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A Colorimeter as a Final Project for a Non-Major Electronic Instrumentation Course

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Abstract

As a final project for our electronic instrumentation practical course, non-electronic major students built their own colorimeter and measured a biochemical reaction of their choice using our recently developed Advanced Learning Platform for Analog Circuits and Automation. In this paper, we elaborate on the utilization of a final interdisciplinary project involving electronics, programming and biochemistry, and present the results and feedback from the students. Given that students considered the colorimeter project not only the most enjoyable part of our course but also highly relevant, we conclude that the colorimeter is an effective final project for our course.

Keywords: Electronics Education, Instrumentation, Practicum, Colorimeter

Introduction

Learning electronics, especially understanding the influence of electronic instrumentation on data, presents a significant challenge [1]. While every student requires a convincing and attractive purpose to make studying more meaningful this necessity becomes even more pronounced for non-electronic major students [2-5]. An effective strategy to provide purpose and motivation is to connect the course content to real-world examples, which shows that the content is relevant [4, 5]. This can be achieved, e.g., through simulations and team projects [6, 7]. In our course, we implemented a final team project that integrates these approaches.

In this paper, we report our colorimeter final project, which ran for 10 years, tailored for an electronic instrumentation course. This final project serves as a robust means of evaluating whether students have acquired the necessary knowledge, practical skills and competencies. Within the project, students integrate the learned electronics and programming, to build a colorimeter and conduct biochemical measurements.

Educational Context

Our educational context for our final project is the bachelor Nanobiology at Delft University of Technology and ErasmusMC in

Rotterdam. Nanobiology students study the complexities of living systems down to the nanometer scale in a quantitative manner. This inter-disciplinary program encompasses mathematics, biology, physics, technology, instrumentation, computation, and chemistry. A significant portion of the curriculum is reserved for laboratory courses and projects, in order to ensure that students can apply their theoretical knowledge in practical scenarios. Electronic Instrumentation is a practical 6 ECTS one-semester, or four-ECTS, course in the second year of the Bachelor. It offers theoretical knowledge on various electronic concepts (including resistors, capacitors, diodes and opamps) alongside hands-on experience in understanding how electronic instruments influence measurement results [8]. The four-hour lab sessions follow a predict-observe-explain format [9]. The prediction is done at home, the observe and explain in the lab on campus, where Teaching Assistants provide support and evaluate the students results.

Similar to many other practical courses [10]. Our Electronic Instrumentation course concludes with an open-ended project. After completing three ECTS covering passive and active electronics, as well as programming and data acquisition skills, students dedicate the last ECTS to constructing their own colorimeter and

presenting their findings in a written report. This project integrates all the theory and skills learned thus far, allowing students ample opportunity to incorporate their own ideas.

Rationale Behind Colorimeter as a Final Project

Any education, including our course, should be forward-looking and train students to become our successful successors, and not capable duplicates. Therefore, students should learn essential 21st-century transferable and multi-disciplinary skills, such as scientific reasoning and critical thinking, which can be achieved through learner-centred, open problem-solving approaches [11]. To ensure active engagement during hands-on activities, it is crucial to align the intended learning outcomes, activities and assessments effectively, avoiding simplistic cookbook-style projects [8, 12, 13].

Problem-based learning, with elements like collaborative work and a context-driven approach, offers a promising method to engage students effectively [14, 15]. By presenting relevant real-life problems, we provide meaningful contexts for learning. Equipment used in biophysics and biochemical labs is very relevant to our nanobiology students, and therefore we selected a colorimeter as perfect topic for a final project. It is straightforward to comprehend, yet presents challenges that require mastery, which is perfect for showcasing the students' knowledge and performance.

A colorimeter, Figure 1, is a device utilized to measure the transmission of monochromatic light through a semi-transparent liquid. By analysing the measured intensity, one can derive the absorption of the liquid given by the formula $C\epsilon D$, where C represents the concentration, ϵ denotes the molar extinction coefficient, and D signifies the distance travelled through the liquid. These recordings in time offers observations of transient behavior and comparison of experimental conditions (Figure 1b). Building upon the concept introduced in [16], we have developed a final project that encompasses both the design and construction of the device, as well as the acquisition of a biochemical reaction with changing absorbance.

While the idea of utilizing a colorimeter for practical applications is not novel [16], existing literature tends to focus on specific aspects of the process and use: some papers report building simple colorimeters for student use, while others involve assembly without requiring electronic understanding, or occasionally incorporating programming, such as using Arduino. In our approach we combine building, and understanding, the colorimeter, with further improvements and application [17-19].

Colorimeter Implementations

Since students need to demonstrate all what they have learned before, the design and utilization of key electronic components, these need to be included in the colorimeter. Additionally, as hardware-software interfacing forms an integral part of the course, students are required to design and implement both data acquisition and data visualization and analysis processes. To accommodate various learning environments, we developed two implementations of the colorimeter. One is designed for classroom use, intended for student pairs with access to necessary equipment. The other implementation is tailored for use during times of Covid-19, allowing students to work individually either at home or in the classroom [20, 21]. This section focuses on detailing these two specific implementations and their associated limitations.

Colorimeter Board, Used in the Classroom: The first colorimeter board, Figure 2, required external hardware, as available in our classroom: an oscilloscope, function generator, multi-meter and power supply (6V and $\pm 20V$) [22]. Students were already accustomed to work with our custom-made, highly robust, and reliable test boards, on which electronic components are securely mounted and connected with BNC connectors or banana plugs (both 4 mm and mini 2mm). Therefore, the design of the colorimeter board closely resembled these test boards to minimize additional, extraneous, cognitive load [23].

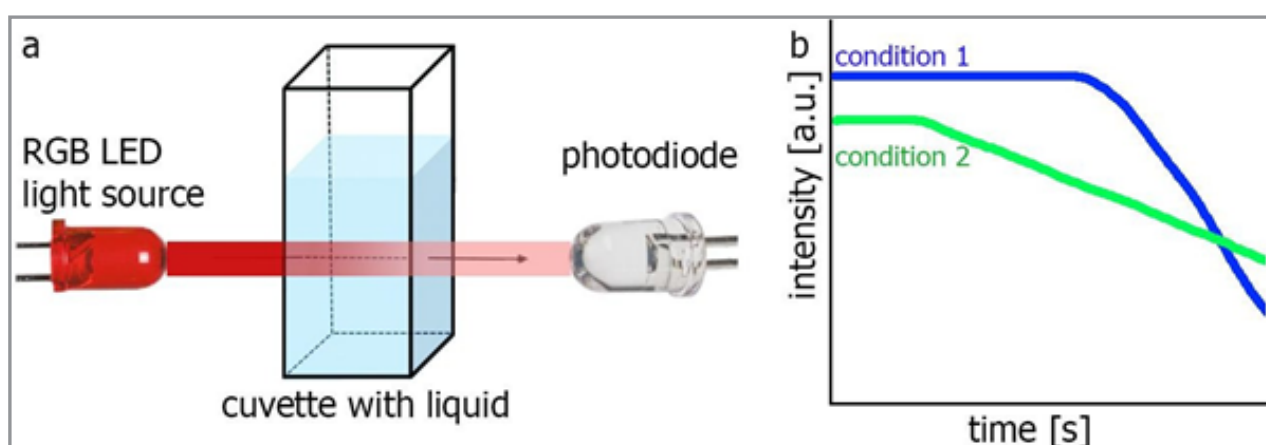


Figure 1: a) Basic colorimeter overview, with the RGB light being attenuated by the liquid in the cuvette, and captured by the photodiode. b) fictive time traces in time, to compare the transient behavior and compare experimental conditions.

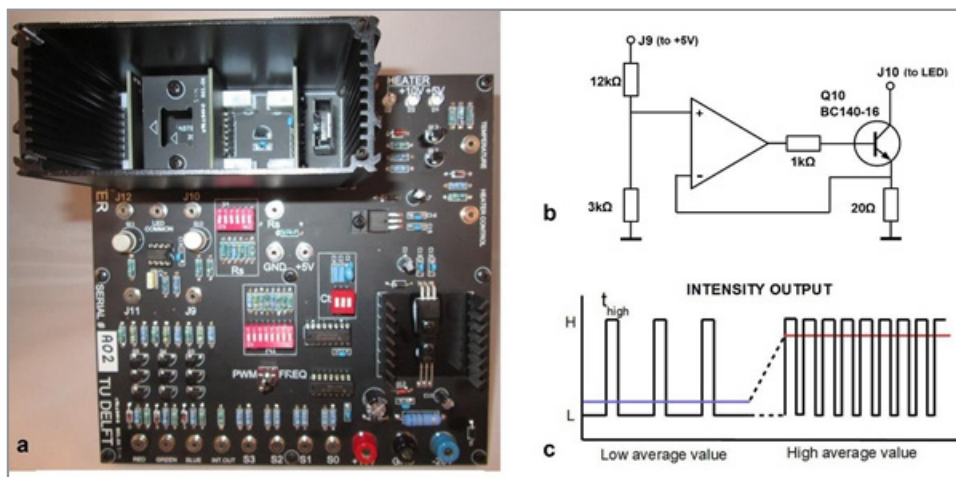


Figure 2: Colorimeter board [22] a) top view of the board, b) circuit diagram of a LED current stabilizer, c) representation of our quasi PWM (pulse width modulation: the high time is kept constant)

The basic operation of shining light through a cuvette, in a dark/shielded enclosure and recording the transmitted intensity, was designed with several optional features:

- Both LED and diode were chosen to be multi-colour to enable measurement of liquids with various colours
- A heater plus temperature sensor were included for possible temperature-sensitive reactions, such as the growth of yeast.
- The current through the LED could be controlled by a resistor alone, a transistor or even a transistor plus opamp circuit. Besides the complexity, these control options mainly differ in the amount and predictability of the current regulation (through feedback).
- The output signal had a frequency proportional to the measured intensity, with optional scaling in both voltage and frequency domains. In an optional quasi 'PWM' mode, the pulse width could be varied by selecting the most appropriate resistor and capacitor.

Allowing students to choose their preferred implementation provided them with the flexibility to focus either on the elec-

tronics or the programming aspect of the project. For example, they could opt to acquire the output signal and analyse its frequency through data analysis. Alternatively, they could use the quasi 'PWM' mode (figure 2c) and integrate the signal with an op-amp, resulting in an intensity-dependent voltage, which is easier to acquire and analyse. The temperature control could be achieved through various methods, such as a simple electronic comparator scheme, or a (programmed) digital output to switch the heater on or off. Offering many options empowered students to tailor their project according to their interests and strengths.

Colorimeter on the ALPACA: During COVID-19, we developed our advanced learning platform for analog circuits and automation (ALPACA), to facilitate the delivery of our practicums without requiring all students to be physically present on campus for every session, see Figure 3 [20, 21]. The platform was developed using a Raspberry Pi Pico controlled through Python, which is the main programming language used by TUDelft students.

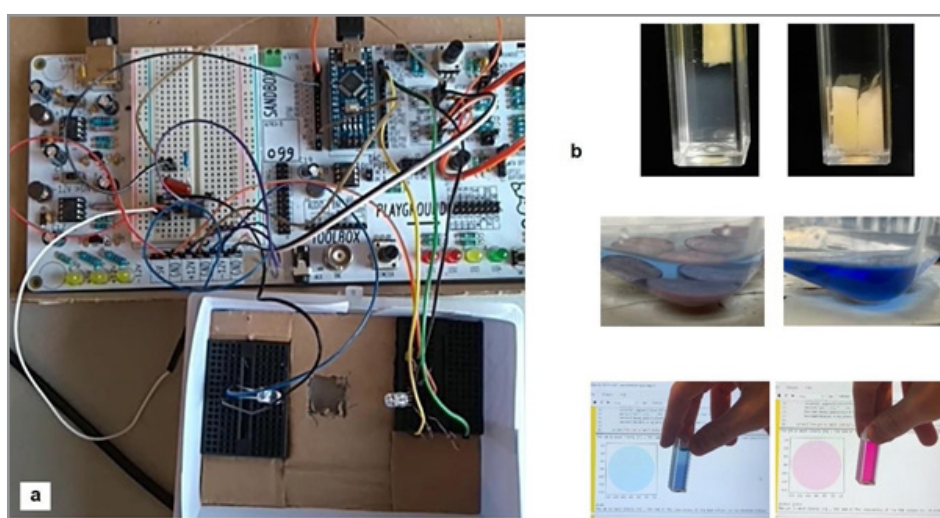


Figure 3: Colorimeter realized with an ALPACA board [20, 21]. a) a typical setup, b) implementations of pineapple eating its way through gelatine, copper coins in ammonia (turning bluer over time), and an automatic colour detector (blue and pink)

On the ALPACA platform, we incorporated a digital-to-analog converter (DAC) to enable analog output functionality. Additionally, we implemented analog input and digital input/output capabilities, along with a suitable power supply. To ensure optimal performance and safety, we included onboard amplifiers and voltage level adaptation mechanisms, which allowed the op-amps to operate at 12V, while safeguarding the Raspberry Pi Pico from negative voltages and voltages exceeding 3.3V. All circuits were to be constructed on a breadboard, with the necessary components supplied alongside the ALPACA platform.

The ALPACA colorimeter offered extensive functionality comparable to that of the colorimeter board. Moreover, it provided the added advantage of accessibility outside the practicum room and beyond campus hours. This allowed for extended measurement sessions and ample time for test runs, enhancing the overall flexibility and usability of the system.

From Guided to Open Inquiry

The students were equipped with a basic manual providing guidance for conducting fundamental measurements, including controlling the LED and photodiode, and basic code for data acquisition. However, they were tasked with integrating these components to fulfil the initial requirement: measuring the absorbance of various concentrations of food colour dyes and deriving the absorption coefficient through Beer-Lambert law [24].

While the first part of the experiment yielded a single data point, the subsequent phase focused on employing the colorimeter for biochemical reactions with time-dependent intensity changes, allowing students to choose their preferred reaction. Over the years several experiments were elected, with the choice of reaction left open in recent years:

- Iodine-clock reaction to assess the vitamin C concentration.
- Determination of the pH of soft drinks using a pH-dependent dye.

- Determination of the concentrations of a mixture of three food colour dye solutions by solving a set of linear equations (three colour dyes, three RGB measurements per colour).
- Examination of the influence of light intensity, colour and temperature on the photosynthesis rate of spinach.
- Observation and manipulation of yeast growth, by varying factors as sugar type, temperature, and light colour.

In addition to the mandatory biochemical reaction, students were encouraged to construct their own light-tight box, from cardboard or 3D printed components, for their colorimeter. They were challenged to expand upon the provided basics by enhancing and extending the code, electronics, and/or biochemical reaction. This could involve tasks such as automating measurements, adjusting measurement settings (e.g. changing colour, intensity, or temperature), or implementing other novel functionalities.

Colorimeter Assessment

The students collaborated in pairs, sharing their knowledge, code, circuit diagrams and discussed their implementations. For the colorimeter board used in the classroom, the report was prepared jointly by the pairs. However, due to COVID-19 restrictions, the report for the ALPACA implementation was submitted individually.

To ensure more consistent grading and transparency for the student, a rubric was developed [25]. The rubric was designed to allow students to earn half of their score, 5 out of 10 points, through the basic implementation of electronics, programming, and the colour dye experiment. The remaining half of their score was derived from their individual contributions, such as constructing a light-tight box, incorporating a transistor/ oscillator, and making optimisations (Table 1).

Table 1: Rubric for Colorimeter assessment. For each subtopic max 0.5 points can be earned. The subtopics in light grey (in topics 1-4) are considered as ‘do’, in white are ‘explain’, and in darker grey (topics 5b, and 6) are ‘advance’.

Topics	Subtopics	
1. electronics	Diagram	picture circuit
	description	noise reduction
2. programming	code	documentation
	test LED	test photodiode
3. Light-tight box	photo box	calibration
4. color-dye	absorbance plot	derived coefficients
5. transistor/opamp	idea	implementation
6. optimalization	biochem: qualitative	biochem: quantitative
	electronics: switch/opamp	electronics: comparator/ temperature
	code: oscillator, read -out	code: automation, color detect

Table 2: Average grades per exam (2014-2022).

	average grade (2014-2022)	Standard deviation
exam 1	6.94	0.46
exam 2	7.04	0.64
exam 3	6.42	0.42
report	7.60	0.20
final grade	6.77	0.28

For each type of optimisation a maximum of 2 points per category (reaction, electronics or programming) could be earned, with a total limit of 3 points. The implementation ('do'), explanation and advancement (go beyond what is given in the manual) were all equally valued in the assessment process

Results

The grades obtained by students in the colorimeter project, along with their evaluations, were utilized to assess the effectiveness of the intervention, providing valuable insights into the success of the project implementation.

Exam and Report Grades: First, the average exam grades will be discussed. Over the years we gradually phased out the final exam (exam4) to achieve a better balance between theoretical assessments (exam1&3) and practical evaluations (exam2 and the final project), thereby placing great emphasis on the practical aspect of the course.

When reviewing the average grades per exam or report, it is clear that the report receives the highest scores, with an average of 7.6 out of 10 (Table 2).

Furthermore, examining the distribution of grades for the 2021 cohort, Figure 4, the report scores on average almost one point higher than the average grades of exam 1,2,3.

When examining the distribution of scores across the rubric items (Table 1), students of the 2021 cohort achieved a score of 93% for the executable tasks ('do'), 84% on the understanding ('explain'), 82% on their first optimization ('advance', often the biochemical reaction). The lower scores for the transistor/

opamp (64%), quantifying the reaction (48%) and further improvements (38%) for improving the basic programming and electronics were attributed to less serious attempts in these areas.

Feedback from Evaluations: From the presented grades, it is evident students seized the opportunity to positively influence their final grade. Many students willingly invested additional effort, as many voluntarily participated in an optional practical session during the exam week, to further polish their results.

Student feedback highlighted their enjoyment of the project, emphasizing its relevance to Nanobiology and the course as a whole. Many students appreciated the practical application of their acquired knowledge and expressed satisfaction with the opportunity to showcase their skills in a real-world context. Their responses indicate a genuine appreciation for the approach taken in the course, with several students suggesting applying this approach throughout the whole course. Some illustrative student responses on the open question 'Which parts of this course do you consider to be good' were:

- "The final project was fun and relevant to both Nanobiology and this course"
- "The final project helps to "feel" the practical application of obtained knowledge, especially for future nanobiologists."
- "It is great that the final project is a real practical task (and not an exam), where we can show all our knowledge we have built over the course."

Overall, the positive responses from the students reflect the value they placed on the minds-on practical nature of the colorimeter project, and its alignment with their academic and professional interests in nanobiology.

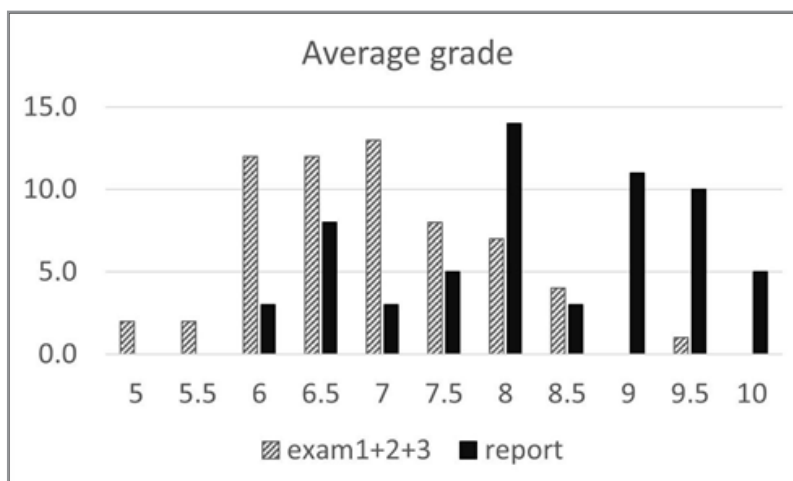


Figure 4: The grade distribution for the 2021 cohort, showing a full point difference between exam1,2,3 and the report.

Discussion and Conclusions

We have presented the final project for our electronic course designed specifically for Nanobiology students which project challenges students to construct their own colorimeter and utilize it as an instrument for conducting their own experiments. The observed engagement was high, with many students dedicating significant effort to achieve the best possible results. Throughout the project, students demonstrated their ability to apply their practical skills by performing basic measurements, effectively communicated their understanding of experimental results, and showcased their creativity by going beyond the specified requirements. The students' active participation was clearly reflected in their grades, as well as in their written course' feedback.

We conclude that integrating practical components into a theoretical course and putting it to the test in a final project can greatly benefit students. Open inquiries, such as the one presented in this paper, allow students to apply their acquired knowledge, skills and competences in a real-life setting. This approach not only enhances their understanding but also fosters critical thinking, problem-solving, and creativity, thereby enriching the learning experience for students.

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Ethical Statement

This study conducted at Delft University of Technology respected the privacy and psychological wellbeing of the individuals observed and posed minimal risk to the students as no personal data was collected.

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