Demonstrating Principles of Spectrophotometry by Constructing a Simple, Low-Cost, Functional Spectrophotometer Utilizing the Light Sensor on a Smartphone

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ABSTRACT

A highly simplified variation on the DIY spectrophotometer using a smartphone's light sensor as a detector and an app to calculate and display absorbance values was constructed and tested. This simple version requires no need for electronic components or post-measurement spectral analysis. Calibration graphs constructed from two molecules that absorb light maximally at different wavelengths (430nm and 630nm) demonstrate linearity with R^2 values of 0.9975 and 0.9848 respectively.

GRAPHICAL ABSTRACT

KEYWORDS

High School / Introductory Chemistry, First-Year Undergraduate / General, Biochemistry, Analytical Chemistry, Laboratory Instruction, Hands-On Learning / Manipulatives, Collaborative / Cooperative Learning, Inquiry-Based / Discovery Learning, Laboratory Equipment / Apparatus, Spectroscopy.

INTRODUCTION

There have been a few recent publications in this *Journal* in relation to DIY spectrophotometers which can provide a functional piece of equipment and act as an aid to students' understanding of the principles behind spectrophotometry. All have aspects of helping students understand what is happening in the 'black box' of a spectrophotometer, to increase students' understanding and scientific literacy[1], as well as provide a functional piece of equipment.

There have been different approaches to constructing a DIY spectrophotometer. Some focus on the basics of reflected and absorbed wavelengths of light, using light reflected from red, green or blue backgrounds sent through a sample and use of a smartphone camera and software to generate results for red/green/blue absorbance[2]. Others[3] have used analysis of diffracted spectral images (with smartphone camera) after light has passed through sample to generate meaningful results. Other approaches include some use of electronics, sometimes basic, such as using two LEDs, one as the light source, one as the detector (linked to a digital multimeter), cleverly exploiting the narrow range of wavelengths of light emitted by some LEDs[4]. Another electronic approach which allows wavelength selection also utilises a multimeter, linked to a photodiode on a rotatable arm[5], to detect light of different wavelengths diffracted after passing through the sample.

Each of these different approaches has generated good results, demonstrating functionality and have their own benefits. The electronic (using digital multimeters) approach typically allows students to gain an absorbance value but are often more complex in construction. The analysis of spectra approach is simpler in relation to construction (and software is readily available) and has the advantage of greater versatility in the way it can be used. The results achieved by software analysis of spectra have allowed for commercial production of inexpensive, functioning spectrophotometers on this theme, most notably by Microlab[6].

A high quality homemade spectrophotometer, based on spectral image analysis, using a DVD to diffract light is also described elsewhere[7] and there have been other instructions for various models of DIY spectrophotometer published in other places[8+9]. The aim of these models is to aid students' understanding and/or provide cheap alternatives to manufactured spectrophotometers.

Both the electronic project based and spectral analysis based approaches offer quite a different experience for students, used to getting a direct absorbance reading without any post-measurement calculations or analysis. This deviation from the typical student's experience of a laboratory spectrophotometer can create a gap between the experience of a UV/Vis spectrophotometer in the lab and the theory behind the technique, exemplified by the DIY, deconstructed learning strategy.

Below is a description of how a simple, functioning spectrophotometer (that provides absorbance values at a push of a button) can be constructed from a shoebox, a LED torch, a DVD, and a smartphone (with a light detector). Construction and use of this, 'shoebox spectrophotometer' demonstrates the principles of diffraction, wavelength selection, calibration and light measurement and absorbance calculation. The emulation of functionality of many undergraduates' experience of laboratory spectrophotometer could support learning in a more direct, experiential way, consolidating the theory taught. I believe this is the first DIY spectrophotometer that exploits the light sensor of a smartphone and provides an extremely simple way of making a functioning spectrophotometer.

Tests on two molecules that absorb light maximally at different wavelengths (430nm and 630nm) show this simple, cheap spectrophotometer works well, and results from calibration graphs constructed show linearity with high R^2 values.

COMPONENTS AND CONSTRUCTION

For the model shown below (Figure 1), a piece of wood was put in the base of the shoebox to allow components to be held in place securely. Most of the inside of the box was lined with black material to minimise reflection of non-diffracted light. The light source was an LED torch; a quarter of a DVD was used to diffract light. The DVD diffractor was glued to a cog from a LEGO set, to allow movement of the DVD to position the appropriate part of the spectrum on the cuvette holder (there is a second, linked cog with part of it accessible from outside the box). The cuvette holder was constructed from LEGO, with a slit at the front, to further allow selection of a wavelength/narrow range of wavelengths of light from the projected spectrum.

Directly behind the cuvette (in the path of the light from the slit) the light detecting sensor of a smartphone was positioned, with the rest of the smartphone exterior to the box, supported by a holder made from LEGO. Positioning of the components took some experimentation, before fixing them in position. The positioning of components would be different for different torches, different dimensions, different diffraction achieved and different smart phones. Figure 1 is an example of a layout that was successful for the components available and was used to generate the results below.

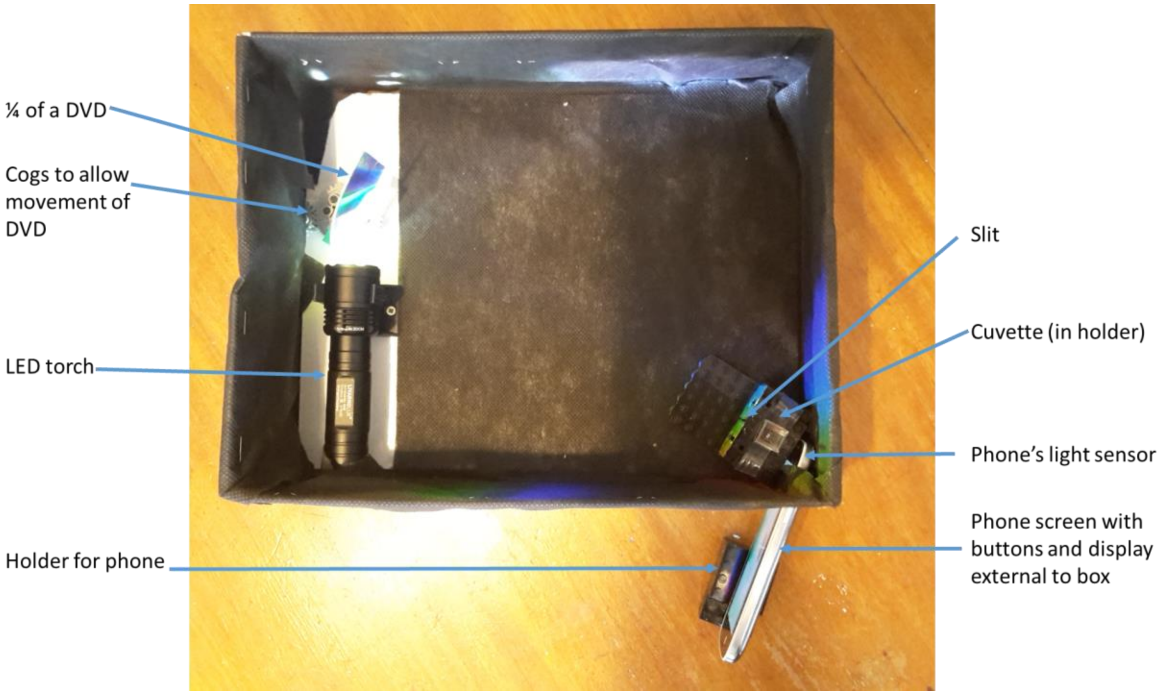

Figure 1. Shoebox spectrophotometer from above, with lid off, to show components.

Smartphone App

To allow for the calculation and display of absorbance values an app was developed using MIT App inventor 2. This, 'Shoebox Spectrophotometer app' is available for free (and advert free) from the Google Play store. As shown in figure 2, it allows the measurement of the amount of light reaching the sensor at calibration (on press of, 'calibration'), and measurement of the light reaching the sensor when a sample is in place (on press of, 'measure abs.'). The app calculates and displays the absorbance value for the measurement. The real time 'light measurement' is useful in positioning the light sensor in the correct position.

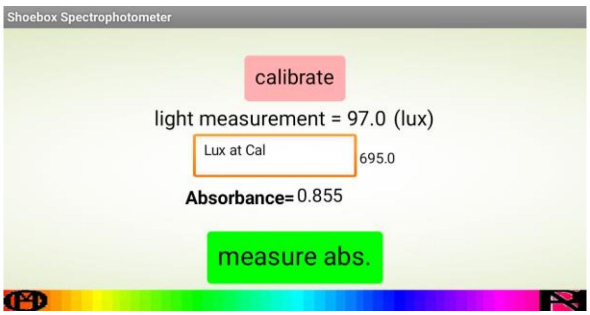

Figure 2. Screenshot of shoebox spectrophotometer app showing calibrate and measure absorbance buttons, absorbance measurement, as well as real time light measurement (in lux) and the lux at calibration.

Validation

The shoebox spectrophotometer was tested at two wavelengths, 430nm and 630nm by constructing calibration graphs for p-Nitroaniline and ethyl - [4 - [[4 - [ethyl -[(3 - sulfophenyl) methyl] amino] phenyl] - (2 - sulfophenyl) methylidene] - 1 - cyclohexa - 2, 5 - dienylidene] - [(3 - sulfophenyl) methyl] azanium (Brilliant blue, E133) respectively (both dissolved in water). Approximate wavelength selection on the shoebox spectrophotometer was achieved by selecting the appropriate part of the spectrum and experimenting with maximal absorbance values with a standard to locate the area of the spectrum with maximal absorbance.

As shown in Figure 3, the relationship between concentration of p-Nitroaniline and absorbance of light (at approximately 430nm) was linear, the R^2 value for the trend line was 0.9975.

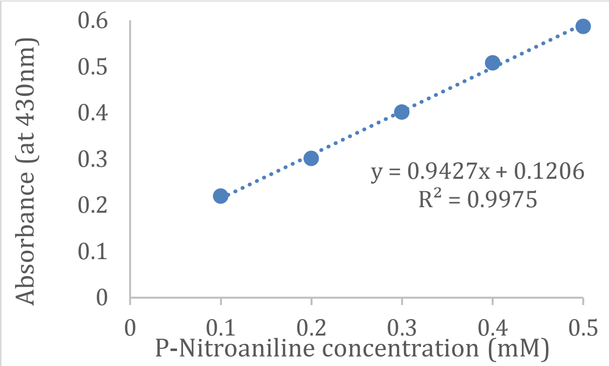

Figure 3. Calibration graph for p-Nitroaniline for the shoe box spectrophotometer. Linear trend line equation and R^2 values are shown. Points are from a single observation, using water as a blank. Approximate wavelength determined as indicated in 'Validation' description.

Figure 4 shows linearity up to concentration 0.0025% (w/w) of brilliant blue against absorbance of light at approximately 630nm, with an R^2 value of 0.98. There was clear negative deviation from Beer's law at the 0.005% concentration tested (eliminated from the trend line equation).

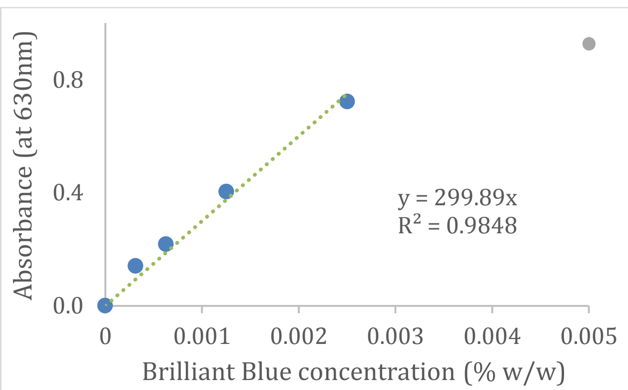

Figure 4. Calibration graph for Brilliant blue for the shoe box spectrophotometer (blue circles). Linear trend line equations and R^2 values are shown. The grey circle represents a data point eliminated from the trend line equation due to clear negative deviation. Points are from a single observation, using water as a blank. Approximate wavelength determined as indicated in 'Validation' description.

DISCUSSION

Spectrophotometry is an important technique in many fields of science, in both research and in the application of the technique in different areas, including healthcare and industrial science. Understanding the theory behind the technique is helpful to students using the method to understand the technical limitations as well as appreciate what is occurring in the laboratory equipment. Deconstructing equipment through a DIY approach can be useful for student understanding. Ideally the approach should emulate, as closely as possible, the equipment the student has experience of, and also be functional.

The results show good linearity for the molecules tested, indicating that this approach to DIY spectrophotometry is not only simple but functional. The R^2 values achieved were similar to those generated with the same samples using a Jenway 6300 spectrophotometer (see supporting information). The gradient on the trend lines for both molecules was lower for the shoebox spectrophotometer than the Jenway, suggesting higher sensitivity for the Jenway compared to the shoebox spectrophotometer. Negative deviation was more apparent for the Jenway (for both molecules tested) and the Jenway spectrophotometer could not generate a valid results for samples with concentrations over 0.00125% (w/v) of Brilliant Blue, indicating the Jenway spectrophotometer had a more limited range than the shoebox spectrophotometer (see supporting information).

SUMMARY

The shoebox spectrophotometer is simple, cheap, easy to make and functional. It can help demonstrate the key principles of spectrophotometry in a way that closely mimics many undergraduate's practical experience of spectrophotometry. It could be a useful tool in consolidating learning of the theory behind technique and develop an understanding of limitations. It could also be a basis of student led projects, to develop the idea and design further, integrating aspects of wavelength calibration, experimentation with different methods of diffraction and slit widths, assessing the range of wavelengths detectable etc. Projects based on app development would also be a possibility, which together with the other, technical aspects mentioned, could allow for some cross-disciplinary collaboration team projects.

HAZARDS

There are no specific hazards. Looking directly at a bright torch can cause discomfort.

SUPPORTING INFORMATION

Smartphone spectrophotometer video tour (MPG) and comparative data for the shoebox spectrophotometer compared to Jenway 6300 (DOCX).

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REFERENCES

1. Bauer, S. H. Scientific literacy vs. Black boxes. With Reference to the Design of Student Laboratory Experiments. *J. Chem. Educ.*, **1990**, *67* (8) 692-693.
2. Kuntzleman, T. S.; and Erik C. Jacobson, E.C. Teaching Beer's Law and Absorption Spectrophotometry with a Smart Phone: A Substantially Simplified Protocol. *J. Chem. Educ.*, **2016**, *93* (7), pp 1249–1252**;** **DOI:** 10.1021/acs.jchemed.5b00844
3. 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), pp 146–151; DOI: 10.1021/acs.jchemed.5b00654
4. 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), pp 1037–1039; DOI: 10.1021/ed400838n
5. Albert, D. R.; Todt, M. A.; Davis, H. F. A Low-Cost Quantitative Absorption Spectrophotometer. *J. Chem. Educ.*, **2012**, *89* (11), pp 1432–1435; DOI: 10.1021/ed200829d
6. Microlab Visual Spectrophotometer, Model 141. http://microlabinfo.com/equipment/spectrophotometry/visual_spectrometer_module/ (accessed Oct 2017)
7. Björn, L. O. The amateur scientist's spectrophotometer. In (Ed.). (2015). *Photobiology: The science of light and life*. Björn, L. O., Eds.; Springer Science and Business Media New York, 2015; chapter 29, pp 437-444.
8. Lema, M. A.; Aljinovic, E. M.; Lozano, M. E. Using a Homemade Spectrophotometer in Teaching Biosciences. *Biochemistry and Molecular Biology Education,* **2002**, 3*0*, (2), pp. 106–110; DOI: 10.1002/bmb.2002.494030020032
9. Tavener, S. J.; Thomas-Oates, J. E. Build Your Own Spectrophotometer. Educ. Chem. **2007**, *44* (5), 151-154; http://www.rsc.org/images/EiC-05_2007-spectrophotometer_tcm18-214788.pdf (accessed Oct 2017)