

Implementing a Raspberry Pi based Digital Measurement System in Undergraduate Physics Education

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Abstract

This paper describes a number of active learning strategies based on implementing the Raspberry Pi as low-cost single-board computing device for carrying out physics laboratory activities. This Microcomputer-Based Laboratory (MBL) Project has been funded by the Baden-Württemberg Foundation and it encompasses the use of high-accuracy yet inexpensive sensors for controlling digital inputs and outputs and for data acquisition in physics experiments. The open-source software package PhyPiDAQ consists of programmed classes in Python which, together with the Raspberry Pi, manage the collection, display, and storage of data obtained from physical sensors. Thus, students select pre-configured default modules of specific sensors such as for position, acceleration, temperature, current or force sensor, as well as a variety of representations and graphical features for the display of real-time data. An extensive range of recorded measurements may be interdisciplinary used in analytical processes for statistic calculation, or for numerical derivative and integration of physical quantities. The rich array of innovative implementations of this Raspberry Pi based MBL fosters an environment in which students can carry out a variety of creative exploratory physics activities within as well as beyond the classroom.

Keywords: Raspberry Pi, Sensors, PhyPiDAQ-Open Source Software

INTRODUCTION

This MBL project aimed to develop and to implement a low-cost yet accurate measurement system for physical laboratory experiments that allows acquisition, display, and storage of data from a wide range of inexpensive sensors connected to the Raspberry Pi (Wikipedia, n.d.) in order to measure particular physical variables.

The interest of students in developing a measurement system based on the Raspberry Pi and different sensors has been growing due to the convenience of the components, enabling them to build their personal devices for particular measurement purposes in the lab as well as in their free time.

In the course of laboratory activities, we found that the results of measuring different physical quantities with the Raspberry Pi based measuring system are comparable or even better, in some cases than those obtained from the commercial systems such as CASSY developed by Leybold Didactic (LEYBOLD DIDACTIC, n.d.). This is because the sensors chosen to work with the Raspberry Pi could be optimized in terms of precision, resolution, and measurement range. Whereas in CASSY, the students have no knowledge of the sensors' characteristics that are embedded in the "Black Boxes". Additionally, the modern sensors used with the Raspberry Pi have several features and benefits, such as very small sizes for tiny assemblies, on-board filter settings, or programmable modes to fine-tune the measuring process and power consumption.

With this strategy, students are introduced to novel learning fields addressing the physical principles of operating sensors, the fundamentals of electronics and communication protocols, and the principles of digital signal processing techniques through activities starting with choosing a sensor for a given application, capturing the sensor signal and then proceeding through the stages of signal processing, display, and recording. The opensource software package PhyPiDAQ (Quast, n.d.) contains a range of classes programmed in Python for easy access and control of the GPIO pins of the Raspberry Pi and includes a collection of specific libraries designed for communication with sensors. Its main advantage is that the signals acquired via sensors are displayed in real-time by choosing different representations like the graph of one or more measured quantities over time, instant bar charts, or graphical dependencies of physical quantities. Additionally, the user can give formulae in the chosen module of a certain sensor in order to obtain a straight visualization of the desired quantity, for instance, the electrical charge of a capacitor computed from the measured voltage and the known value of capacitance. In experiments with analog sensors, the students work on the selected module of the analog-to-digital converter to transform the obtained digital voltage in the actual physical value. The storage of the recorded data in .csv files for future use and analysis is also possible.

Provided with these hardware and software tools, the students are engaged in complex learning experiences aiming to develop the conceptual understanding of physics

content, as well as of basics of electronics, and of mathematical approaches for processing a large amount of data.

HARDWARE OF THE RASPBERRY PI BASED DIGITAL MEASUREMENT SYSTEM

The Raspberry Pi is a single-board computer known for its low-cost and powerful computation capability based on the Raspbian (Raspberry Pi OS, n.d.) operating system. It is equipped with numerous interfaces to interact with small electronic devices such as sensors and actuators. These can be attached to the general-purpose input/output GPIO pins of the Raspberry Pi to react to the changes of different physical quantities. Many sensors used in this project, like the INA219 (Texas Instruments, 2015) as current and power sensor, MMA845 (NXP Semiconductors, 2017) as three-axis accelerometer, MLX90393 (Melexis, 2020) magnetic field sensor or BME280 (Bosch, n.d.) as digital humidity, pressure, and temperature sensor have an I²C-compatible interface allowing the sensors to transmit measured data to the Raspberry Pi. Analog sensors like miniature straight bar load cell Tal221 (HT SENSOR TECHNOLOG, n.d.) for measuring forces, linear Hall-effect TO-92 (ALLEGREO microsystem, n.d.) sensor for the strength of the magnetic field, or NTC thermistor used as temperature sensor need to be interfaced with the Raspberry Pi via analog-to-digital convertor ADC-module for converting analog values into digital data. For example, to record the current–voltage characteristic of a light-emitting diode, a light-dependent resistor, or the charging and discharging characteristic of a capacitor, the ADS1115 device is well suited as a precision, I²C-compatible analog-to-digital converter with an incorporated programmable gain amplifier (Texas Instruments, 2018). Four single-ended or two differential input channels can be used to perform a measurement. In some laboratory investigations like measuring small forces under 1N or magnetic field values of a current-carrying coil, the sensors provide very weak signal voltages (in μV) which is too low for the ADC module to start the conversion process. In these cases, operational amplifiers are used to boost the voltage to the necessary voltage range. The three circuit diagrams, one with operational amplifier (Aupperle, 2018), one with electrometer-amplifier, and one with level shifter, used for translation of negative signals into positive voltage are presented on the PhyPiDAQ Project's (Braig, 2020) website.

OPEN-SOURCE SOFTWARE PACKAGE PhyPiDAQ

The data acquisition, display, and record start with the graphical user interface `phypi.py` of the software package PhyPiDAQ, where the students can choose and edit different configuration files with the extension `.daq` for recording measured data, as well as specific configurations for devices and sensors having the extension `.yaml`. For each of the last ones, there are features like measuring ranges, number and type of channels, values limits, that

students select in the graphics window of the interface according to the experimental purposes. Having introduced the sensor characteristics, the next step is to configure the graphical display of the measurements in the window of the .daq file. Built-in commands and instructions allow the user to pick different display modes, like the graph of measured quantities over time, instant bar charts of measured signals to quickly compare data and to highlight specific values at a glance, or XY-graphical relationship of physical quantities if using multiple sensors at the same time. Other data visualization capabilities, like introducing title, measurement name and units, proper graphical ranges, as well as the conversion of the output sensors' voltage into physical quantities or use of formulae for displaying desired quantities are provided.

Moreover, the software gives the possibility to store the measured data, which can easily be converted to a format compatible with spreadsheets such as the LibreOffice (Wikipedia, n.d.) running directly on the Raspberry Pi for more extensive analysis.

For the beginners, there are ready-to-use configured .daq files for different measurement tasks with specific sensors, which can be accessed in the ./examples/ directory available after installing the PhyPiDAQ-Software packages. After choosing all the commands for data record and display as well as the suitable features of the sensors, one can run the program to display the measurements in real-time on a graphics display window, so that students get immediate feedback of their prior actions and analyze the results.

CHARGING AND DISCHARGING OF CAPACITORS USING THE ANALOG-TO-DIGITAL CONVERTER ADS1115

Charging and Discharging of Capacitors with Two Voltage Steps

An example of Raspberry Pi-based investigation with the PhyPiDAQ Software package is the charging and discharging of a $10\mu\text{F}$ electrolytic capacitor over an Ohmic resistor connected in series to the +3,3V-pin of the Raspberry Pi. In a simple version of the experiment, the voltage across the capacitor U_C can be measured and converted into a digital signal with the analog-to-digital converter ADS1115 by connecting the positive lead of the capacitor to the analog input channel A0 and the negative lead to the ground. The potential difference U_R across the resistor can be measured as differential input between the A0 and A1 channels of the ADS1115 convertor. In order to examine the discharging of the capacitor through the resistor, the students move the connecting wire between the +3,3V pin of the Raspberry Pi and the ground. In the PhyPiDAQ-configuration file, one can use the *ChanFormula*-command for displaying in real-time the amount of charge stored on the capacitor $Q = CU_C$ and the current flowing through the resistor $I = U_R/R$. The outcome shown in the Fig.1, allows students to observe how the charge Q and the current I vary as a function of time during the charging and discharging process.

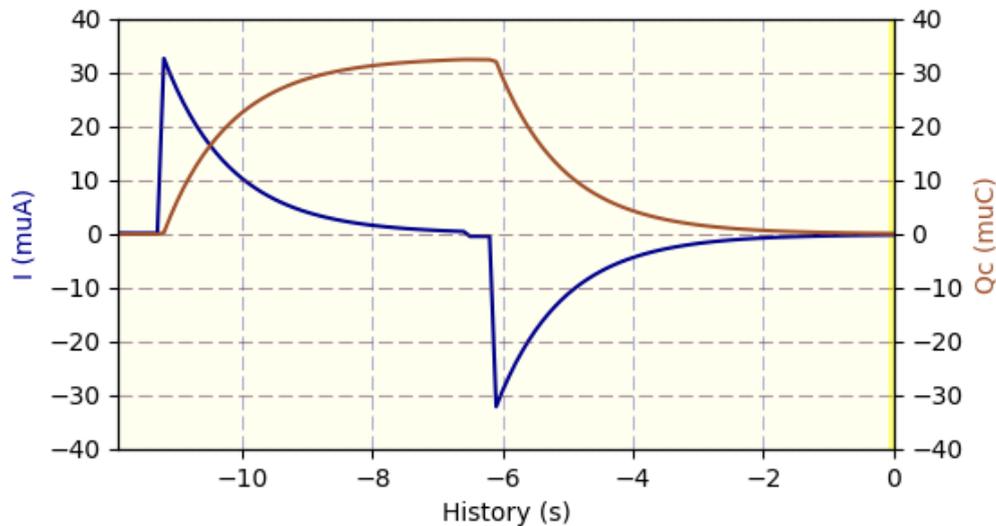


Figure 1: Real-time plotted electric charge Q and current I in an RC-circuit acquired with the data logger module in the ADS1115 configuration

Experimental Circuit with Light Dependent Resistor (LDR) Operated Switch

In another experimental task, a time-varying voltage with a square waveform is generated at two pins of the Raspberry Pi by a light-dependent resistor (LDR) operated switch. Through the covering/uncovering of the LDR, the input signal at the GPIO-Pin-IN of the Raspberry Pi changes back and forth from a constant positive value to zero volts. The GPIO-In_Out.py application programmed in *Python* can be started in the Console of the Raspberry Pi and runs in the background (Quast, n.d.).

The values of the LDR resistance fall in bright light causing the enhancement of the voltage across the capacitor during the charging process. The response signal at the GPIO-Pins of the Raspberry Pi as well as the potential difference across the capacitor collected at the sampling rate of 0,1s, shown in Fig.2, are displayed in real-time by choosing the *DataGraphs*-Modul in the ADS1115 configuration. The collected data can be saved in .csv file for a more thorough analysis.

INTERDISCIPLINARY APPROACHES BASED ON THE RASPBERRY PI MEASUREMENT SYSTEM

Understanding Exponential Functions with Recorded Data

Both experimental settings allow quick acquisition of a large number of quality measurements otherwise difficult to reach in ordinary experiments. The collected data can be used in many interdisciplinary ways, like for instance in Math for modelling certain

growth and decay processes with the exponential functions. To analyze their properties, spreadsheets like LibreOffice or Excel to process the measurement stored in .csv files are well suited. The recursive method of computing the ratio between any two consecutive values of the voltage across the capacitor or of the current through the resistor leads to a constant which is the common ratio or the base of the exponential function. This investigation opens the way to the understanding of other mathematical structures, like the geometric sequences.

Growth and decay constants of the exponential functions can be deduced from the common ration values and put in relation to the time constant $\tau = RC$ of the RC circuit. For example, the experiment of charging and discharging of a capacitor can be repeated to analyze the effect of different values of capacitance and resistance on the time constant and on the shape of the exponential function, which becomes steeper or shallower respectively.

10 μ F-Kondensator, 100KOhm-Widerstand

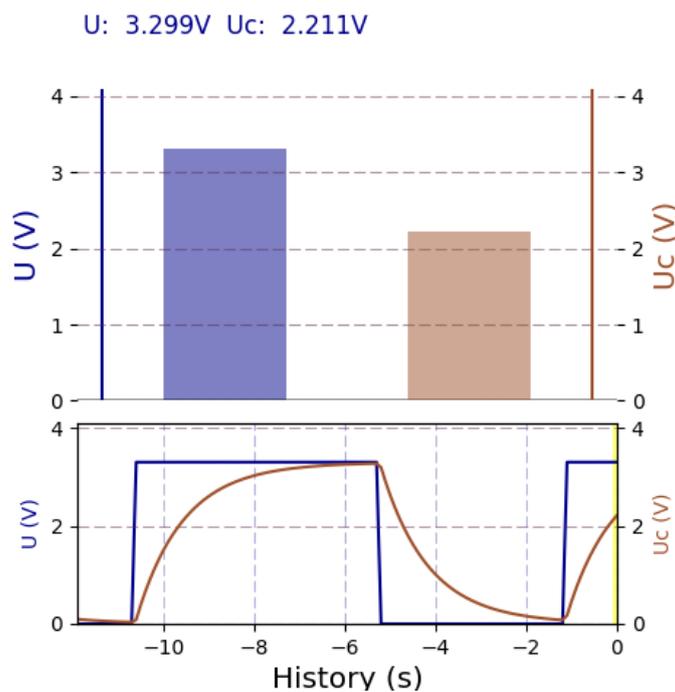


Figure 2: Charging and discharging characteristic of a capacitor $U_c(t)$ controlled by the square waveform voltage $U(t)$ generated by an LDR connected to the GPIO-Pins of the Raspberry Pi

From the graph of the voltage across the discharging capacitor, one can work out the relationship between the time constant and Euler's number e . Other characteristics of the graph can be used to deepen the students' understanding of abstract concepts like limits at infinity of functions.

The measurements are used also to introduce, motivate and explain other mathematical structures, like differential equations, providing the students with a deeper insight into mutual relationships between physics concepts and laws and mathematical tools to model them. Thus, the students associate the real-time displayed voltage across the capacitor to the exponential function of voltage $U_C(t)$ against time, which is the solution of the differential equation deduced from the Kirchhoff's loop law.

Different inductive and deductive learning strategies based on this experiment broaden the students' knowledge and understanding of mathematical and science concepts. An important property of an exponential function with a variable x can be expressed through the proportionality of the derivative of the function to the function itself. This can be exemplified with the collected values of the electric charge of the capacitor. In a spreadsheet program, the numerical differentiation of the discrete values of electrical charge as a ratio of the difference of any two consecutive values ($Q_{i+1} - Q_i$) divided by the sampling rate introduced into the configuration file of the ADS1115 convertor Δt , is computed and compared to the electric charge of the capacitor. At any time t , this value differs from the approximated value of the rate of flowing charge through a constant, which is the inverted time constant.

The exhibited graph of the difference quotient $(Q_{i+1} - Q_i) / \Delta t$ computed in the spreadsheet compared to the real-time current in the RC circuit displayed on the PhyPiDAQ window facilitates the understanding of the abstract definition of the electric current, as well as the relation between the motion of the electric charge in a circuit and the stored charge on the capacitor. The related values of electric charge and current lead back to the Kirchhoff's loop law. By changing the sampling rate Δt values in the configuration file of the ADS1115 convertor to lower values, the students get an in-depth insight into the differentiation of continuous functions. Hence, the current is the derivative of the electric charge as a function of time.

Investigating the Effective Capacitance of Different Capacitor Combinations

Other relevant physical contents, like the expressions for the effective capacitance of capacitors connected in series and parallel, can be achieved with the recorded data. Thus, the natural logarithm of the voltage across the capacitor at each moment t is given by the linear function $\ln(U_C) = \ln(U) - t/\tau$, where $U = 3,3V$ is the voltage at Raspberry Pi and $\tau = RC$ is the time constant, which changes by connecting more capacitors or resistors together. Knowing this, the natural logarithm of the recorded values of the voltage across the capacitor, or the combination of the capacitors is computed with a spreadsheet program at each time t . A plot of $\ln(U_C)$ against time produces a straight-line graph with the slope equal to the negative reversed time constant $-\tau^{-1}$. By using the trend line option in Excel to draw the best fit line to the computed $\ln(U_C)$ as a function of time, the slope of the line and consequently the time constant can be determined. The plotted values of the natural

logarithm of the voltage of the capacitor in the discharging process, when connecting two identical capacitors in series and parallel, are presented in Fig.3. The graph of $\ln(U_C)$ for one capacitor is used here as a reference to compare the slopes of the graphs for the series and parallel combinations. The inferred values of the time constant $\tau_{\text{Parallel}} = 2\tau = R(2 \cdot C)$ and $\tau_{\text{series}} = \tau/2 = R(C/2)$ match very well with the expected expressions of the effective capacitance in parallel and series respectively. Measurements with combinations of resistors can also be carried out.

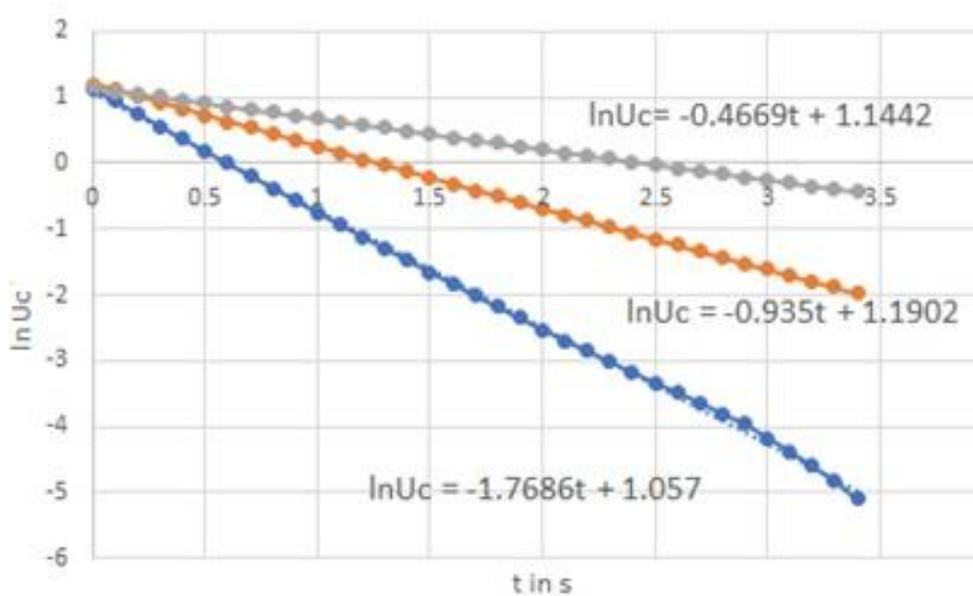


Figure 3: Plotted values of the natural logarithm of the voltage across two identical capacitors connected in series (blue) and parallel (grey) displayed for one single capacitor of capacitance $10\mu\text{F}$.

The similarities and the differences of the effective resistance and effective capacitance for series and parallel connections are cleared and correlated to the expressions deduced theoretically.

Determine the Stored Energy in a Capacitor

Some other complex interdisciplinary investigations, like the calculation of the energy dissipated in discharging a capacitor through a resistor, can be carried out based on numerical integration methods. In the spreadsheet program, the squared values of the current are integrated over the sampling rate Δt introduced into the configuration file of the ADS1115 converter, based on the trapezoidal rule for a better approximation. The obtained value multiplied by the resistance of the RC circuit gives the dissipated energy. The students

can repeat the measurements of the flowing current in the RC circuit, to observe the effect of resistance on the value of dissipated energy. For long enough chosen discharging time, they discover that the dissipated energy is independent of the resistance in the circuit. All the obtained values approximate the stored energy in the capacitor known from the theory as $CU^2/2$.

CURRENT-VOLTAGE CHARACTERISTICS WITH THE INA219 SENSOR

Problem Statement

An alternative option to the ADS1115 converter for accurate measurements of physical quantities in DC circuits, like current, voltage, and power is the INA219 sensor with I²C interface. An inquiry-based laboratory project aimed at analyzing the current-voltage characteristic of a light-emitting diode can start with an introduction of the measuring principle of the current flow. Since the current is difficult to measure directly, the teacher formulates questions about the possible measurement methods based on the effect of current flow. One such question is to introduce to the students the basic idea of inserting a resistor with known resistance in series into the circuit. The current value can be derived from the measured voltage across this resistor according to Ohm's law. On the next stage, the students correlate the theoretical knowledge to their investigations about the functionality and characteristics of the INA219 sensor. They start by reading the datasheet of the sensor, where the method of current-measurement based on the voltage across a very small 0.1Ω shunt resistor is described. The device enables the direct readout of the current through the conversion of the shunt voltage drop when using the default 12-bit resolution at 320mV shunt full-scale range.

Electrical Circuit for the Current-Voltage Characteristic of a LED

After acquiring the necessary information, the students proceed to the design of the electric circuit, for which they need to know the functions and features of electronic components, as well as to understand how those components are connected together to form a circuit. In order to represent their experimental setup, they draw the schematic diagram of the INA219 based current-measurement circuit. To measure and record the current-voltage characteristic of the LED, the four pins of the sensor; +5V, Ground, the serial clock (SCL) and serial data (SDA) pins for the I²C communication have to be connected to the Raspberry Pi. The sensor measures the shunt voltage between the IN+ and IN- input pins and gives it out directly as current value, as well as the bus voltage between the IN- pin and ground, where the LED is connected. A potentiometer connected to the +5V voltage supply of the Raspberry Pi varies these voltages. A current limiting resistor of 100Ω connected to the IN+ pin of the sensor is used to limit the current when the potentiometer resistance is reduced to zero.

To start the measurements, the *INA219Config.yaml* configuration with the activated xy-display option for the current-voltage characteristic $I(U)$ must be chosen in the graphical interface *phypi.py* of the *PhyPiDAQ* program. The current through the LED is plotted in real-time against the voltage across the LED, as shown in Fig.4.

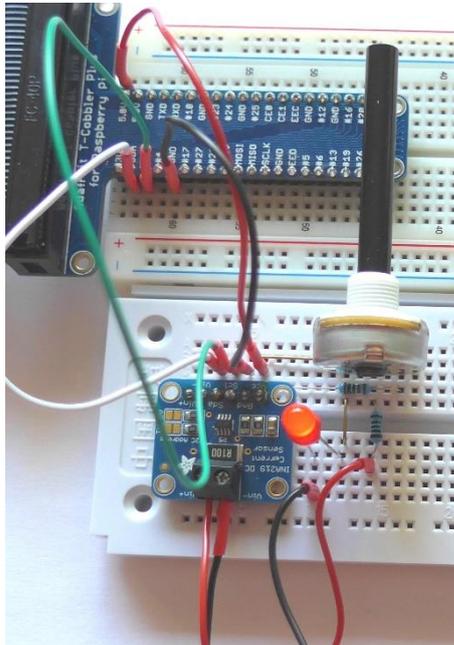


Abb.4 a)

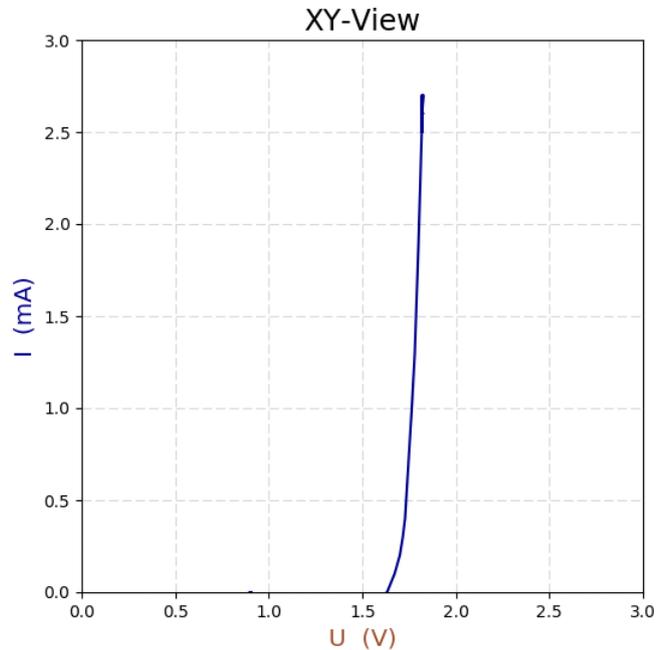


Abb.4 b)

Figure 4: a) Circuit board layout with INA219 sensor and Raspberry Pi to record the current-voltage characteristic $I(U)$ of a light-emitting diode; b) Real-time xy-displayed characteristic $I(U)$ on the graphical interface *phypi.py* of the *PhyPiDAQ*-program

Interpreting the Current-Voltage Characteristic of a LED

A more sophisticated scientific reasoning and conceptual understanding require the functionality of a diode. The xy-display mode of the graphical interface shows the nonlinear growth of the current through the diode when the voltage across the LED is increased. All the significant features of the $I(U)$ -characteristic, such as the exponential increase of current when the external voltage is higher than the p-n junction voltage, are clarified from macroscopic, mathematical, and sub-microscopic perspective. The graph of the Shockley's ideal diode current as a function of the voltage across it in either forward or reverse bias is compared with the displayed characteristic $I(U)$ of the real LED connected in the circuit. The curved current-voltage characteristic of the real LED is contrasted to the one obtained for an ohmic resistor to emphasize that the electrical resistance doesn't remain constant in

all components. Various technical applications based on the asymmetric conductance of the diode in real-world contexts are discussed. Integrated mathematical concepts enhance the understanding of the electrical conduction and its physical quantities. Thus, the recorded data can be processed with spreadsheet programs to calculate the difference quotient $(U_{i+1} - U_i) / (I_{i+1} - I_i)$. The calculated values are compared to differential resistance $R = dU/dI$ as derivative of the voltage with respect to the current obtained from the $I(U)$ - Shockley's function. Working with graphical representations, students find out that the differential resistance is inversely proportional to the gradient of the tangent line to the $I(U)$ -characteristic at a given value of the voltage across the electric component. As a result of this observation, students are encouraged to expand their investigation of current-voltage characteristics to some advanced electronic devices with negative differential resistance and reflect on their applications in real electric circuits.

BUILDING SCIENTIFIC ABILITIES OF INTRODUCTORY ELECTRICITY WITH THE RASPBERRY PI MEASUREMENT SYSTEM

A cross-curricular approach allows different experiments built on measuring electric quantities with the INA219 sensor for middle school to upper secondary school students to be developed.

Experiments and learning activities aimed at exploring simple electric circuits provide the fundamental framework for building the formal concepts and scientific abilities of introductory electricity. In the lower secondary school, students can explore a whole range of electrical phenomena by replacing the light-emitting diode with a simple ohmic resistor in the previous setting. The INA219 sensor can measure the current through the resistor, the voltage across it, and the power at the same time and thus provide a coherent framework in which the electrical concepts are related to each other. Different types of visualizations available in the sensor configuration deepen the students' understanding of the abstract nature of electric current. The *DataGraphs*-Modul allows a dynamic view of the electrical quantities over a period of time. By keeping the voltage supply constant, students notice that the current remains constant in time. This can be correlated with the nature of the current and the conservation of charge-carrier in a closed circuit. Therefore, the students understand the electrical conduction and the electric current through the three levels of representations (Treagust et al., 2003).

The macroscopic representation related to the electrical circuit and measured values is closely connected to the symbolic representation given by the graphically displayed evolution in time of the physical quantity associated with the mathematical notations and algebraic formulae and further to the sub-microscopic representation of the electric current as a movement of the charge-carrier. By choosing the *DataGraphs*-Modul in the INA219-configuration, the real-time current-voltage characteristic of the resistor is obtained as a straight-line graph. The potential difference is the independent variable controlled by the

potentiometer connected at the voltage supply and the electric current is the dependent variable responding to the variation of the potential difference. Thus, the students can distinguish between the cause and effect in a simple electric circuit by putting the electric current in the right mathematical relationship to the potential difference and can emphasize their direct proportionality. On the graphical interface *phypi.py*, one can have a combination of both diagrams, the dynamical view of the current in real-time, as well as the current-voltage characteristic $I(U)$ of the resistor, leading to a better comprehension of the nature and cause of electric current (Wong et al., 2016).

The experimental setup offers the possibility of changing the resistor in the circuit and resuming the measurements in order to analyze the effect of different resistances on the electric current. By connecting resistors with increasing values of resistance, students observe the lowering of the slope in the current-voltage characteristic, thereby allowing them to complete the mathematical equation of the Ohm's law.

A sub-microscopic perspective of the electrical resistance explained through the interaction of electrons within the lattice of the resistor during their flow in the resistor's lattice due to the potential difference, round off the whole conceptual construct of electric conduction into a consistent structure.

The sub-microscopic approach also emphasizes the limits of models and laws such as Ohm's law. The direct proportionality of the current and the potential difference is normally measured at room temperature. By heating the resistor, the students are asked to observe and interpret the evolution of current in the circuit shown on the graphical interface. Additionally, the sub-microscopic perspective allows students to understand the electrical conduction in different materials. In this respect, one can replace the regular resistor with a thermistor in the previously described experimental setting and visualize the evolution of electric current when this element is heated up. The growth of the electric current by constant voltage across an NTC (negative temperature coefficient) thermistor when heated, is shown in real-time. The Start/Stop Save and Resume Buttons of the graphical interface enable dynamic visualization of electric quantities over a period of time under different external conditions such as temperature, or static representations used for quantitative deduction of mathematical relationships. The real-time display of the electric current in the NTC is explained with the conduction model of semiconductor material.

DETERMINE THE PLANCK'S CONSTANT WITH THE ANALOG-TO-DIGITAL CONVERTER ADS1115

Problem Statement

The measurement system based on Raspberry Pi and PhyPiDAQ-Software package can be implemented also across the grade levels, while conceptual understanding, scientific reasoning, and practical skills progress. Thus, the current-voltage characteristic of several

LEDs emitting at known wavelengths can be analyzed in the experimental arrangement with the sensor INA219 to determine the threshold voltage U_0 , the LED turn-on voltage. The measured quantities can be saved and analyzed with a spreadsheet program to obtain an accurate value of the activation voltage at which the LED starts to emit light. The obtained value of U_0 is put in equation with the energy of the emitted photon with the goal to calculate the Planck's constant. A sub-atomic representation of quantic phenomena related to the movement of electrons between the valence and conduction band helps students to understand the relationship between different colors and threshold voltage values of LEDs. By plotting the threshold voltage as a function of the reciprocal of the wavelength for at least six LEDs, students obtain the value of the Planck's constant and they can compare that with the literature value.

Electrical Circuit for Recording the Current-Voltage Characteristic of three LEDs Simultaneously

An experimental circuit based on the analog-to-digital converter ADS1115, implemented with the breadboard layout depicted in Fig.5, is a more effective and meaningful setup to display the current-voltage characteristics of three different LEDs at the same time. This representation enables a deeper understanding of the relationship between the colors of the emitted light and the electric conduction in LEDs, by emphasizing the joint features of the three characteristics, but at the same time the different values of the threshold voltages. The three LEDs, each of them in series with a current limiting resistor of 100Ω , are connected at the three channels A0, A1, and A2 of the ADS1115 convertor. The measured voltage across the resistor is converted directly into current value by using Ohm's law in the ADS1115 configuration.

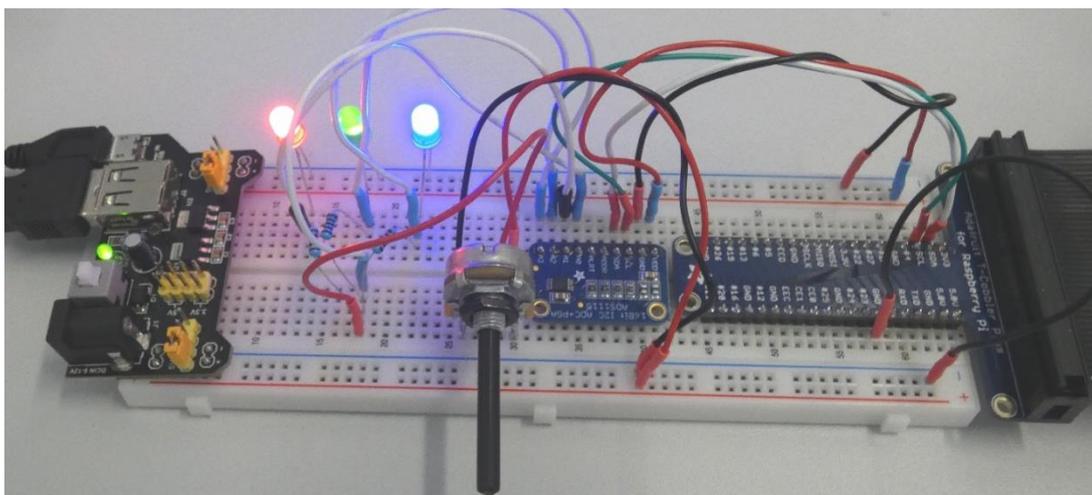


Figure 5: Breadboard layout with ADS1115 and three different LEDs for recording their current-voltage characteristic $I(U)$ at the same time.

With a spreadsheet program, the threshold voltage of each of the three LEDs can be read out from the current-voltage characteristics. A quick swap of new LEDs in the same circuit allows enough data to be collected to determine the value of the Planck's constant from the graph of threshold voltage as a function of the inverse value of the wavelength.

Thus, students move back and forth between various representations of physical concepts, extract information from experiments, connect these to mathematical structures and physical laws and communicate observations and conclusions in a rich learning environment where science, mathematics, and technology are closely interconnected.

AFFECTIVE DIMENSION OF LEARNING ENVIRONMENT BASED ON RASPBERRY PI MEASUREMENT SYSTEM

The continuous process of knowledge construction reveals the affective components within the learning environment based on the Raspberry Pi measuring system. First, the students show curiosity when design a schematic diagram with components and connections of the circuit, build the real electrical circuit, and observe how the measured values change while they change parameters such as the voltage. This kind of learning instruction offers them an open-ended situation, where they search for the characteristics of electrical components, reflect on their connections in the circuit, calculate voltage and current at some points, apply physical laws and formulae and correlate the measured values with the computational instructions in the software. This enhances the persistence in solving scientific and technical problems. The simple curiosity evolves to a deeper interest in learning the physical principles of operating sensors, communication ways with the Raspberry Pi, use of appropriate computing instructions in the PhyPiDAQ-software for data collections, display, and processing. Searching for the relevant parameters of sensors and putting them in equations to other physical quantities of the circuit and the instructions in the software configuration requires a continuous learning effort supported by the constant growth of students' motivation. Implementing interdisciplinary approaches and complementary knowledge from different subjects in experimental learning with real components fosters the progress of creative thinking.

CONCLUSIONS

The Raspberry Pi based Measurement System is a low-cost yet accurate measurement system with a wide range of sensors for teacher-led and student-centered physical laboratory experiments. The open-source PhyPiDAQ-Software manages the acquisition, display, and storage of data obtained from physical sensors through one Graphical Interface, and it can be further developed to encompass programmed classes for new sensors. Multiple graphical representations for the display of real-time data can be used in complementary ways for fostering a deeper understanding of physical concepts. Various visualization capabilities

include adapting the range of measurement to the characteristics of the sensors and the experimental goals, and adding formulae into the configuration of a select sensor in order to obtain direct visualization of the desired quantity

The work with the Raspberry Pi based Digital Measurement System offers a wide range of learning opportunities for science concepts and practices spreading within and across the disciplines and grade levels in an integrated curriculum. Several described experimental activities in this paper reveal these aspects. Hence, the electric circuit design and its setup on the breadboard is directly correlated to the open-source software PhyPiDAQ-package, where the students introduce instructions to control the collection and display of data. Other practical abilities, like gauging the voltages and currents at some elements in the circuit with respect to the characteristics of the sensors, such as sensitivity, measuring range, precision, or resolution are developed.

The scientific abilities to conduct experimental investigations, display and collect measurements from experiments, analyzing them in the framework of the physical theories with mathematical tools, improving the experimental setup to perfect the measuring methods and enhance the quality of results, progress continuously.

An extensive range of recorded measurements can be used in multiple interdisciplinary ways, for instance in Math, to introduce and explain mathematical structures such as numerical derivative and integration of physical quantities or differential equations, providing the students with a deeper insight into mutual relationships between Physics concepts and mathematical tools in modelling them.

Students experience satisfaction and self-confidence once they meet the experimental goals, with the added advantage of empowering them to search for more advanced experimental circuits for getting more accurate measurements related to meaningful ways of displaying and processing of data. Thus, the experimental activities with the Raspberry Pi based Measurement System promote affective components of learning such as curiosity, interest in understanding complex structures, satisfaction, and self-confidence leading to the constant growth of students' motivation.

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