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Combining theory and practice to solve a common problem: a simple circuit for indoor plants watering

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Abstract

We introduce here an activity for high school students to get them more acquainted with simple electronics circuits. The aim is to build a simple circuit that lights up a LED when a plant needs watering. The only prerequisites are the knowledge of Ohm's law and Kirchhoff's laws.

The circuit that we designed is extremely simple, so students can build it during one regular class period (60 min). The soil is treated as a variable resistor in series with two regular resistors. The reference value is obtained using a potentiometer. The two branches of the circuit are connected in parallel. This approach can emphasize the understanding of the cited laws and of the difference between series and parallel circuits.

1. Introduction

Italian secondary schools are differentiated according to different curricula. Depending on the main theme of the curriculum, there are variations on the sets of subjects that are taught and the amount of time spent on each subject (e.g. 'scientific' high schools have 99 h per year dedicated to Physics [1], high schools for social studies have only 66 h [2]). Teaching physics in non-science oriented schools might be challenging for several reasons (e.g. lack of time, students tend to be less motivated toward STEM subjects or the perception that Physics is too difficult for them). The general aim of our activities, in such high schools, is to develop teaching paths that could emphasize the different aspects of Physics: theory, problem-solving, applications, practice and socio-cultural impacts.

This project in particular is focused on the problem-solving and practical sides. We present here a teaching path that applies the concepts of Ohm's and Kirchhoff's laws to a real-life situation. We propose to solve a problem that can occur in the students' daily lives: determine when an indoor plant needs watering. This is a common enough situation that anybody mights have faced.

Our intention of developing such a learning path was driven by the students difficulties in the understanding of the circuits laws. As stated by Kipnis [3], 'difficulties in learning Ohm's Law suggest a need to refocus it from the law for a part of the circuit to the law for the whole circuit. (...) This suggestion comes from an analysis of the history of the law's discovery and its teaching'. In fact we wanted to show that even a plant pot can behave like a resistor, in other words we wanted to show that resistors are not just specific components far from our daily experience. Moreover the introducing the historical setting as well, we can highlight how the scientists comprehension developed and felt the necessity of defining laws that mathematically describe the physical behavior.

Concering Kirchhoff's laws, we noticed in our students that they tend to be not motivated toward the study of such laws. They consider them too complicated and lead to long calculations in the exercises. Other authors are working on this aspect as well, in fact recently a videogame about Kirchhoff's laws was released by Kortemeyer [4]. The catchy slogan of the videogame describes very well what we noticed on our students: *Kirchhoff is annoyed because nobody appreciates his circuit laws!* [4].

2. Physical concept: the soil resistance

The soil electrical resistance has a rough correlation with the soil wetness. A wet soil exhibits less resistance than a dry one. Intuitively we know that something wet conducts electricity better than something dry. Therefore we could attach a battery and a light bulb to a pot soil and see the different light intensity (figure 1). The problem of this approach is that the light would be ON only when the plant has just been watered, and not when it needs water. As we want a circuit that can notify us when the plant needs water we will build a different circuit. For the intent of measuring the wetness, we can simply apply Ohm's and Kirchhoff's laws and compare the soil resistance with a reference value.

3. Circuit description

3.1. Measuring the soil humidity by determining a measurable quantity

Figure 2 shows the first part of the circuit that we will employ. Let us define the elements:

- R_1 and R_2 are two regular resistors;
- R_s is the resistance of the plant soil;
- ΔV_{gen} is the generator's potential difference;
- I is the current flowing through the circuit;

and analyze this simple circuit. V_{A} is directly connected to the positive side of the generator and V_{C} to the negative side, therefore the potential difference between the two is equal to ΔV_{gen}:

$$\Delta V_{\text{gen}} = V_{\text{A}} - V_{\text{C}}. \tag{1}$$

In this circuit the resistors are in series and therefore the equivalent resistor is

$$R_{\text{eq}} = R_1 + R_s + R_2. \tag{2}$$

Remembering Ohm's law,

$$V = IR, \tag{3}$$

we can calculate the current flowing through the circuit as

$$I = \frac{\Delta V_{\text{gen}}}{R_{\text{eq}}} = \frac{\Delta V_{\text{gen}}}{R_1 + R_s + R_2}. \tag{4}$$

Remembering Kirchhoff's loop rule, we can calculate the potential of V_{B} in respect to V_{C}. For simplicity we can say that $V_{\text{C}} = 0$ V and therefore

- $\Delta V_{\text{AC}} = V_{\text{A}} - V_{\text{C}} = V_{\text{A}} = \Delta V_{\text{gen}}$,
- $\Delta V_{\text{BC}} = V_{\text{B}} - V_{\text{C}} = V_{\text{B}} = IR_2$.

Substituting the value for the current I that we just calculated we get

$$V_{\text{B}} = IR_2 = \frac{\Delta V_{\text{gen}}}{R_{\text{eq}}} R_2 = \Delta V_{\text{gen}} \frac{R_2}{R_1 + R_s + R_2}. \tag{5}$$

According to our daily experience, we know that water conducts electricity well and therefore we can identify two cases

(i) **Wet soil**: there is a lot of water in the soil and then we expect that the soil conducts well, in other words: R_s is small.
(ii) **Dry soil**: there is no water in the soil and then we expect that the soil conducts badly, in other words: R_s is big.

3.1.1. Wet soil: small R_s.

What happens when we have a wet soil? $R_s \approx 0$, therefore we can see what happens to V_{B}:

$$V_{\text{B}} = \Delta V_{\text{gen}} \frac{R_2}{R_1 + R_s + R_2} = \Delta V_{\text{gen}} \frac{R_2}{R_1 + R_2}. \tag{6}$$

So V_{B} becomes an intermediate value between 0 V and ΔV_{gen}, depending on the values of R_1 and R_2.

3.1.2. Dry soil: big R_s.

In this case we have that R_s is big and therefore:

$$V_B \to 0\ \mathrm{V} \tag{7}$$

in other words V_B becomes very small.

We see that we have found a way to generate a variable potential that is related to the soil humidity.

3.2. Defining a reference voltage

For having a healthy plant we can decide what is the minimum level of humidity that we want to keep in the soil. How do we create a reference voltage that can tell us if V_B is too high or too low? We can use a potentiometer that can give an adjustable voltage. Figure 3 shows a circuit in which a potentiometer is used to define a reference voltage V_{ref}. Potentiometers have a sliding contact that can select a voltage that goes from the minimum voltage V_C to the maximum voltage V_A:

$$V_C \leqslant V_{ref} \leqslant V_A. \tag{8}$$

3.3. Comparing voltages

Now that we have a reference voltage V_{ref} and a voltage that we want to compare it to V_B, we need an instrument that can tell us if the unknown voltage is less or more than the reference. For this task we can employ an operational amplifier, also commonly called op-amp. Op-amps are complicated devices, but their use in this application is rather simple. They are usually not introduced in the high school settings, as they require a non-trivial knowledge of the circuit components and laws. We can use an op-amp as *comparator* in a extremely simple configuration. The educational purpose is not to describe in details the op-amps, but just to show to the students that there exist components that cam be utilized to compare values.

Figure 4 shows the circuit diagram of an op-amp. It is an active device and therefore it needs to be powered by the generator. The power supply need is represented by the two vertical lines, one is connected to the generator voltage and the other to the zero voltage of the circuit. This device has two inputs V_+ and V_- and one output V_{out}. When an op-amp is used as a comparator its behavior can be described by the following:

$$\text{if} \quad V_+ - V_- > 0 \Rightarrow \ V_{out} = \Delta V_{gen} \tag{9}$$

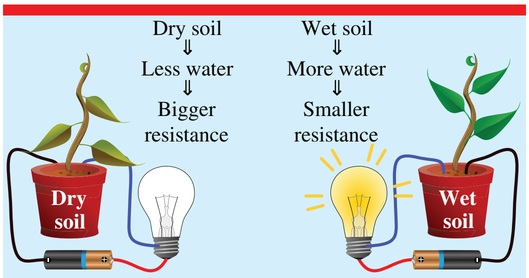

Figure 1. Diagram showing the effect of a dry or wet soil in a simple resistive circuit.

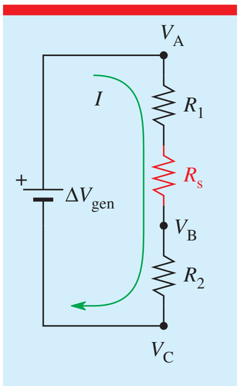

Figure 2. Circuit diagram for measuring the soil humidity. The soil is treated as a resistor (R_S) in a series with two regular resistors.

$$\text{if} \quad V_+ - V_- < 0 \Rightarrow \ V_{out} = 0\ \mathrm{V}. \tag{10}$$

Therefore if we connect V_{ref} to the V_+ input and V_B to the V_- input, we can compare the two voltages and determine which one is greater. What if we connect a LED to the output of the comparator? Let us analyze the two cases:

(i) **Wet soil** $\Rightarrow$ soil has a small resistance $\Rightarrow R_s$ is small $\Rightarrow V_B$ is high $\Rightarrow V_{ref} - V_B < 0 \Rightarrow V_{out} = 0$ V $\Rightarrow$ LED is OFF.

(ii) **Dry soil** $\Rightarrow$ soil has a big resistance $\Rightarrow R_s$ is big $\Rightarrow V_B$ is low $\Rightarrow V_{ref} - V_B > 0 \Rightarrow V_{out} = \Delta V_{gen} \Rightarrow$ LED is ON.

Figure 6 shows a diagram describing the logical steps that describes the circuit functioning. Figure 5 shows the complete circuit diagram. On the output we connected a LED in series with a resistor R_L, that is necessary for the good functioning of the LED.

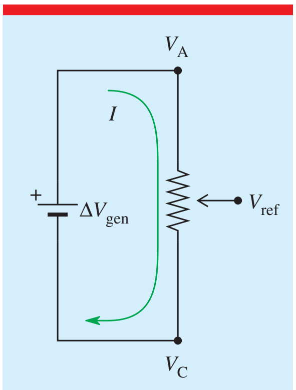

Figure 3. Circuit diagram with a potentiometer defining a reference voltage V_{ref}.

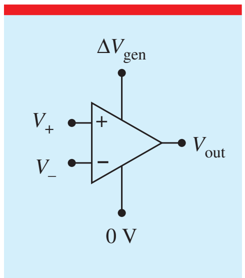

Figure 4. Circuit diagram of an operational amplifier used as a comparator.

3.4. Practical considerations

The potentiometer can be any kind of potentiometer, total resistances of 10 kΩ or 100 kΩ are good values. The op-amp can be a LM358 that is very easily found and it is cheap. The LED can be a regular red LED.

A set of three or four AA batteries in series can be used as a generator. With this option ΔV_{gen} will be either 4.5 V or 6 V, that work well with the LM358. A breadboard is a good option as the circuit support.

The rationale for having two resistors around R_s is to clamp the possible values of V_B, in order to guarantee the ability of setting a value of V_{ref} that is above or below the extrema. Suitable values for R_1 and R_2 can be calculated with a sample measurement of the soil resistance, in order to have a reference value for the particular case of that plant pot. We suggest to have the soil with a intermediate humidity for this measurement. In order to measure the soil resistance, two electrodes should be inserted in the soil. The electrodes can be simple pieces of iron wire as long as the pot height. Three parameters are necessary for determining suitable values for the resistors, here we give reasonable values:

- $V_{diff} = 2$ V, that is the difference between ΔV_{gen} and the maximum input value of the op-amp. This value depends on the chosen op-amp and it is commonly defined in the datasheet in the *input common-mode voltage range* section.
- $m = 0.05$, that is the relative minimum value of V_B for the maximum value of R_s.

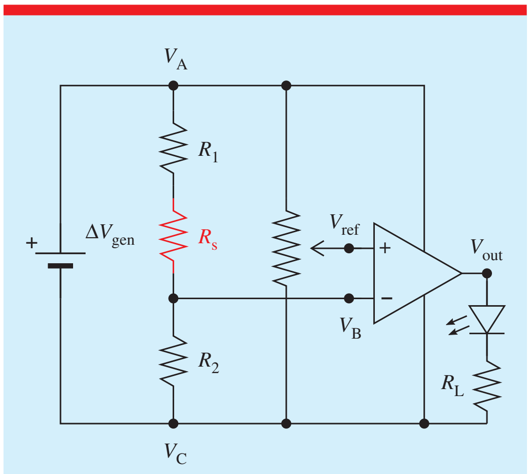

Figure 5. Circuit diagram of the complete circuit.

- $D = 10.0$, that is the relative maximum value of R_s for a dry soil.

If V_B is given by the formula (5):

$$V_B = \Delta V_{gen} \frac{R_2}{R_1 + R_s + R_2} \tag{11}$$

we want that V_B goes up to

$$V_B^{max} = \Delta V_{gen} - V_{diff} = \Delta V_{gen} \frac{R_2}{R_1 + R_2} \tag{12}$$

and down to

$$V_B^{min} = m \cdot \Delta V_{gen} = \Delta V_{gen} \frac{R_2}{R_1 + D \cdot R_s + R_2} \tag{13}$$

solving that system of equations we get for the resistor values

$$R_1 = -\frac{D \cdot R_s \cdot m \cdot V_{diff}}{V_{gen}(m-1) + V_{diff}} \tag{14}$$

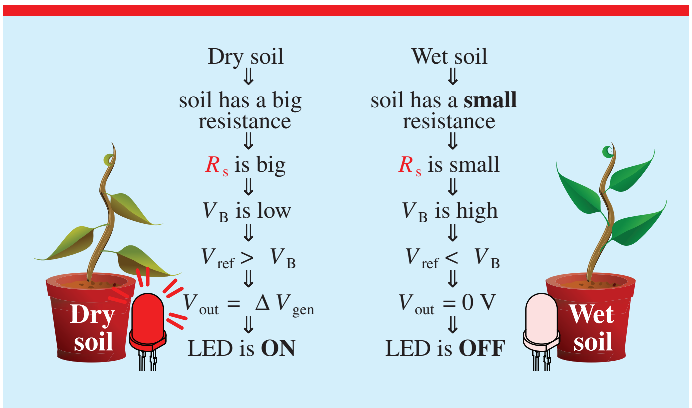

Figure 6. Diagram showing the effect of a dry or wet soil in our circuit.

Figure 7. Students building the circuit in the hands-on experience.

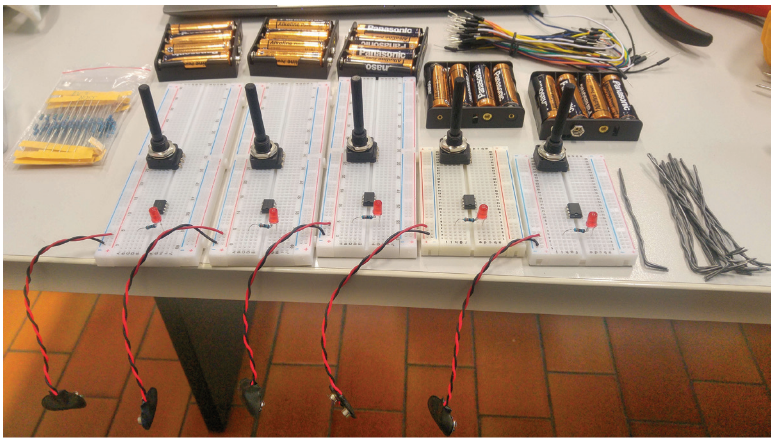

Figure 8. Material provided to the students includes breadboards, batteries, potentiometers and a few electronics components.

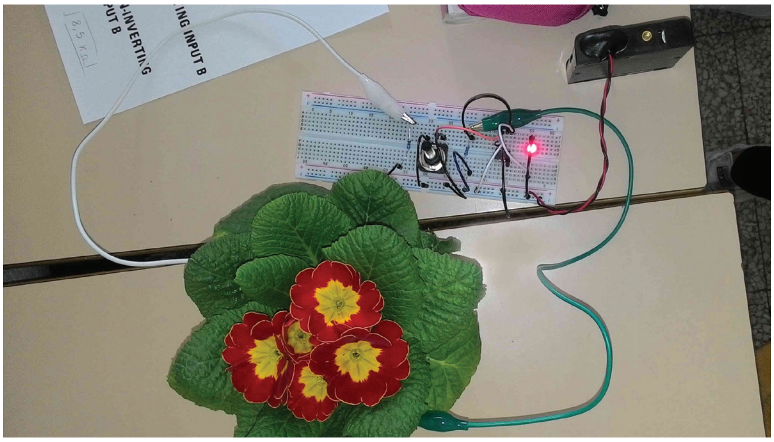

Figure 9. Picture of the working circuit built by a group of students.

$$R_2 = -\frac{D \cdot R_s \cdot m \cdot (V_{\text{gen}} - V_{\text{diff}})}{V_{\text{gen}}(m-1) + V_{\text{diff}}} \qquad (15)$$

where R_s is the measured value for the soil resistance.

4. Educational implementation

The introductory lessons are structured as a combination of lectures, in-class demonstrations, and group discussions. The learning path foresees a combination of strategies:

- theoretical introduction of Ohm's law and Kirchhoff's laws;
- modelization of the circuit elements;
- a description of the historical setting of the presented laws;
- experimental applications;
- a final problem-based laboratory (60 min long).

The strategies were cross referenced during the whole unit. A detailed description of the strategies follows.

4.1. Theoretical introduction

Before the hands-on activity, the theoretical bases were presented to the students, and web applets were employed as teaching aids. The teacher prepared some theoretical notes describing the Ohm's law and the Kirchhoff's laws. The notes had examples of exercises as well. Among the examples the difference between series and parallel circuits were emphasized. To ensure the student's comprehension *Kahoot!* [5] was utilized in class. Overall the explanation took three periods of 60 min. To ensure a deeper understanding several exercises were done in class by the students, with the teacher support, and given as homework.

4.2. Modelization of the elements

The modelization of the circuit elements was partially described during the theoretical explanation and the experimental sessions. The functioning and application of each element was described, in the context of the schematic representation of the circuits. After the theoretical introduction, the functional parts of the circuit are presented as specific exercises. Finally, all the parts were put together theoretically defining the complete circuit. The demonstrations and exercises took about two periods.

Simple circuits were demonstrated in class, by the teacher, as well. Some examples are a resistive circuit with a incandescent light bulb and a battery, or the series and parallel of the light bulbs. These aids were used to leave a mark on the students' memories [7].

4.3. Historical setting and applications

The historical setting was introduced, in order to highlight the evolution of the theoretical understanding, the cultural value of the discoveries and their socio-economical impact. The necessity of improving the efficiency of the first light bulbs brought the development of the theoretical background of circuits and of the black body radiation

Table 1. The tests were composed of several exercises on electrical circuits, but there was always a specific exercise about series and parallel circuits.

Time after activity	N. of students[a]	Average grade[b]
One week	17/17	7.7/10
Three months	17/17	7.9/10
Year end's exam (four months)	15/17(88%)	12.8/15 (85%)

[a] Number of students that correctly answered to the specific exercise.
[b] Average grade of all the tests of the class.

[6]. This explanation was carried out in about one period. The laboratory activity followed.

4.4. Problem-based laboratory

The circuit is extremely simple, so the students were able to build it during one regular class period (60 min). In the circuit building lesson, students were split into groups of up to four members (figure 7). Plants, electronics components and supports were provided to each group (figure 8). The instructor traced the circuit step-by-step, supporting the students during the developing of the activity. The final circuit (figure 9) turns on a LED if the plant needs watering. After the circuit construction, the theoretical explanation was reviewed in light of the practical experience.

5. Conclusions

In our real-life application of the project, the students were supported by three people: the class teacher, an external expert in electronics and another teacher that acted as an in-class peer reviewer. Having had a concrete problem, and a goal ahead, motivated the more practically-oriented students to comprehend the real meaning of the theory. The questions that the students raised during the laboratory activity highlighted how the previous lessons were understood. During the activity: four out of five groups constructed a working circuit. Moreover, the exercises that followed showed that the students really understood the difference between series and parallel circuits (table 1). The students' reaction was very positive; they both showed enthusiasm and interest. We stress the fact that this is a social studies oriented high school. At first they felt intimidated by the task, but the instructors' guidance allowed them to build functioning circuits. As anecdotal evidence, we report that, at the end of the hour, one of the students uttered 'has the class already ended!?'.

6. In-class peer reviewer's comments

The proposed activity is oriented on a concrete and practical point of view, using a learning by doing approach. The student's appropriation [8] is enhanced by the hands on experience [7]. Students also are gratified by the perception of solving a 'difficult' problem, that is actually connected to their real lives. The contextualization of their knowledge increases their motivation and allows the emergence of multiple intelligences. A learning path of this kind can also engage to the more practically oriented students, as well as the theoretically oriented ones; because the activity can be followed along two different modalities:

- *practical modality*: by applying the expert's instructions, and then by retroactively deepening their understanding of the theory.
- *theoretical modality*: by studying the theory and the schemes introduced by their teacher, and then by constructing the circuit with a better awareness.

Having present both the modalities allows to reach the students with different learning styles. Thank to this key aspect of the learning path, all the students in the classroom actively participated to the experience. The presence of the electronics expert helped to quickly solve all the technical issued that arose. The teacher closely supported the groups and induced the students to reflect on the connections between the theoretical laws and the circuit functioning. Being a complex activity, it enhanced the team working and the importance of having different intelligences in the groups.

The in-class peer reviewer was initially skeptic about the activity, because the circuit might have been perceived as too difficult by the students. However the students were rewarded by the trust given by the teacher, even if worried by the initial complexity of the problem. They also realized that, with just a little bit more explanation and some new concepts, they were able to understand the functioning of a real and useful circuit. Therefore, the results certainly helped the students in their learning and in building motivation toward the subject.

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References

[1] Allegato F al Decreto del Presidente della Repubblica n. 89 del 15 marzo 2010 (GU Serie Generale n.137 del 15-06-2010-Suppl. Ordinario n. 128)
[2] Allegato G al Decreto del Presidente della Repubblica n. 89 del 15 marzo 2010 (GU Serie Generale n.137 del 15-06-2010-Suppl. Ordinario n. 128)
[3] Kipnis N 2009 *Sci. Educ.* **18** 349–82
[4] Kortemeyer G 2018 Introduction to the video-game 'Kirchhoff's Revenge' https://msu.edu/user/kortemey/kirchhoff.html (Retrieved: August 2018)
[5] Kahoot official website https://kahoot.com/
[6] Kumar M 2009 *Quantum: Einstein, Bohr and the Great Debate about the Nature of Reality* (London: Icon Books)
[7] Hemmer S, Moretto S and Pantano O 2016 Integrating simulations and hands-on activities in physics *Selected Papers from the 20th Int. Conf. on Multimedia in Physics Teaching and Learning* 93–99
[8] Levrini O *et al* 2015 Defining and operationalizing appropriation for science learning *J. Learn. Sci.* **24** 93–136

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