# Reproducibility and development of open source ICT projects for chemistry education: A case of spectrometer development

Aleksi Takala

The Unit of Chemistry Teacher Education, Department of Chemistry, University of Helsinki, Finland

**Abstract:** Various open source ICT projects promise teachers and other educators means to build their own devices that help facilitate learning by promoting the accessibility, user-friendliness, low cost and high educational value of the projects. But at the same time, there's a lack of understanding of what skills are needed for ICT projects and solutions to be implemented in education. In this article, an open source fluorescence spectrometer was constructed as part of a chemistry pre-service teacher course. The planning and implementation of the device for teaching were done individually and following course guidelines, but the project took multiple shifts in focus. Initially, the project was to construct a UV-Vis spectrometer, but the project was reduced to a fluorescence spectrometer. The goal was to build and test an open source fluorescence spectrometer as a proof of concept to discuss its educational value in open source ICT and project-based learning.

**Keywords:** Spectroscopy, project-based learning, ICT, open source

## 1 Introduction

Technology is a vast and varied resource that involves both hardware and software to be utilised with clear goals for the use and the life cycle of devices and their units in mind. New and emerging technologies such as AI and machine learning are being implemented in education research and by teachers themselves (e.g., Celik et al., 2022). A plethora of technologies are available for teaching because of open-source development, distribution, and implementation. These include hardware (e.g., Arduino) and software (e.g., Edumol, Molview, Molcalc) applications to further scientific inquiry and provide meaningful learning outcomes, which can be succinctly summarised as resembling *doing* science or learning to do and think like a scientist using modern technology.

The principles of modern STEM education stem from research and literature that assesses the need for new tools and skills required to better education so that it would influence learning outcomes. This could then realise itself by having an impact on students' future careers choices and positive attitudes towards the relevance of science in society, the very meaning of why we teach science in the first place. In modern work and study environments, expectations are high, and the work requirements and conditions for learning can change quickly, which can be exemplified by the shifts in focus to remote work and distance education during the COVID-19 pandemic in both developed and developing countries (Agu et al., 2021; Aykan & Yıldırım, 2021). And with increasing demand to learn new skills that include ICT literacy, collaboration, creativity and competencies in different socio-cultural contexts, in addition to critical thinking and problem-solving skills (Voogt et al., 2013), teachers are required to face new global and national challenges in education, research, sustainability and society. And in turn, these challenges are also met by the students.

Technology has helped us tackle the aforementioned problems in times of crisis in STEM education. While at the same time, technology can be said to provide better outcomes in tasks that are done with well-defined instruments and methods, i.e., technology, the requirements to use such technologies can be vexing and hard for students and teachers alike. Especially this can be the case when using novel technologies, but even so, studies such as Rodríguez-Becerra et al. (2020) and Lohning et al. (2019) have shown that novel technologies can have an effect on learning outcomes by making the learning assignments motivating and well-structured with an emphasis on *doing* science with modern methods. In schools, this could be generalised as, rather than problem-solving, technically challenging issues that come up with using older, less accurate, and less vocationally relevant tools such as drawing and logging data by traditional methods, such as with pen and paper, students would familiarise themselves with modern tools. For example, modern technology can help students maintain a better grip on data management, acquisition and accuracy of the basis set (e.g. Measurements) in a computer environment, which is especially true when the data sets are very large. Technology can be seen as a tool to further inquiry of a phenomenon, in this context, a natural phenomenon. The attitudes, methods and settings in which this can be facilitated further in the field of science education research are to understand better the inquiry and needed skills of teachers to use technology (Dawson, 2006).

This article describes a chemistry teacher student course-work project of constructing a device that has educational value during a course called 'Tutkiva ja eheyttävä kemian opetus'. The device was decided to be a spectroscopic device, which was initially planned to be a cheaper alternative to a UV-Vis spectroscope but was reduced to a simplified fluorescence spectroscope. This fluorescence spectroscope was designed based on an open source project and its educational value addressed by designing an educational utility within a spectroscopy workshop that is framed to the

Finnish Curricula for general and upper secondary education. This paper aims to address the possibilities and disadvantages of open source technology projects that teachers can reproduce and apply to their teaching as part of STEM education and project-based education by evaluating the nature of available open source projects from scientific and hobbyist communities.

## 2 Theoretical framework

This section discusses the project's premise regarding methods implemented for the building of the open-source fluorescence spectrometer for teaching purposes. Technology as STEM education and project-based learning (PBL) are discussed, and the scientific background of spectroscopic phenomena and chemical objects for analysis with fluorescence and UV-Vis spectroscopy.

### 2.1 Technology as part of STEM and PBL

#### Project-based technology learning approach in STEM education

Project-based learning (PBL) in STEM education is an approach to teaching that emphasises the student-centred form of instruction, interdisciplinary use of knowledge and skills in a continuous and directional work towards solving a problem. This is done by framing the work done as scientific inquiry, which reflects the nature of science as well as the use of technology if everything is well-aligned in regards to time management, forwards student self-management and management of groups, working outside of classrooms, assessing own and other projects, using technology resources and with a clear teacher-led orientation towards completing the project. (Kokotsaki et al., 2016)

To better understand chemistry-related technology and its applications, PBL-approach can be implemented as a way to familiarise students with working with technology. Such projects can be implemented in a variety of ways that involve a context, motivation, relevance and reasonable contemplation of desired learning goals and activities for desired learning outcomes. For example, integrated STEM education integrates at least two of the concepts in STEM, that is science, technology, engineering and mathematics (Thibaut et al., 2018), and the engineering approach by Wells (2016) could be implemented if students are tasked to build their own device. Modern devices have a history of scientific discoveries behind them, and they rely on empirical theories behind the methods and hardware that have properties that can help us understand empirically matter as measurements that humans physiologically cannot interpret, such as light's quantum yield or non-visible light, to determine characteristics and properties using theories and models. These phenomena can be well-defined and the results from measurements evaluated with an acceptable margin of error to acquire valuable chemical and physical information of matter. This thinking is both abstract and non-visible but very much related to the general paradigm of the empirical study of matter using analytical methods and instrumentation. This is why it's important in education to go deeper into the nature of analytical chemistry using modern methods, and not just older but easily interpretable methods such as using pH paper to determine a qualitative pH level within a sample, instead of using a reference electrode and determining the proton activity within a sample. Project-based learning involves students thinking critically by obtaining data, identifying research tasks and reflecting on observations and methods to knowledge about the subject and finally making a conclusion based on the experience (ChanLin, 2008). These are all aligned with the key aspects, as stated by Kokotsaki et al. (2016), of successful PBL in education.

## 2.2 Fluorescence and UV-Vis spectroscopy

Spectroscopy is the study and methods employed as scientific inquiry of the characteristics of matter and its properties by observing physical systems and the electromagnetic radiation that they either interact with or that they produce (Herrmann & Onkelinx, 1986). Spectrometry is the act of measuring spectroscopic phenomena for analysis using instrumentation. In chemistry, the most useful form of instrumentation for spectroscopy is the spectrophotometer for both quantitative and qualitative analysis of chemical samples to determine the species and the amount of substance in a sample.

Spectrophotometry is the quantitative measurement of the absorbance or transmission properties of matter as a function of wavelength Laitinen and Ewing (1977, as cited in Myers, 2019). In schools, the most likely version of spectrophotometry in use is the visible range spectrometer, or Vis-spectrometry, with various contemporary spectrometers reaching both UV-range and near IR range (Shidiq et al., 2020).

Two empirical laws make it possible for spectrophotometry to give spectra of substances that are both informative and readily measured. These are two empirical absorption laws: Lambert's law states that the fraction of incident light is absorbed independently of the intensity of the source, and Beer's Law says the absorption is directly proportional to the number of absorbing molecules. These two laws make up the Beer-Lambert law, shown in Equation 1. (Fleming & Williams, 1995).

Absorbance, $A$ is also: $A = \log_{10}(I_0/I)$

$$A = elc$$

Equation 1. Where A is absorbance, *e* is the molar attenuation coefficient, *l* is the optical path length that the light passes through, and *c* is the concentration of the attenuating species.

The intensity that was the incident light and the one that passes through a sample that absorbs light needs two measurements at least. This is done by determining the drop of intensity because of absorbance by comparing it to a baseline measurement. The baseline light intensity is defined in liquid samples as the intensity of light that passes through the pure solvent, which is used to solvate the sample. The sample, therefore, is the solvated solute in the same solvent. Liquid and dilute samples are most preferred in the field, with a standardised silica cell of 12,5 mm x 12,5 mm x 48 mm dimensions called a cuvette that holds the samples. The sample absorbs light, photons of discrete wavelengths depending on the characteristics of matter in a sample. Baseline intensity is measured with a blank sample, and both samples are irradiated with the same light source from a fixed distance between the sensor, the light source and the cuvette. After both measurements have been taken, a computer can plot measurement data as $\log_{10}(I_0/I)$ ordinate and wavelength abscissa. Different factors affect the measurement quality, such as the number of impurities and other light sources not intended to be used., and in scientific publications and analysis of error, the results are often converted to $\log_{10}$ molar attenuation coefficient to wavelength or just molar attenuation versus wavelength. (Fleming & Williams, 1995)

Yet, another useful method for gas, liquid and solid chemical systems analysis is rarely utilised distinctly with a spectrometer: fluorescence, luminescence where first there's an absorption of light energy within the system, which is released as a lower energy light emission within the visible light bandwidth. When light, which consists of photons, interacts with matter, it can be absorbed by electrons at the energy ground level, and these electrons get excited to a higher energy level. This can be reversed, however, by the electrons emitting a photon and returning to the energy ground level. Whether it's the same energy level or lower depends on the system and light absorbed (e.g., Hydrogen-1 atom energy levels).

Both phenomena: fluorescence and the absorption of light intensity, have a directly proportional linear relation to the concentration of species of substance in a sample in addition to optical loss and optical density as well as cell concentration (Luong et al., 2011). This is a very integral part of light interactions with matter as stated within the definition of spectroscopy, and is widely utilised in chemistry to interpret quantities and properties of matter since absorption of light is connected to the concentration of chemical species in a sample and fluorescence can be seen within the visible light spectrum, and can be interpreted with our eyes and photography.

Quantitative fluorometry, also known as fluorescence spectroscopy, uses the ratio of the number of photons emitted to the number absorbed, known as fluorescence quantum yield. Fluorescence intensity, $F$, is defined as the quantum yield ($\varphi$) times the difference in intensity in a sample that absorbs light. The quantum yield is the ratio of the number of photons emitted to the number absorbed. This is also affected by the Beer-Lambert law of light absorbed. This relation is shown in Equation 2. (Christopolos & Diamandis, 1996).

Qualitative fluorometry can only measure the shift in absorption and emission wavelength. It is frequently used in medicine and microbiology but is less desired because of its accuracy (Carter et al., 1984).

$$F=\varphi I_0(1-10^{-elc})$$

Equation 2. Where $\varphi$ is the quantum yield, $I_0$ is the intensity of incident light, $e$ is the molar attenuation coefficient, $l$ is the optical path length that the light, $c$ is the concentration of the attenuating species.

## 3 Methods

This section describes the methods implemented for the design of the open source ICT project that was initially designed to be a UV-Vis spectroscope based on a scientific article, but would eventually be reduced to a fluorescence spectroscope that would work as a proof of concept that a hobbyist device was far more reproducible by the means and time taken into consideration. The built device is a fluorescence spectrometer for qualitative analysis of absorption and emission of light designed by Wright (2021), while the design taken from a scientific journal on scientific instrumentation was based on Poh et al.'s (2021) article. The device also followed course objectives outlined as a single-board computer (SBC) device that would consider previous designs and would have a morphological matrix and educational value as part of project-based learning in STEM education. The overall aim in this article is to describe this device's nature as an Open Source ICT project with a description of the background, designs, prototyping and the testing of the built device – a fluorescence spectroscope.

## 3.1 Background and phases in the project

The initial motivation was to build a UV-Vis spectrometer for educational chemistry and biology laboratory purposes that was comparably many times (5-10x) cheaper alternative to commercial spectrometers. The UV-vis spectrometer needed to be accurate and well-defined in its capabilities, so a scientific article by Poh et al. (2021) was chosen as the basis for the device because of its capacity to measure biomolecular concentrations such as DNA and protein concentrations and many inorganic chemical species in the visible spectrum of light. This was desired because of the lack of these devices available for education in Finnish Upper Secondary schools. The bill of materials for the device by Poh et al. (2021) was around 300 EUR, and some purchases were made for the device that was to be similar to Poh et al.'s (2021) design for a UV-Vis spectrometer. A morphological matrix for the device was completed and presented as such:

- The main principles were low-cost, measurement accuracy, large bandwidth, including the UV-light range and reproducibility, and reproducibility
- The functions were UV- and visible light, data transfer and usability

But during the designing phase of the course the idea of building such a device was deemed too problematic because of the workload and apparent practical problems and knowledge gaps in designing three-way switches, aligning light sources using adjustable reflective mirrors towards the sample and eventually the UV photodiodes. It was thought that teachers were not the primary actors to be self-assembling such laboratory equipment as presented by Poh et al. (2021), and it was considered to be unobtainable as a goal.

This shifted the project to focus on a device that would work as a proof of concept, and this was helped by the course instructors. This was deemed more feasible due to course schedule induced time constraints and skills at hand but was also felt as more desirable. Also, the poor availability of electronic components such as UV photodiodes and equipment, such as soldering irons, to build the device facilitated this kind of thinking. It was decided to first build a fluorescence spectrometer from GitHub (Wright, 2021) that was higher in its reproducibility, and could be in theory further developed into a UV-Vis spectroscope. This was thought because one could later design a UV-Vis spectrometer based on the fluorescence spectrometer hardware by changing parameters in the software. This was not attempted, however.

## 3.2 Designing the spectroscope with Open source SBC engineering

The course guidelines stated that students would frame their projects to use an SBC, single-board computer, a Raspberry Pi 3B+ in their devices. The goal was to build some kind of automated device that could measure something of a chemical phenomenon using a sensor or sensors. The sensor data could then be interpreted with software by the user to be further analysed by users such as students as part of scientific inquiry in a classroom.

Students were allowed to brainstorm from presented SBC projects dubbed challenges or come up with their own. Multiple scientific articles describing the development of spectrometers as a low-cost and high-quality tool for both quantitative and qualitative methods for chemistry education and research were assessed. Especially Poh et al. (2021) was considered because the property to measure DNA and protein concentrations in liquid samples were comparable to commercial spectrometers. O'Donoghue's (2019) spectrometric application was also considered because of its simplicity.

Poh et al.'s (2021) design was deemed the most desirable because of the interdisciplinary application in chemistry and biology classrooms and a much lower price compared to commercial devices. And even though, eventually, it was deemed that the devices completion was too complex to complete in time based on the principles in the morphological matrix and the properties of Poh et al.'s (2021) device – the author would eventually settle with a proposed project by the instructor. This project was based on Wright's (2021) GitHub project for a fluorescence spectrometer that, in theory, could be converted to a UV-Vis spectrometer, but would first work as a proof of concept that it was educationally valuable and could fit with the principles of the morphological matrix.

Wright's (2021) device is an open source ICT device that uses materials readily available and used in schools, and their integration to the SBC was also deemed straightforward. The downsides to were stated on the GitHub page as calibration non-linearity (Wright, 2022). Wright's (2021) device consisted of a Raspberry Pi computer, a Raspberry Pi camera, a Zoom lens, a tubular handheld diffraction grating and support for the camera and lens to connect to the diffraction grating. The camera was attached to the SBC, which then was connected to a monitor and a keyboard and mouse. It was decided that a Zoom lens was not completely necessary, and the project proceeded to a prototyping phase.

## 3.3 Prototyping of the spectrometers

The prototyping phase for the spectrometer included 3D-modelling and 3D printing of models to be utilised for the device. Since Wright's (2021) design has a holder for the camera, lens and diffraction grating, these models were most focused on, but also a casing for the device was designed to allow it to be transformed later into UV-Vis spectroscope that had room, in addition to the instruments, for cuvettes, light sources (UV and visible light LEDs). The case was of black PLA-plastic and its function was to protect the instrumentation of the spectrometer and not to let outside light or light reflections to interfere with measurements. These pieces were photographed for reference, as seen in Figure 1.

Figure 1. Modelled parts produced by 3D-printing

In the final prototype, however, only the holders for the diffraction grating were found useful, because the fluorescence spectrometer needed to be freely adjustable and it was not deemed necessary to have a casing for it. The holders are simple rectangular pieces of plastic with a half-circle pocket to keep the tubular diffraction grating in place. One of them was from the project GitHub community discussions page as a link in a different repository (Mash.m, 2021), and the other holder was made by 3D-modelling in FreeCAD and later 3D-printed with MakerBot Replicator 5 Generation 3D printer as well as all the other designs shown in Figure 1.

The prototype was assembled from the following components: Raspberry Pi computer (SBC), a Raspberry Pi camera, tubular handheld diffraction grating and supports for the diffraction grating. The camera was attached to the SBC, which then was connected to a monitor and a keyboard and mouse. Then it was time to test it.

### 3.4 Testing the spectrometer

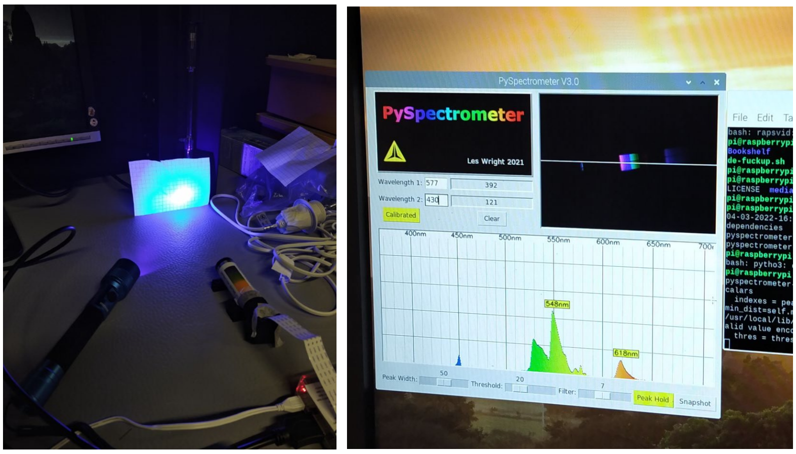
The spectrometer was tested by assembling it in an educational physics laboratory Fotoni, at the University of Helsinki. This was done because of the equipment available there, such as gas discharge tube lamps, that could be made to emit emission spectra from a variety of gases using high voltage and low current. The assembled device was pointed at different gas-discharge lamps, including Helium-2, Argon-18 and Krypton-36 were assessed, and the calibration was done with Argon-18 because the peaks were clearly defined in the visible spectrum of light. This was done because it was harder to determine UV range detection without a proper UV pass filter attached to the camera. In addition to the wavelengths emitted by the lamps, the angle and distance from the lamp affect the measured values, and because of this, the calibration was thought to be repeated and carefully outlined by the aforementioned variables for accurate use for measurements in experiments. The software works by inputting two selected peaks that it will quantify, and these peaks were selected from Argon-18 emission spectra that were at 577 nm as 392 px and 430 nm as px 121 px. It was also found that the calibration would need to be repeated as the software did not retain the earlier information about the values of peaks and pixels. This was determined to be fixed by tweaking the code, but the most reliable measurements are always determined with a recalibration that takes into account the peak width (quality) and the distance from the measured source of light.

## 4 Discussion of educational setting

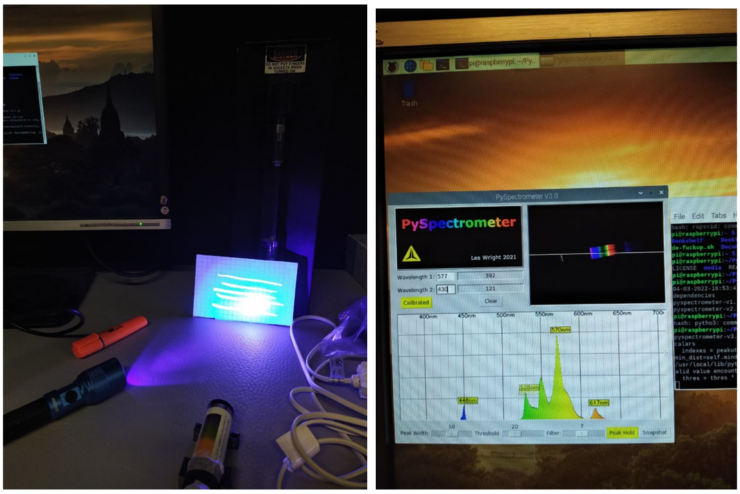
### 4.1 Fluorescence spectrometry workshop

Understanding the phenomena between matter and light can be hard to assess on the microscopic and submicroscopic levels of chemistry, things one cannot see and quantify without the use of technology. The theory behind photon absorption and emission can be difficult to model mentally, and the complex nature of the phenomena can be hard to frame as a simple narrative. One practical approach to tackle these issues would be to conduct experiments after an introduction to the key concepts and examples of spectroscopy in systems that have fluorescence. Fluorescence is a good example of understanding absorption and emission of light because the wavelengths differ especially using UV light to irradiate a sample. This experiment can be done safely and without solvents or gases present if need be.

A very simple experiment of fluorescent matter detection would be the following: shining UV light on two types of notebook paper: one with highlight marker drawn lines and another one without any drawn lines. Both objects would be observed with the fluorescent spectroscope while shining them with a UV lamp, starting with a measurement of the blank notebook paper, and snapshotting or photographing the spectrum (Figure 2 and Figure 3) and then switching to a notebook with highlighter marker lines and make a comparison (Figure 4 and Figure 5).



Figures 2 and 3. On the left is the setup of the equipment, and on the right is the spectrum detected from a blank notebook paper page. Note that the horizontal line is the line where measurements the wavelengths are reported. The line is not recoding the whole spectrum, but the most important fluorescent shift bandwidth is recorded.



Figures 4 and 5. On the left the notebook paper has been changed and coloured with drawn lines with a pink red highlight marker. A clear fluorescent difference can be seen on the right. Students are guided to observe the difference in both wavelength and area of peaks in the spectrum and explain the phenomenon.

The fluorescence of both the notebook paper and the highlighter drawn lines on paper was performed using a UV-A flashlight (range 395-400 nm). This experiment was done for the purposes of this article in a physics classroom since it was the only available space where calibration with Argon-18 discharge tube could be performed at a fixed distance. Calibration is done by selecting two peaks from the spectra that are detected from a fixed distance (~20 cm) by the spectrometer by clicking on the two peaks with a mouse to gain the pixel data and then inputting the approximate wavelengths stated by the software in the GUI. They were, in this case, the same as used in the testing: 577 nm as 392 px and 430 nm as px 121 px. The outcome of this calibration can be seen in the white boxes on the left in Figure 5. The software and the method were provided on the GitHub page (Wight, 2021). The results of this experiment were that paper is highly fluorescent (emission) at peaks 528, 548 and 617 nm, while fluorophores in the highlight marker that was orange peaked with high intensity around 570 nm in addition to the fluorescence of the paper. White notebook paper absorbs UV light because of optical brightening additives and cellulose. The UV-light's drop in intensity when comparing Figures 3 and 5 contribute is linked to the difference in fluorescent matter in a sample, and paper with fluorescent markings in addition to the white paper will absorb more light than just a piece of the same paper.

This simple experiment can be further implemented to other objects that have fluorescent properties, such as Nile red solutions, chlorophyll a and b extracts or to assess the skin colour of apples and reference them to measurements from scientific articles to make assessments about the ripeness of apples.

The objectives for such a workshop would be to understand the basics of fluorophores, substances that absorb light at shorter wavelengths with higher energy, known as electron excitation, and then emit light at longer wavelengths and lower energy, respectively. This workshop could, for example, be part of project-based learning where a number of different commercial and open source spectrometers would be employed in different contexts to understand how such technologies can help us to determine the properties of matter.

## Framing to the Finnish Curricula

Fluorescence or spectroscopy is not mentioned explicitly in the Finnish national core curriculum for general education or upper secondary education, but it is implicitly part of upper-secondary school chemistry and physics learning goals in identifying and interpreting spectra (Finnish National Board of Education, 2015; 2019). Spectra are analysed in upper secondary school chemistry in course modules KE3 and in the physics modules FY8 and FY9, respectively (Finnish National Board of Education, 2019), and are mentioned in the curriculum for Helsinki schools that were introduced at Finnish general upper secondary schools since August 2021 (City of Helsinki, 2021).

### 4.2 Aspects of the reproducibility of ICT projects

Simple and inexpensive hardware and software solutions are very much desired by teachers and engineers if they can function and deliver outlined functions required by scientific inquiries to matter and its characteristics. These functionalities are guided by principles, and so to understand the educational value and applicability of technology solutions for classrooms, teachers need to be aware of how to assess and integrate these technologies into teaching. This requires both predetermined skills and familiarisation with the natural phenomena to be assessed, the purposes and study goals of lesson plans, and the limitations of technology that could be used. Needless to say, to integrate ICT projects, they need to be open source and available with clarified instructions on how to operate and build the devices and what can be done with them since this can help readers to interpret the limitations and reproducibility of the device.

In this paper, the author has stated that the shift in focus on what kind of device is feasible and desirable did not meet the amount of work put into the project. Time and appropriate components were too scarce to meet the requirements outlined initially as a comparable device to commercial devices such as the design from Poh et al. (2021), but instead the project would be reduced from a scientific journal-based ICT device to an open source hobbyist ICT device. This was done because the intensity of planning, time consumption and general reproducibility from readily or much easily available components was higher without compromising the educational value of the spectrometer. On the other hand, it's clear that measurement accuracy and nonlinearity would be compromised, but at the same time without downgrading the educational value of such a device for project-based learning about spectroscopy in chemistry and physics.

In summary, there is great potential in harnessing the positive characteristics of both scientific and hobbyist ICT projects for STEM education as part of PBL, but the reproducibility in regards to the nature of teachers work, skill sets, teacher student attitudes and aptitudes need to be taken into careful considerations when considering the outcomes of such projects.

## 5 Conclusions

The desire to examine upper-secondary school students' views on technology also reflects the science educators' ability to use technologies in a meaningful way for the future of science education (Rasa & Laherto, 2022), and to assess open source ICT technology's place in society. Using a spectrometer that is open source, curriculum-aligned, and reliable in measurements is something that could be used as an educational device. But as stated in this paper's methods section regarding the background, designing and building ICT devices based on scientific publications can be hard to reproduce compared to similar and comparable hobbyist projects. Teachers will have to assess the need for such a device regarding its reproducibility because the designing and building of such devices can lack resources amid the educational responsibilities of teachers. Also, a culture of doing ICT projects can somewhat be lacking on an individual basis based on the characteristics of most proposed projects since they require skills in modelling 3D models for 3D printing, soldering of components that can be very small and coding skills. Building and designing devices also require skills in problem-solving unexpected problems and acquiring new skills by doing – this includes failing, which can be quite fruitful as a stepping stone in learning, but a hindrance when facing a deadline for a project. These problems can be reduced by focusing on resources at hand, such as open source software already in circulation, designing a device by taking into account earlier builds and outlining the application for the device as well as and limiting the scope of the device and its functions early on.

We learn by doing, and that's what open source ICT projects can offer the most for students and teachers alike but the knowledge regarding their reproducibility is highly sought to assess the overall aspects of achieving goals – as presented in this article, the shifts in focus for the device were drastic and constantly evolving towards a more simplified device with the elimination of some functions such measuring concentrations of chemical species in a sample.

Evaluating the needs of pre-service teachers to start implementing ICT projects in the context of the project-based learning paradigm requires probing the applicability and reproducibility of projects that teachers can realistically undertake. In addition, this can be viewed as aligned with what is needed in science education that emphasises project-based learning, teachers' transitional skills in ICT and technology implementation in teaching. These can have beneficial effects if such ICT applications and devices are built, which can further the understanding of the teacher about instruments in science education, which can, in turn, be implemented as teaching to the students. Such an idea is well-aligned with the objectives of project-based learning for education, but the amount of work that is needed for open source ICT devices that would be comparable to commercial spectrometric devices can be unrealistic for pre-service teachers and service teachers alike to reproduce. The key might be somewhere in the middle of hobbyist and scientific article-based ICT projects, or just hobbyist devices with intrinsic educational value to be determined by the teacher, as shown in this article with the built fluorescence spectrometer.

## References

Agu, C. F., Stewart, J., McFarlane-Stewart, N., & Rae, T. (2021). COVID-19 pandemic effects on nursing education: Looking through the lens of a developing country. *International Nursing Review*, *68*(2), 153–158. https://doi.org/10.1111/inr.12663

Shidiq, A. S., Permanasari, A., & Hernani. H. (2020). Simple, Portable, and Inexpensive Spectrophotometers for High Schools Lab Activity. *Proceedings of the 4th Asian Education Symposium (AES 2019)*, 150–154. https://doi.org/10.2991/assehr.k.200513.034

Aykan, A., & Yıldırım, B. (2021). The Integration of a Lesson Study Model into Distance STEM Education during the COVID-19 Pandemic: Teachers' Views and Practice. *Technology, Knowledge and Learning*. https://doi.org/10.1007/s10758-021-09564-9

Bryan, L. A., Moore, T. J., Johnson, C. C., & Roehrig, G. H. (2015). Integrated STEM education. STEM road map: A framework for integrated STEM education, 23-37.

Carter, M. S., Fantinl, G. A., Sammartano, R. J., Mttsudo, S., Silverman, D. G., & Boley, S. J. (1984). Qualitative and quantitative fluorescein fluorescence in determining intestinal viability. *Papers of the Society for Surgery of the Alimentary Tract*, *147*(1), 117–123. https://doi.org/10.1016/0002-9610(84)90044-8

Celik, I., Dindar, M., Muukkonen, H., & Järvelä, S. (2022). The Promises and Challenges of Artificial Intelligence for Teachers: A Systematic Review of Research. *TechTrends*. https://doi.org/10.1007/s11528-022-00715-y

ChanLin, L. (2008). Technology integration applied to project-based learning in science. *Innovations in Education and Teaching International*, *45*(1), 55–65. https://doi.org/10.1080/14703290701757450

Christopolos, T. K., & Diamandis, E. P. (1996). 14—Fluorescence immunoassays. In E. P. Diamandis & T. K. Christopoulos (Eds.), *Immunoassay* (pp. 309–335). Academic Press. https://doi.org/10.1016/B978-012214730-2/50015-7

City of Helsinki. (2021). *Helsingin kaupungin lukioiden opetussuunnitelma 2021*. https://eperusteet.opintopolku.fi/eperusteet-ylops-service/api/dokumentit/11513126

Dawson, K. (2006). Teacher Inquiry. *Journal of Research on Technology in Education*, *38*(3), 265–292. https://doi.org/10.1080/15391523.2006.10782460

Finnish National Board of Education. (2019). *National Core Curriculum for General Upper Secondary Schools 2019*.

Finnish National Board of Education. (2015). *National Core Curriculum for General Education 2015*.

Fleming, I., & Williams, D. H. (1995). Spectroscopic methods in organic chemistry. (5th edition). McGraw-Hill.

Herrmann, R., & Onkelinx, C. (1986). Quantities and units in clinical chemistry: Nebulizer and flame properties in flame emission and absorption spectrometry (Recommendations 1986). *Pure and Applied Chemistry*, *58*(12), 1737–1742. https://doi.org/10.1351/pac198658121737

Kokotsaki, D., Menzies, V., & Wiggins, A. (2016). Project-based learning: A review of the literature. *Improving Schools*, *19*(3), 267–277. https://doi.org/10.1177/1365480216659733

Lohning, A. E., Hall, S., & Dukie, S. (2019). Enhancing Understanding in Biochemistry Using 3D Printing and Cheminformatics Technologies: A Student Perspective. *Journal of Chemical Education*, *96*(11), 2497–2502. https://doi.org/10.1021/acs.jchemed.8b00965

Luong, J. H. T., Mahmoud, K. A., & Male, K. B. (2011). 2.59—Instrumentation and Analytical Methods. In M. Moo-Young (Ed.), *Comprehensive Biotechnology (Second Edition)* (pp. 829–838). Academic Press. https://doi.org/10.1016/B978-0-08-088504-9.00139-2

Mash.m. (2021). *Spectro halt 2a*. Tinkercad. https://www.tinkercad.com/things/basXpPEWYCm

Myers, D. N. (2019). Chapter 10—Innovations in Monitoring With Water-Quality Sensors With Case Studies on Floods, Hurricanes, and Harmful Algal Blooms. In S. Ahuja (Ed.), *Separation Science and Technology* (Vol. 11, pp. 219–283). Academic Press. https://doi.org/10.1016/B978-0-12-815730-5.00010-7

O'Donoghue, J. (2019). Simplified Low-Cost Colorimetry for Education and Public Engagement. *Journal of Chemical Education*, *96*(6), 1136–1142. https://doi.org/10.1021/acs.jchemed.9b00301

Poh, J.-J., Wu, W.-L., Goh, N. W.-J., Tan, S. M.-X., & Gan, S. K.-E. (2021). Spectrophotometer on-the-go: The development of a 2-in-1 UV–Vis portable Arduino-based spectrophotometer. *Sensors and Actuators A: Physical*, *325*, 112698. https://doi.org/10.1016/j.sna.2021.112698

Rasa, T., & Laherto, A. (2022). Young people's technological images of the future: Implications for science and technology education. *European Journal of Futures Research*, *10*(1), 4. https://doi.org/10.1186/s40309-022-00190-x

Rodríguez-Becerra, J., Cáceres-Jensen, L., Díaz, T., Druker, S., Bahamonde Padilla, V., Pernaa, J., & Aksela, M. (2020). Developing technological pedagogical science knowledge through educational computational chemistry: A case study of pre-service chemistry teachers' perceptions. *Chemistry Education Research and Practice*, *21*(2), 638–654. https://doi.org/10.1039/C9RP00273A

Thibault, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., & Depaepe, F. (2018). Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education. *European Journal of STEM Education, 3*, *1*(2). https://doi.org/10.20897/ejsteme/85525

Valtonen, T., Hoang, N., Sointu, E., Näykki, P., Virtanen, A., Pöysä-Tarhonen, J., Häkkinen, P., Järvelä, S., Mäkitalo, K., & Kukkonen, J. (2021). How pre-service teachers perceive their 21st-century skills and dispositions: A longitudinal perspective. *Computers in Human Behavior*, *116*, 106643. https://doi.org/10.1016/j.chb.2020.106643

Voogt, J., Erstad, O., Dede, C., & Mishra, P. (2013). Challenges to learning and schooling in the digital networked world of the 21st century. *Journal of Computer Assisted Learning*, *29*(5), 403–413. https://doi.org/10.1111/jcal.12029

Wang, Q., & Zhang, C. (2021). Can COVID-19 and environmental research in developing countries support these countries to meet the environmental challenges induced by the pandemic? *Environmental Science and Pollution Research*, *28*(30), 41296–41316. https://doi.org/10.1007/s11356-021-13591-5

Wells, J. G. (2016). *PIRPOSAL model of integrative STEM education: Conceptual and pedagogical framework for classroom implementation.* (Vol. 75).

Wright, L. (2022). *Update README.md · leswright1977/PySpectrometer@671c83c*. GitHub. Retrieved 5 April 2022, from https://github.com/leswright1977/PySpectrometer/commit/671c83cea3d3b4db35bde2b88dd25af21cb134dd

Wright, L. (2022). *PySpectrometer 2021-03-05* [Python]. https://github.com/leswright1977/PySpectrometer (Original work published 2021)