Laboratory Teaching Proposal on the Characteristics of an RC Circuit

Ninfa Radicella

Liceo scientifico Filippo Silvestri, Portici (NA), Italy

Abstract

This abstract outlines a teaching proposal devised for a fifth-grade scientific high school class in Italy (13th grade) focusing on the behaviour of an RC circuit. By using a constructive approach, it enables students to explore and analyse the properties of an RC circuit, focusing on the behaviour of capacitors and resistors in series, and to understand the transient response of the circuit. Through exploratory teaching methodologies involving both practical experimentation and theoretical discourse, students delve into the process of charging and discharging of a capacitor, the concept of time constant (τ) and its significance in RC circuits, and - through data analysis techniques - to visualise and interpret voltage-time graphs. The tools facilitating this interdisciplinary proposal, spanning physics and mathematics with potential extensions into other scientific domains, include virtual simulators, low-cost circuit construction materials, free data analysis software, and digital sensors. All activities are highly adaptable, allowing for selective experiment execution and material utilisation. Evaluation of the pathway employs a process-oriented approach, combining observational and summative assessments within the final report.

Keywords: *RC circuit, physics lab, exponential fit, active learning strategies*

1. Introduction and motivations

This educational proposal arises from the need to create interdisciplinary and meaningful pathways. This entails addressing one or more topics pertaining to different disciplines but within a unified framework that naturally integrates multidisciplinary abilities and knowledge, aiding in the development of significant skills.

The key topic was the study of an RC circuit in physics. This was introduced exploratively after studying the characteristics of DC circuits with resistors and, separately, capacitors with their respective properties.

After experiencing the properties of such a simple circuit, students were asked to quantify their hypotheses and verify them through the implementation of an exponential fit to visualise the transient that characterises the voltage or current of an RC circuit. Finally, mathematics comes into the game; through the formal study of the circuit, with the application of Kirchhoff's voltage law and by verifying the solution of the associated differential equation, it is possible to think about the role of initial conditions or system parameters, that in this case refers to physical properties of the circuit that can be adjusted according to the final use.

This activity was carried out in the final year of a scientific high school (13th grade), although some topics are related to the second two-year period of study [1], due to specific scheduling within the class where it was implemented. However, this made it possible to implement an educational proposal that has been effective, both for physics and mathematics.

2. Preparation and implementation of the activity

The activity is introduced with a worksheet (Table 1) to guide an explorative phase of the properties of an RC circuit through a virtual simulator, that is free and available thanks to the PhET Interactive Simulations project at the University of Colorado Boulder [2]. Phet Colorado offers a rather intuitive simulator, in which it is possible to add the necessary components and appropriate sensors. It is not

possible to view the data graph but it is very intuitive. Another option is Tinkercad [3]. It is a platform designed for electronics and robotics but has a circuit section in which you can simulate with Arduino or even with a simple base (in order to reproduce exactly the circuit to be built in the laboratory) and practice.

The platform also includes digital teaching activities, so there is the possibility of creating virtual classes and projects to share with students. The students work in heterogeneous groups consisting of no more than three members, and they have a finite amount of time (for example, 30 minutes) to explore the phenomenon. A conclusive phase follows, to share the answers and formulate a final proposal.

1	Create a circuit with a battery, a resistor, and a capacitor connected in series using the simulation [2]. Take a screenshot and paste it below.
2	What happens in the simulation? Display the direction of the electrons at the beginning.
3	What happens after some time?
4	Now, try to describe in more detail what you obtained with the simulation. How did the presence of the capacitor change the circuit's behavior? Why does this happen?
5	Now, put voltage and current sensors into the circuit. Take a screenshot and paste it below to show how you inserted them, and annotate the reason for each operation.
6	What do the measurement tools indicate?
7	Record the nominal values of the battery, resistance, and capacitance.
8	Now, manipulate the circuit variables (not all at once!) and try to understand how each one affects what happens once the circuit is closed. Record your reflections below.

Table 1. Student worksheet for exploratory work on the properties of an RC circuit.

As homework, with the support of digital resources, students are required to organise what has been discovered and shared during the lesson.

A second phase of synchronous work is dedicated in the physics laboratory to build an RC circuit with resistor and capacitor according to what was found with the virtual simulator in order to have a time constant of approximately twenty seconds (Figure 1).

Once the circuit is constructed, the activity can go on with the phase of data visualisation and analysis, which was here carried out using the Go Direct Vernier sensors [4] and the Graphical Analysis software in the free version [5]. The multimeter is then activated in voltage measuring mode, selecting the appropriate range (here 20 V). This operation can be done either at the beginning when the sensor is connected to the app or later by clicking on the probe symbol at the bottom right of the Graphical Analysis window. Additionally, the data collection mode is chosen as a function of time, and the sampling time is selected (here 50 samples per second), at the bottom left of the Graphical Analysis window (see figure 2). In the same window, the manual start and end of the data collection phase are selected. The data collection phase is carried out; the capacitor will be quickly charged to the battery voltage, then the battery is short-circuited, and the discharge of the capacitor is observed. When the voltage tends to zero, the battery is reconnected, and so on, to display one or more cycles. Figure 2 is a screenshot of the window of the software.
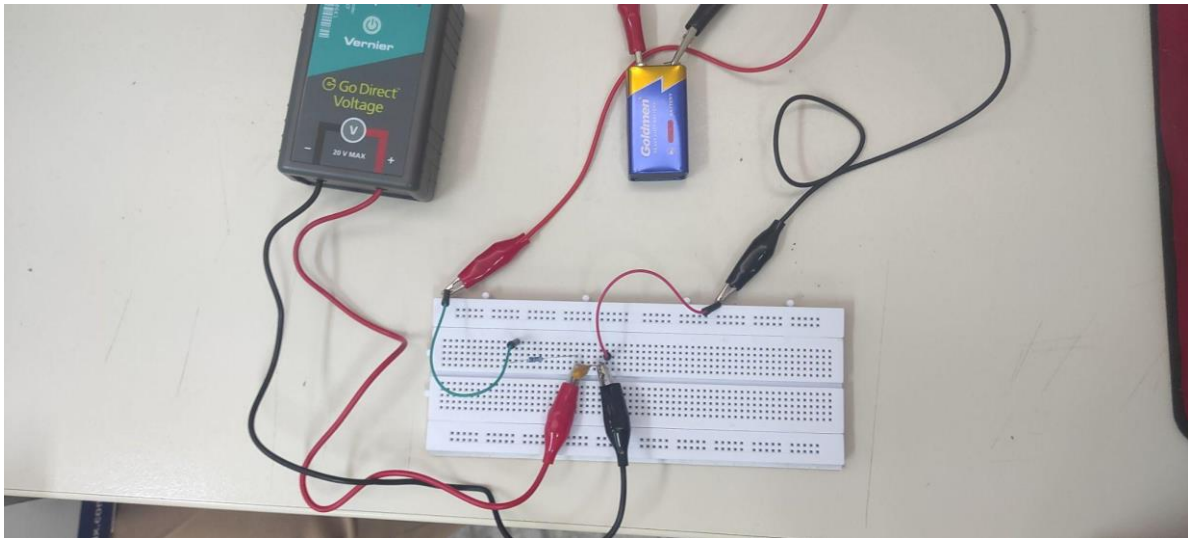
Figure 1: Students build their own RC circuit using a breadboard available in the laboratory, and select R and C in such a way that the characteristic time is easily observable. In the prototype experiment depicted in the images, a 9V battery (charged to 6V), R~30 kΩ e C~ 10 μF were used.
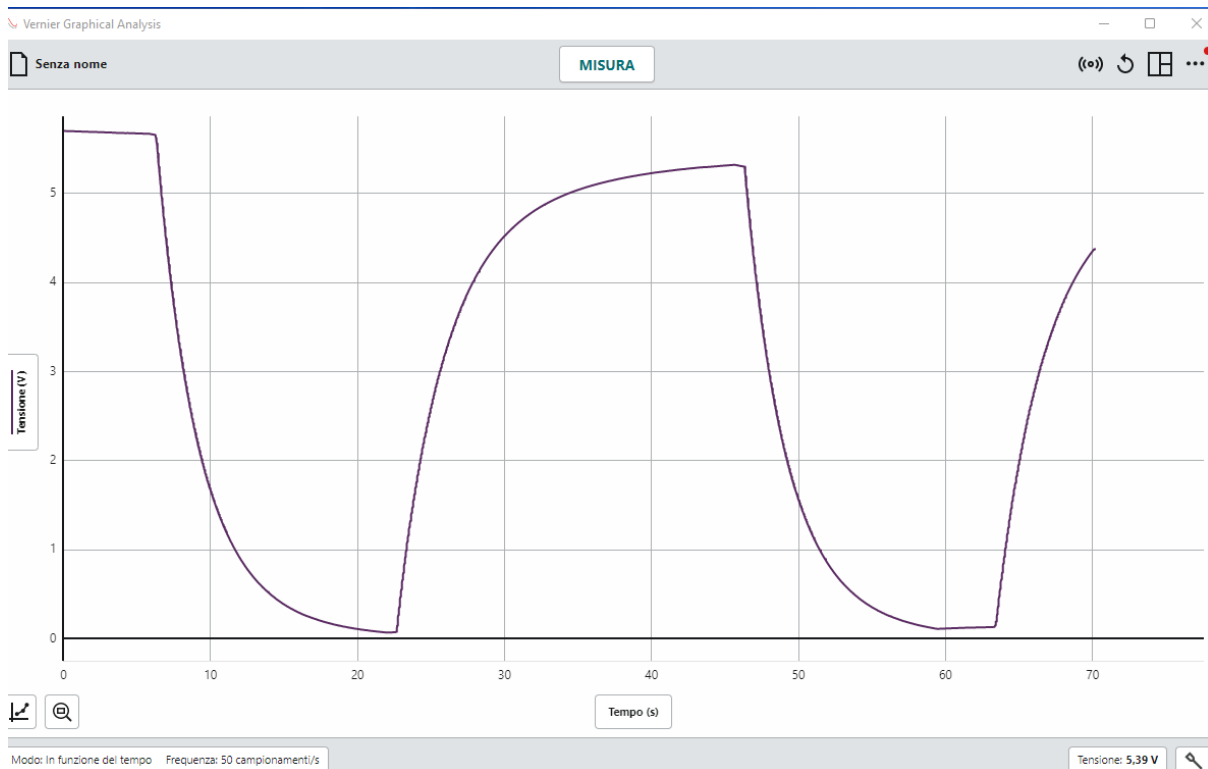

Figure 2: Graph of the voltage across the capacitor. It is possible to view the charging and discharging cycle, obtained by short-circuiting the voltage generator.

At this point we proceed with the analysis of the system which integrates the mathematical aspect with the indications that physics offers, such as the dimensional analysis of the parameters. Table 2 shows an example of a worksheet for the student's independent work, which can be done both at home and in class, which then prepares for data analysis with an exponential fit.

1.	Which quantities are shown on the graph of the data taken from the voltage sensor?
2.	Carrying out the exponential fit which is the dependent variable y and which is the independent variable x?
3.	What physical dimensions should the parameters a, b and c have? Justify your answer.
4.	Let's focus on the exponent. Considering the previous answer, and remembering that the physical variables at play in the system are the capacitance of the capacitor C, the resistance of the resistor R and the battery voltage V, determine how the parameter c must depend on a combination of R, C and V (not necessarily all e three) in order to obtain the required physical dimensions.

Table 2: Example of a worksheet for the student's independent work, which then prepares for data analysis. The notations explicitly refer to the ones used in the class (see Figure 3).

Figure 3: In order to perform a best fit with Graphical Analysis, first of all select the set of data involved; this can be done by highlighting the area directly on the graph.
Then, by clicking at the bottom left, on the icon representing a data trend, you choose the "Perform a curvilinear fit" option ("Effettua un fit curvilineo", in italian). Among the possible options, choose the exponential function with the natural base and apply the operation.

Then, students can be asked to perform a best fit analysis to estimate the time constant of the circuit, and compare the result with the nominal value. In the references there is an interesting blog article on what a data fit is [6], an educational piece that can be submitted to students from the early years of high school.
The interesting parameter here is c (see figures 3 and 4), which represents the characteristic time of the circuit, which the students initially chose by selecting the most suitable resistors and capacitors.
We can then proceed with the comparison between the results obtained, determining their compatibility or otherwise by calculating the discrepancy.
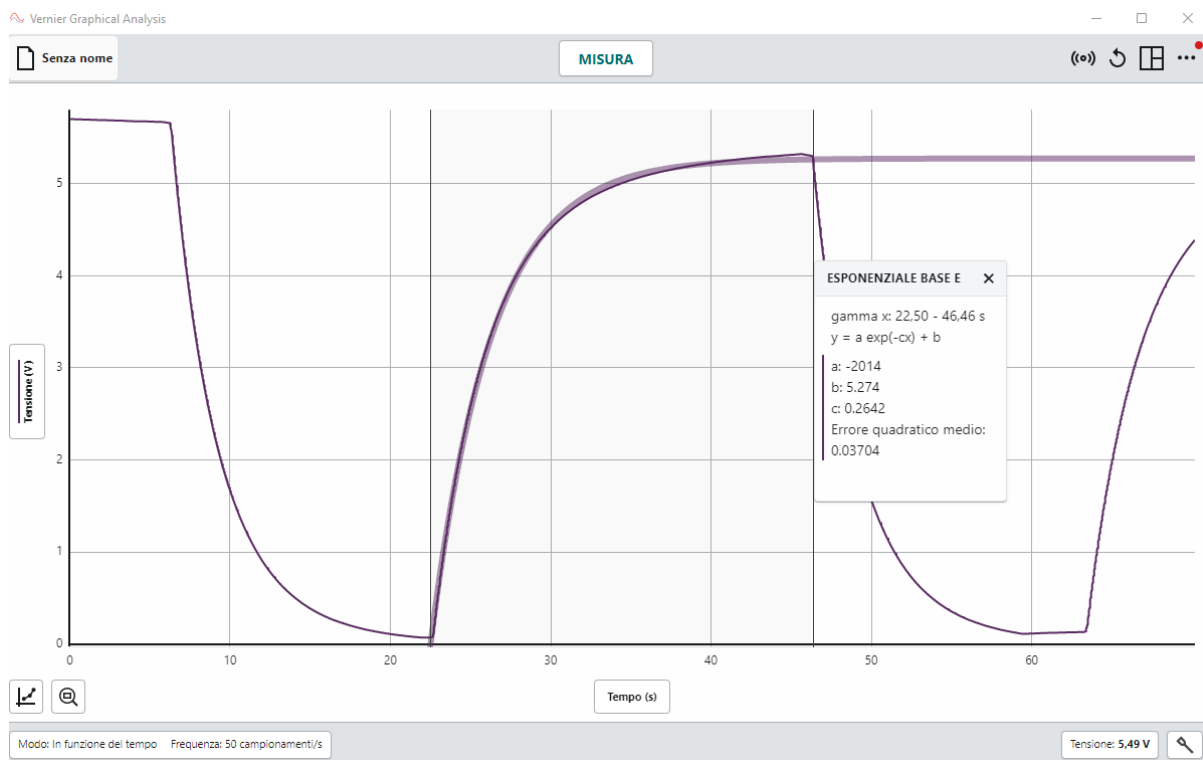
Figure 4: The outcome of the fit is shown on the graph. The best estimate of the parameters appears in the window as well as an indicator of the goodness of the fit, indicated as the mean square error ("errore quadratico medio", in italian).

3. Conclusions and potential implementations.

The evaluation of student learning at the end of this teaching activity involves both a formative and a summative assessment. The first one takes into account the various phases of the learning process and refers to the group work of the initial, explorative phases, some parts of the laboratory work, and the analysis of the worksheet, either in groups or individually. Then a summative evaluation is possible at the end; specifically in what is realised here, it refers to a lab report. For both the activity in groups or in lab and the lab reports, an assessment rubric is shared with the students before starting the activities; in fact it was shared at the beginning of the year.

A final phase of this activity is considered: research and study the applications of an RC circuit. It is easy to find many examples of the wide-ranging applications of RC circuits, highlighting their versatility and importance in modern electronics and electrical engineering, such as timing circuits, battery charging and discharging, filters, audio tone control. But the students were very impressed with the applications of RC circuits in advancing medical and biological research, enhancing diagnostic capabilities, and improving patient care outcomes. They highlight the versatility of RC circuits in interfacing with biological systems and enabling innovative healthcare technologies. Among others, we recall here those that the students chose to explore in depth:

1. Electrocardiography (ECG) and Electroencephalography (EEG): RC circuits are integral components of biomedical sensors used in ECG and EEG devices. They help in signal conditioning, filtering out noise, and amplifying weak bioelectric signals from the heart (ECG) and brain (EEG). RC circuits ensure accurate detection and recording of physiological electrical activity, aiding in the diagnosis of cardiac and neurological conditions.

2. Implantable Medical Devices: RC circuits are used in implantable medical devices, such as pacemakers, defibrillators, and neural stimulators. They help in energy storage and delivery, as well as in regulating the timing of therapeutic interventions. RC circuits enable these devices to deliver precise electrical pulses or stimuli to targeted tissues or organs, thereby managing cardiac rhythm disorders, neurological conditions, and other medical issues.

3. Biopotential Recording and Stimulation: RC circuits are employed in biopotential recording systems, including electromyography (EMG) and electroencephalography (EEG), to capture and analyse

electrical signals generated by muscle or brain activity. Additionally, RC circuits are used in neuromuscular stimulation devices, such as functional electrical stimulation (FES) systems, for restoring motor function in individuals with paralysis or neuromuscular disorders.

4. Biosensing and Bioimpedance Measurements: RC circuits are utilized in biosensing applications, including bioimpedance spectroscopy (BIS) and impedance-based biosensors. They enable the measurement of electrical impedance changes in biological tissues or fluids, facilitating non-invasive assessment of physiological parameters like tissue composition, hydration status, and cell viability. RC circuits are also used in impedance-based biosensors for detecting biomolecules, pathogens, and analytes in clinical samples.

5. Tissue and Cell Culture Systems: RC circuits are incorporated into tissue and cell culture systems for monitoring and controlling environmental conditions, such as temperature, pH, and nutrient levels. They help in maintaining stable culture conditions, ensuring cell viability and reproducibility in experimental studies and bioproduction processes.

6. Electrical Stimulation Therapy: RC circuits are employed in electrical stimulation therapy devices, such as transcutaneous electrical nerve stimulation (TENS) units and deep brain stimulation (DBS) systems. They deliver controlled electrical stimuli to targeted tissues or nerves, modulating neural activity and providing pain relief or therapeutic effects in conditions like chronic pain, Parkinson's disease, and depression.

This final phase was not part of the evaluation because it has spontaneously arisen at the end of the activities, and in this sense it is part of a new implementation of the educational path, which will involve other subjects and teachers.

References

[1]   Indicazioni Nazionali per i licei, d.m. n. 211 del 2010.
[2]   https://phet.colorado.edu/sims/html/circuit-construction-kit-ac-virtual-lab/latest/circuit-construction-kit-ac-virtual-lab_en.html
[3]   https://www.tinkercad.com/
[4]   https://www.vernier.com/product/go-direct-voltage-probe/
[5]   https://www.vernier.com/downloads/graphical-analysis/
[6]   https://www.mathisintheair.org/wp/2015/01/fit-dei-dati-lunisci-i-puntini-degli-scienziati/