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Docter, M. W.; Bastemeijer, J.

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PAPER • OPEN ACCESS

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To cite this article: M W Docter and J Bastemeijer 2024 *J. Phys.: Conf. Ser.* **2727** 012023

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The Advanced Learning Platform for Analog Circuits and Automation for hybrid electronic practicals

M W Docter[1, 0000-0002-3863-9657], **J Bastemeijer**[2, 0000-0001-7152-2154]

[1] Department of Bionanoscience, Delft University of Technology, the Netherlands
[2] Microelectronics department, Delft University of Technology, the Netherlands

m.w.docter@tudelft.nl, j.bastemeijer@tudelft.nl

Abstract. To maintain experimental lab course work during the COVID-19 lockdowns, we chose a hybrid approach for our electronic instrumentation course and developed thereto the Advanced Learning Platform for Analog Circuits and Automation (ALPACA). To further meet our goals and standards, the ALPACA platform has been updated, using a Raspberry Pi Pico with Python instead of an Arduino. Our educational materials and approach are illustrated here through the typical example of a relaxation oscillator assignment. As student's feedback was overall positive and grades remained comparable, we continue the use of the ALPACA in the non-COVID era.

1. Introduction

Nanobiology at the Delft University of Technology (DUT) and ErasmusMC is a relatively young study which focuses on the nanometer scale boundary of physics and biology. Physics, biology, chemistry, and mathematics are taught, as well as instrumentational and computational skills. It is given in English, with 25% international students and 50/50 male/female, with around 100 students starting each year.

In our 2nd year Bsc Electronic Instrumentation course, theory and practice are intertwined (hands on & minds on) in a predict-observe-explain approach [1]. The main goal is to develop sufficient knowledge and skills for students to design, conduct, and evaluate their own instrumentation-based electronic experiment. To attain this goal, we normally use a linear learning route in a blended, multi-modal way. The pandemic and lockdowns only allowed sparse time on campus. As many other lab courses [2-6], we adapted our course and conducted hybrid practicals, alternating on and off campus. To be able to do so, we developed the Advanced Learning Platform for Analog Circuits and Automation (ALPACA).

As it is known that teaching conceptual knowledge through practical work is difficult and often unsuccessful [7, 8], we aim to answer the question whether this platform is successful in terms of attaining the set learning goals. Moreover, as non-major students are less motivated to learn core physics [9], we question as well whether the ALPACA and the associated approach contributes to students' motivation to engage in an electronic course. Students continuing to use the ALPACA for on campus and asynchronous learning after the pandemic, confirms the platform's success.

In this paper we will give brief theoretical background on learning through practicums, explain the details of the ALPACA design, both hardware and software, give an example of the use of the ALPACA in an oscillator practical assignment, and evaluate the use of the ALPACA.

2. Course structure

Our course runs for four octals: 4 weeks of teaching, plus 1 exam week per octal. Each week includes 2 hours of theory (including simulation and exercises) plus 4 hours of practicums. The first octal is about passive components, electronic networks, and measurement equipment introduction. In the second octal Python programming skills are developed to automate measurements. The last two octals focus on semiconductor electronics (diode, opamps). At the end students are challenged to design and build their own colorimeter, exceeding the basic electronics and code provided [10].

Before the pandemic, all practical assignments required classroom equipment only available during course hours (4 hours per week). Students would do a homework quiz on beforehand, and guided inquiry in pairs in classroom, which was evaluated by a Teaching Assistant (TA).

During the preparation of the Pandemic adapted approach, we carefully selected about half of the practical assignments to be conducted at home. These activities involved simulations with LTSpice [11], which provided opportunities beyond the limitations of instrumentation, and hands-on experiments at home requiring a new platform. We therefore developed the ALPACA [12, 13]. Students received their ALPACA at the start of the course to work with it at home, outside the laboratory, during the full course. As remote help is challenging [3] we envisioned this learning platform to be mainly used for the simpler, more reproducible, lower sampling frequency measurements.

3. Theory & general implementation

In literature, it is often mentioned that practical work hardly contributes to the learning of conceptual knowledge [7, 8, 14]. Practical work is, however, effective in teaching students how to manipulate equipment [15]. The main course goal is to integrate theory on electronics with experiments, including the influence instrumentation has on key features of the circuit. Students learn to work with, e.g., oscilloscopes, function generators, digital multimeters and so on, and simultaneously develop conceptual understandings of the investigated circuits and electronic components.

To attain both goals, a blended multimodal approach with a mix of online and offline activities, is used. Blended learning is more effective than traditional learning, possibly caused by the fact that students can learn on their own pace, which might lead to higher motivation and helps develop time-management skills [16]. Although a blended approach [17] is advocated for traditional lecture style courses, we did not yet encounter such approaches for lab courses. We thus explore, though in a very limited way, whether a blended learning approach has the potential to increase the learning outcomes of practical work. To further optimize the approach we made use of the recommendations of several scholars.

In order for learning through practicals to be effective, Hodson [14] emphasizes that a teacher should carefully consider its goals and use, and match the goal and the method of each activity. Goals for hands-on experiments should be achievable, and supportive for students' self-confidence. Millar [18] questions the effectiveness of recipe style practical work. To foster learning in and from practicals, he recommends the use of minds-on activities, i.e., integrate thinking and evaluation tasks in a teaching sequence.

To integrate such minds-on activities, we follow the predict-observe-explain approach [1], which is implemented in our general teaching sequence:

- Lecture preparation: students watch instructional videos and study the theoretical background
- Active participation during lecture: students engage in exercises and group discussion
- Connecting theory (lecture) and practice (practical): students use the theory to make predictions on the outcomes of the practical
- Active participation during practicals: students make assignments, discuss with peers, are probed by teaching assistants

The mix of online and offline activities offers more freedom and agency, where students decide on the pace: they either prepare in advance or catch up afterwards. This does, however, require time-management skills on students' side.

4. ALPACA hardware & software features

The minimal requirement for an experiment at home was that students are able to build a circuit, generate input signals, and acquire the output signal. The platform thus at least required:

- several digital I/O lines (for TTL logics, 0-5V)
- two analog input lines, for data acquisition.
  - possibility to acquire positive and negative signals, to attenuate or amplify the signal
  - safety precaution to avoid damage to the hardware (make it student-proof).
- one, preferably two, analog output lines for signal generation.
- DC and AC signal levels (0-5V), preferably also negative signals
  - At least till 500 Hz, preferably higher (up to 10 kHz)
- open-source software, programmable in Python (preferred language at the DUT)
- a bread board for building electronic circuits
- to be affordable, relatively low cost

4.1. Hardware

Our initial design used an Arduino Nano which covered most requirements, except for programming in Python. As the Raspberry PicoPi arrived shortly after releasing our first version of ALPACA, we redesigned the ALPACA (Figure 1), allowing direct programming in Python, at higher frame rates.
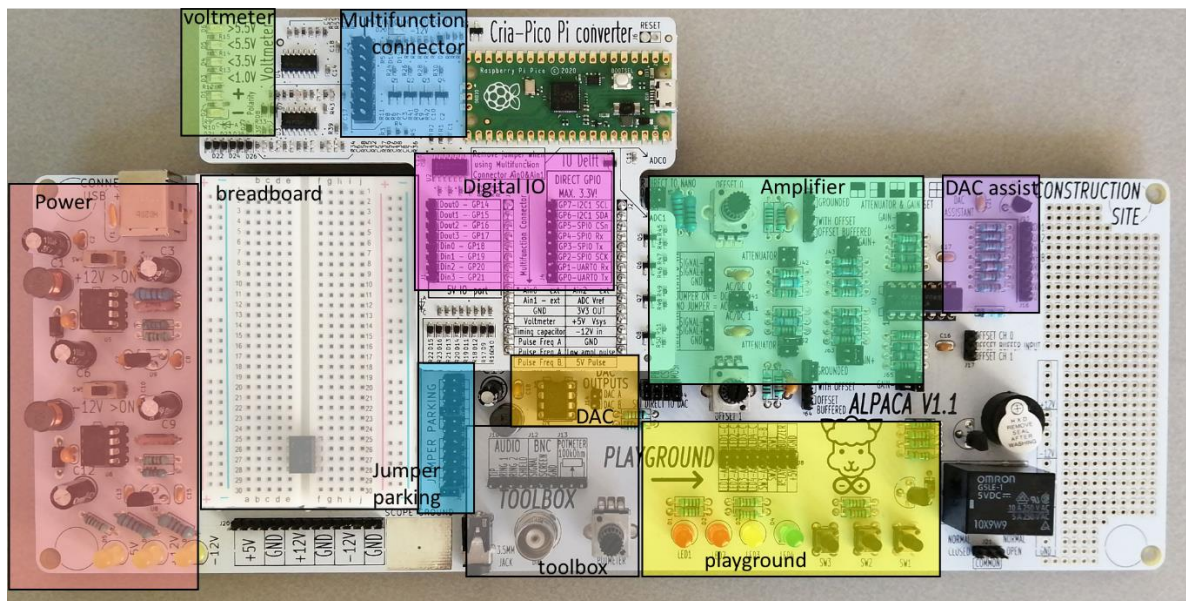

Figure 1. Overview of the ALPACA (lower big rectangle) with the added Cria (top middle). The Cria contains the voltmeter, multifunction connector, PicoPi and digital IO. The ALPACA contain section for power, breadboard, DAC, DAC assist, amplifier, toolbox, and playground [12]

The generation of analog output was made possible via an additional DAC (digital to analog converter). The ALPACA could generate a sine wave via the DAC, range 0 and 4.096V. For the DAC and opamps, an onboard power supply for +5V, +12V and -12V, was powered through an USB cable. The microcontroller module was protected against overload on the input pins (limiting them to 0-5V). A small breadboard allowed to build simple circuits. With the 'DAC assistant' the DAC output voltages could be adjusted in DC offset level and amplified to max -10V till +10V. Before acquisition the input signal could be amplified or attenuated (1-10x), with AC or DC coupling and possible DC offset, such that the acquired signal was within safe voltage boundaries. Lastly, for interfacing a toolbox with audio jack, BNC connector and potentiometer were added.

An additional board, named Cria (literate translation = young ALPACA), was made to fit the PicoPi on the ALPACA, see Figure 1. It converted the max 5 V for the ALPACA with Arduino to max 3.3V for the Cria & PicoPi. The Cria also housed a Voltmeter, which visualized the voltage level and polarity and could generate its own square-wave test signal with a variable frequency (orders 1 Hz to 1 kHz).

4.2. Python software
The new Raspberry PicoPi, directly controlled via MicroPython, was found superior over the Arduino Nano with the slower PyFirmata (required for Arduino interfacing). A dedicated software module [19], nb2211.py, was written for communication between PicoPi and DAC. This module students could generate a DC voltage or time-varying signal, e.g. a sine, with speeds depending on the number of steps (Nstep=16 at 1.1kHz, or Nstep=128 at 141 Hz, Figure 2b), parallel to acquisition at 50 kHz.

Both PicoPi cores are used at the same time, to acquire and generate signals in parallel (Figure 2a). The arbitrary wave generation (AWG) starts on core0, is moved to a core1, and then the acquisition process starts on core0. A lock on core1 makes sure both processes/ cores are finished at the end of the program.
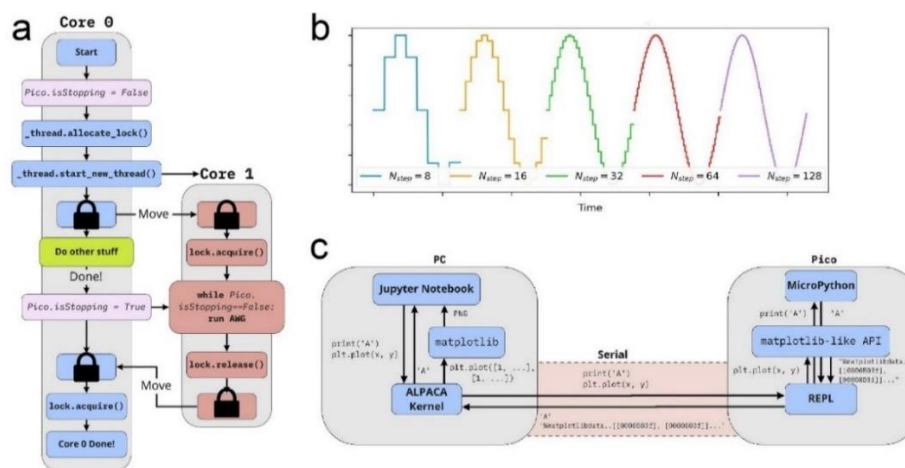

Figure 2: (a): The PicoPi uses two cores to acquire and generate a signal through DAC simultaneously. (b): sine signals generated by the DAC, with Nstep automatically set. (c): the ALPACA Kernel, allowing data acquisition, analysis and plotting run live and in the same kernel. [19]

A new ALPACA kernel was developed, which reduced complexity for students, since it provided plotting, PicoPi control, and data manipulation functioning on one kernel. An under-the-hood serial connection allowed communication with the MicroPython (REPL) interpreter. (Figure 2c).

5. ALPACA assignments
In this section we give an overview of all ALPACA assignments, and look at one specific assignment, the relaxation oscillator. We used the online cloud-based Python platform Vocareum [20] for all assignments. It allowed us to run code, comment, and grade, but for use of the required PicoPi drivers students must still download the PicoPi assignments locally.

5.1. Overview ALPACA assignments
From our originally fully on-campus program, we carefully re-evaluated all existing practical assignments for the COVID-19 period. Assignments which required classroom equipment (oscilloscope, multimeter, function generator) were still carried out on campus. For the ALPACA we selected the simpler experiments, which required lower acquisition rates and were relatively easy to build on a breadboard. For the simulations, assignments were selected which were either tedious, error-prone, or would require ideal equipment. This led to the ALPACA assignment selection specified in Table 1.

Table 1. Overview of the ALPACA assignments, with description focusing on experimental content.

	Topic	Details
1.	Intro	Install and use the new Kernel, test ALPACA + Cria features
2.	Stacked resistor divider	Predict, observe, explain the order of stacking two voltage dividers
3.	RC – low pass filter	Measure the step response of a low pass filter, determine the time constant.
4.	RRCC – band pass filter	Combine a high and low pass filter (and vice versa).
5.	Diode	Investigate diodes, eventually build and examine a simple rectifier
6.	Diode bridge	Build & understand a full bridge rectifier and verify its function
7.	Non-inverting opamp	Build the circuit, use the ALPACA for attenuation, observe clipping
8.	Inverting opamp	Use AC/DC coupling and DC offset to correctly measure a negative signal
9.	Relaxation oscillator	Use an integrator plus comparator to make an oscillator.
10.	Temperature sensor	Use a diode + temp sensor to measure the temperature of a transistor
11.	MOSFET switch	Use a MOSFET as voltage controllable switch to switch the buzzer on
12.	Colorimeter (final) assignment	With very basic electronics and code build your own colorimeter to do more advanced measurements.

5.2. Example ALPACA assignment – blended learning approach
The relaxation oscillator is a good example for an assignment using the ALPACA (Figure 3), which has a combined use of and integrator and a comparator.
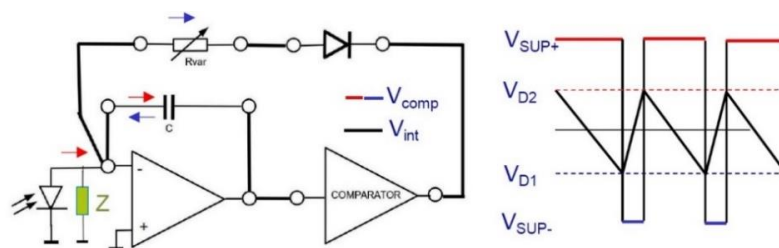

Figure 3. Relaxation oscillator circuit (left) for frequency readout of a photodiode (right),
as given in the theory session

Before the actual building of their own oscillator starts, the students already (actively) encountered the relaxation oscillator through (preparation of) theory, exercises, and simulations. In between theory and practicum, the student should predict the outcome of the future measurements.

In the practical task a relay – instead of a comparator - was used for the oscillator [21]. The circuit's complexity was gradually increased during the assignment (Figure 4). The manual included schematic representations of the circuit, to simplify the data acquisition and leave time for reflective questions.

Students were encouraged to predict the expected output signal, measure, and evaluate the real output signal. Students were asked to answer the following questions (per step of Figure 4) :
   a) *With only the capacitor in place, why do you only see a constant positive signal out?*
   b) *What happens if you press the switch? Can you explain this behavior?*
   c) *Explain how the circuit is working. At which voltage is the capacitor short circuited?*
   d) *Measure + explain the output signal's frequency, for a lower input resistor (<66 kΩ)*
Questions c & d were discussed with a TA in class (preferred way) or checked online after online submission. Feedback was provided, and in case of a non-acceptable answer also a resubmission.

6. Evaluation
As input for our evaluation we have grades, students' evaluations (Likert scale + written comments), feedback from TAs, data (like submission date) of the online submitted notebooks, and content of the final report. The number of participating students remained stable after the second octal: the student numbers finishing the course were 80 (2018), 82 (2019), 65 (2020-ALPACA+Arduino, half of the practicums obligated at home), 62 (2021-ALPACA+Pico, full practicum time on campus).
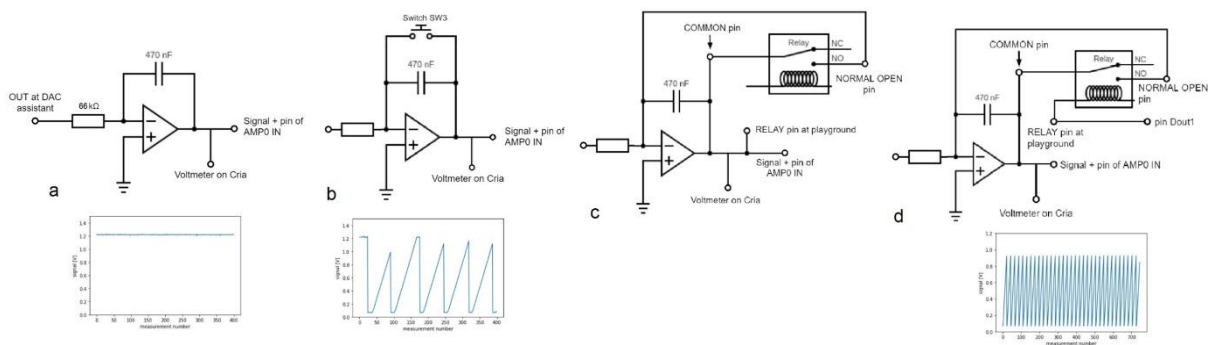
Figure 4. Steps taken during the practicum. (a) integrator circuit, (b) switch added to reset, (c) automatic reset via relay, (d) automatic reset via PicoPi with variable threshold.[10]

6.1. Numbers on the guided assignments (2021 cohort)

From the online submission dates for all 2021 assignments was found that overall 79% of them succeed within the first attempt. This indicated the level of complexity was appropriate, and students managed to answer the reflection questions by the Teaching Assistant correctly.

However, there was a big difference in time it took to finish an assignment: on average 77% of the students got their on campus assignments (which cannot be done at home) approved by a TA within 7 days. Only 45% finished the practicums not requiring the classroom equipment (also available at home) within a week; these were the simulation, programming and ALPACA assignments. The difference between the time it took to do (or start) an assignment could be attributed to the limited time in the classroom each week, in comparison to plenty of time for the at-home assignments. Some students made a decision to have a "relaxed" session in the classroom, and did more work at home, finishing all their practicums just before the overall deadline at the start of the next octal.

6.2. Impact of oscillator assignment on final assignment (2021 cohort)

We demanded students to incorporate either a transistor or an oscillator in building a colorimeter in the final assignment. Students often chose the transistor (48 out of 62 submissions) while the oscillator is only used in 6 out of 62 cases. We assume students wanted to avoid the additional required code for using the oscillator. The grades of the final assignment were correlated to the use of a (more difficult) oscillator or (easier) transistor, but not necessarily causally related: an average 8.9 for the oscillator users, a 7.9 for the transistor users, and a 6.8 for the ones with lack of implementation.

6.3. Student's perception and positive feedback (2018-2021):

In 2020 with the ALPACA + Arduino, we observed an increased score on the category's 'clear objective', 'prior knowledge' and 'learned a lot' (Figure 5). In 2021 the scores with the ALPACA + Picopi are a back to old levels, but the most interesting 'learned a lot' category remains higher than pre-corona. Since the most important difference is the ALPACA, we attribute this increase to the use of our ALPACA platform.

In 2020, the first year of the ALPACA with Arduino, we got positive and dedicated feedback on the device: "The ALPACA practicals were a really good solution for doing practicals at home", "The content of the distance-education was very good; good job on changing the content of the course to fit online education", "The possibility to work in own pace". In 2021 the feedback was more general (only indirect on the ALPACA): "I loved doing all the assignments and building the colorimeter was the most fun", "The practical assignments were very useful in teaching me, more so than the lectures."

In both years, the students often mentioned that when you get stuck at home, a TA cannot easily watch over your shoulder and help. TA and teachers could not agree more. Fortunately, still many questions could be answered via online discussions, for which the students showed a lot of appreciation.
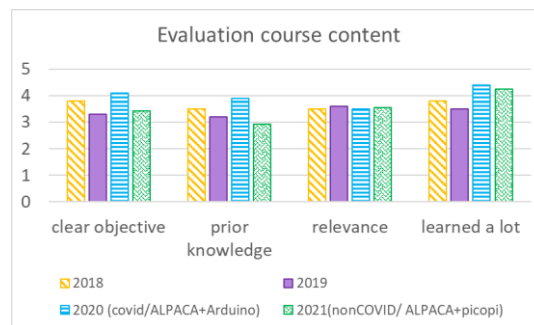
Figure 5. feedback on a 5 point Likert scale (1: totally disagree – 5: totally agree). The number of participants and respondents were 80-52 (2018), 82-48 (2019), 65-19 (2020), 62-22 (2021). 2020&2021 had less respondents because of digital evaluation (versus the earlier written after exam)

Students in 2021-2022 only had the opportunity to work with the ALPACA and PicoPi (not with the Arduino anymore, so students could not compare both implementations). The students appreciated being able to program in one language, Python, which is a challenge on its own for them. The teachers and TA, who used both the Arduino and Picopi implementation, were in favor of the Python approach, which allowed for more focus and therefore more understanding for the students and ourselves.

6.4. Points for further improvement

A main challenge was to finish the assignments within reasonable time; we saw many more students 'failing' time wise to finish their assignments during the practical session. We believed this cannot be attributed to the ALPACA, because we saw the same challenges in the classroom as for the assignments at home (simulations and ALPACA). The three main challenges for the students, derived from teacher's observations, were: 1. Think before acting: often the TAs had to point at the correct information in the manual, which students overlooked. 2. Think critically, do not accept any outcome: we too often saw doing the measurements gets all the attention, while prediction and evaluation are equally important. 3. Be confident and self-reliant: students' needed a lot of confirmation during the assignments.

The capability of handling unexpected events seemed less developed, which could be due to the higher guidance level in teaching the previous (Covid-19) year, or to the lack of peer feedback for the at home assignments (despite our efforts of promoting working together online). The focus of further improvements on our course next year will be on exploring ways to develop trouble-shooting skills and becoming self-reliant.

7. Conclusion

In this paper we presented our Advanced Learning Platform for Analog Circuits and Automation (ALPACA) in a blended, multimodal, learning environment and gave an example of an integrated teaching sequence with reachable goals; 79% of the students manages to pass the high quality control by Teaching Assistants in one attempt, which implies we successfully integrated thinking and evaluation in our learning sequence. The ALPACA allowed blended education in an asynchronous way, which was well-appreciated by the students. However, too often we saw bigger delays in finishing the at-home assignments, also because online help was harder to give. Therefore we will provide guidance when using the ALPACA on campus, and allow students to continue afterwards (less-supervised) at home.

In a forthcoming article, we further explore the use of a blended learning approach for practical work. There we make use of another didactical strategy called 'just-in-time teaching' [22].

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