizing Fluorescence: Using a Homemade Fluorescence "Microscope" To View Latent Fingerprints on Paper. *J. Chem. Educ.* **2010**, *87* (10), 1105–1107.

(82) Kiiski, V. An Educational Spectrograph Using a Digital Camera as a Training Aid for Physics Students. *Eur. J. Phys.* **2014**, *35*, 035013.

- (83) Gordon, J.; Harman, S. A Graduated Cylinder Colorimeter: An Investigation of Path Length and the Beer-Lambert Law. *J. Chem. Educ.* **2002**, *79* (5), 611.
- (84) Quercioli, F.; Tiribilli, B.; Mannoni, A.; Acciai, S. Optomechanics with LEGO. *Appl. Opt.* **1998**, *37* (16), 3408–3416.
- (85) Knagge, K.; Raftery, D. Construction and Evaluation of a LEGO Spectrophotometer for Student Use. *Chem. Educ.* **2002**, *7* (6), 371–375.
- (86) Hosker, B. S. Demonstrating Principles of Spectrophotometry by Constructing a Simple, Low-Cost, Functional Spectrophotometer Utilizing the Light Sensor on a Smartphone. *J. Chem. Educ.* **2018**, *95* (1), 178–181.
- (87) Asheim, J.; Kvittingen, E. V.; Kvittingen, L.; Verley, R. A Simple, Small-Scale Lego Colorimeter with a Light-Emitting Diode (LED) Used as Detector. *J. Chem. Educ.* **2014**, *91* (7), 1037–1039.
- (88) Kvittingen, E. V.; Kvittingen, L.; Sjursnes, B. J.; Verley, R. Simple and Inexpensive UV-Photometer Using LEDs as Both Light Source and Detector. *J. Chem. Educ.* **2016**, *93* (10), 1814–1817.
- (89) Kvittingen, E. V.; Kvittingen, L.; Melø, T. B.; Sjursnes, B. J.; Verley, R. Demonstrating Basic Properties of Spectroscopy Using a Self-Constructed Combined Fluorimeter and UV-Photometer. *J. Chem. Educ.* **2017**, *94* (10), 1486–1491.
- (90) Pokrzywnicka, M.; Koncki, R.; Tymecki, Ł. A Concept of Dual Optical Detection Using Three Light Emitting Diodes. *Talanta* **2010**, *82* (1), 422–425.
- (91) Bougot-Robin, K.; Paget, J.; Atkins, S. C.; Edel, J. B. Optimization and Design of an Absorbance Spectrometer Controlled Using a Raspberry Pi To Improve Analytical Skills. *J. Chem. Educ.* **2016**, *93* (7), 1232–1240.
- (92) Pokrzywnicka, M.; Koncki, R.; Tymecki, Ł. A Very Simple Photometer Based on Paired-Emitter-Detector Diodes. *Chem. Anal.* **2009**, *54*, 427–435.
- (93) Anzalone, G. C.; Glover, A. G.; Pearce, J. M. Open-Source Colorimeter. *Sensors* **2013**, *13* (4), 5338–5346.
- (94) Mendez, J. D. An Inexpensive 3D Printed Colorimeter. *Chem. Educ.* **2015**, *20*, 224–226.
- (95) 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.
- (96) 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.
- (97) Conte, B.; Landis, W.; Boyce, N.; Frederick, J.; Frederick, L.; Elmer, J. J. Design and Application of 3D-Printed Photometers Controlled with an Arduino. *3D Printing and Additive Manufacturing* **2018**, *5* (4), 292–300.
- (98) 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.
- (99) Calcabrini, M.; Onna, D. Exploring the Gel State: Optical Determination of Gelation Times and Transport Properties of Gels with an Inexpensive 3D-Printed Spectrophotometer. *J. Chem. Educ.* **2019**, *96* (1), 116–123.
- (100) Mozo, J. D.; Galan, M.; Roldán, E. Application of Light Emitting Diodes to Chemical Analysis: Determination of Copper in Water. *J. Chem. Educ.* **2001**, *78* (3), 355.
- (101) Forte, V. C. Understanding Ultraviolet LED Applications and Precautions. *Marktech Optoelectronics*. <https://marktechopto.com/technical-articles/understanding-ultraviolet-led-applications-and-precautions/> (accessed 2020-06-14).
- (102) Scheeline, A.; Kelley, K. *Cell Phone Spectrometer*. https://www.asdlib.org/onlineArticles/elabware/Scheeline_Kelly_Spectrophotometer/index.html (accessed 2020-06-14).
- (103) Scheeline, A. Teaching, Learning, and Using Spectroscopy with Commercial, Off-the-Shelf Technology. *Appl. Spectrosc.* **2010**, *64* (9), 256A–268A.
- (104) Field Tested Systems, LLC. *RSpec Real-time spectroscopy*; Field Tested Systems, LLC. <https://www.rspec-astro.com/> (accessed 2020-06-14).
- (105) Place, B. J. Activity Analysis of Iron in Water Using a Simple LED Spectrophotometer. *J. Chem. Educ.* **2019**, *96* (4), 714–719.
- (106) Tran, Y.; Whitten, J. E. Using a Diode Laser for Laser-Induced Fluorescence. *J. Chem. Educ.* **2001**, *78* (8), 1093.
- (107) Wigton, B. T.; Chohan, B. S.; Kreuter, R.; Sykes, D. The Characterization of an Easy-to-Operate Inexpensive Student-Built Fluorimeter. *J. Chem. Educ.* **2011**, *88* (8), 1188–1193.
- (108) Santos, W. G.; Cavalheiro, E. T. G. Assembling and Using an LED-Based Detector To Monitor Absorbance Changes during Acid–Base Titrations. *J. Chem. Educ.* **2015**, *92* (10), 1709–1715.
- (109) LaFratta, C. N.; Jain, S.; Pelse, I.; Simoska, O.; Elvy, K. Using a Homemade Flame Photometer To Measure Sodium Concentration in a Sports Drink. *J. Chem. Educ.* **2013**, *90* (3), 372–375.
- (110) McClain, R. L. Construction of a Photometer as an Instructional Tool for Electronics and Instrumentation. *J. Chem. Educ.* **2014**, *91* (5), 747–750.
- (111) Algar, W. R.; Massey, M.; Krull, U. J. Assembly of a Modular Fluorimeter and Associated Software: Using LabVIEW in an Advanced Undergraduate Analytical Chemistry Laboratory. *J. Chem. Educ.* **2009**, *86* (1), 68.
- (112) Forbes, P. B. C.; Nöthling, J. A. Shedding Light on Spectrophotometry: The SpecUP Educational Spectrophotometer. *S. Afr. J. Sci.* **2014**, *110* (1–2), 1–5.
- (113) Gaião, E.; dos Santos, S. R. B.; dos Santos, V. B.; do Nascimento, E. C. L.; Lima, R. S.; de Araújo, M. C. U. An Inexpensive, Portable and Microcontrolled near Infrared LED-Photometer for Screening Analysis of Gasoline. *Talanta* **2008**, *75* (3), 792–796.
- (114) Sorouraddin, M. H.; Saadati, M. Simple, Cheap, and Portable Colorimeter for Introductory Analytical Chemistry Laboratories. *Chemistry* **2009**, *18*, 176–182.
- (115) Fragale, C.; Bruno, P. A Simple and Inexpensive Flame Emission Apparatus. *J. Chem. Educ.* **1976**, *53* (11), 734.
- (116) Kovačić, M.; Asperger, D. Low-Cost Turbidimeter, Colorimeter, and Nephelometer for the Student Laboratory. *J. Chem. Educ.* **2019**, *96* (11), 2649–2654.
- (117) Rocha, F. R. P.; Reis, B. F. A Low-Cost Device for Automatic Photometric Titrations. *J. Chem. Educ.* **2000**, *77* (2), 258.
- (118) Mims, F. M., III. How to Use LEDs to Detect Light | Make. *MAKE* **2013**, 136.
- (119) Mims, F. M. Sun Photometer with Light-Emitting Diodes as Spectrally Selective Detectors. *Appl. Opt.* **1992**, *31* (33), 6965–6967.
- (120) Lindsay, R. H.; Paton, B. E. Inexpensive Photometer Using Light-emitting Diodes. *Am. J. Phys.* **1976**, *44* (2), 188–189.
- (121) Fraden, J. Light Detectors. In *Handbook of Modern Sensors: Physics, Designs, and Applications*; Fraden, J., Ed.; Springer: New York, 2010; pp 461–501.
- (122) Tabbert, B.; Goushcha, A. Optical Detectors. In *Springer Handbook of Lasers and Optics*; Träger, F., Ed.; Springer Handbooks: Berlin, Heidelberg, 2012; pp 543–619.
- (123) Anh Bui, D.; Hauser, P. C. Absorbance Measurements with Light-Emitting Diodes as Sources: Silicon Photodiodes or Light-Emitting Diodes as Detectors? *Talanta* **2013**, *116*, 1073–1078.
- (124) Sengupta, S. K.; Farnham, J. M.; Whitten, J. E. A Simple Low-Cost Lock-In Amplifier for the Laboratory. *J. Chem. Educ.* **2005**, *82* (9), 1399.
- (125) Néel, B.; Crespo, G. A.; Perret, D.; Cherubini, T.; Bakker, E. Camping Burner-Based Flame Emission Spectrometer for Classroom Demonstrations. *J. Chem. Educ.* **2014**, *91* (10), 1655–1660.
- (126) Jones, B. T.; Smith, B. W.; Leong, M. B.; Mignardi, M. A.; Winefordner, J. D. A Simple, Portable Fluorimeter with a Compact, Inexpensive Nitrogen Laser Source. *J. Chem. Educ.* **1989**, *66* (4), 357.
- (127) Grasselli, J. G.; Ritchey, W. M. *Atlas of Spectral Data and Physical Constants for Organic Compounds*, 2nd ed.; CRC Press: Cleveland, OH, 1975.
- (128) Devi, O. Z.; Basavaiah, K.; Vinay, K. B. Application of Potassium Permanganate to Spectrophotometric Assay of Metoclopramide

Hydrochloride in Pharmaceuticals. *J. Appl. Spectrosc.* **2012**, 78 (6), 873–883.

(129) Sigma Aldrich. *Specification Sheet: Bromothymol Blue*. <https://www.sigmaaldrich.com/catalog/DataSheetPage.do?brandKey=SIAL&symbol=318752> (accessed 2020-06-14).

(130) Skoog, D. A.; Holler, F. J.; Crouch, S. R. *Principles of Instrumental Analysis*, 7th ed.; Cengage Learning: Belmont, CA, 2017.

(131) Smith, G. D.; Sanford, C. L.; Jones, B. T. Continuous Liquid-Sample Introduction for Bunsen Burner Atomic Emission Spectrometry. *J. Chem. Educ.* **1995**, 72 (5), 438.

(132) Bright, R. M.; Momoh, P. O.; Bozeman, A. D.; Seney, C. S.; Sinclair, K. V. Development of a Multiple-Element Flame Emission Spectrometer Using CCD Detection. *J. Chem. Educ.* **2005**, 82 (12), 1826.

(133) Bruce, M. R. M.; Wilson, T. A.; Bruce, A. E.; Bessey, S. M.; Flood, V. J. A Simple, Student-Built Spectrometer To Explore Infrared Radiation and Greenhouse Gases. *J. Chem. Educ.* **2016**, 93 (11), 1908–1915.