MODESTUM
EURASIA Journal of Mathematics, Science and Technology Education, 2026, 22(2), em2773
ISSN:1305-8223 (online)
OPEN ACCESS
Research Paper
https://doi.org/10.29333/ejmste/17825

A low-cost smartphone-connected electroscope

Róbert Szabó [1], Károly Piláth [2], Helena Franke [3*]

[1] Doctoral School of Physics, ELTE Eötvös Loránd University, Budapest, HUNGARY
[2] ELTE Trefort Ágoston Practice High School, Budapest, HUNGARY
[3] Institute of Physics Education, Leipzig University, Leipzig, GERMANY

Received 11 November 2025 ▪ Accepted 18 December 2025

Abstract

When teaching electrostatics, it is often difficult to convey that electric charge is an abstract concept because it is invisible to the naked eye. Although traditional plate electroscopes react visibly to the presence of charges, they do not provide clear feedback regarding the sign or exact quantity of the charge, which makes it difficult for students to understand the phenomena. In our article, we aim to fill this gap by presenting the design and operation of a charge meter device developed in-house, as well as various possibilities for its use in education. Our device is not only capable of detecting the presence and sign of charges but is also innovative in that it indicates the magnitude of the electric field of a nearby body, which is proportional to the amount of charge. To encourage our colleagues to follow our example, we discuss in detail the selection of the units used in the development and the steps of the application. Additionally, we present five selected experiments in detail that can be performed with the device. From student feedback we conclude a great potential to foster conceptional understanding of electrostatic phenomena and to enhance students' motivation.

Keywords: electrostatics, electroscope, low-cost, smartphone

DEVELOPMENT BACKGROUND

In recent years, several simple, inexpensive do-it-yourself electronic sensors have appeared that can indicate charge polarity. In addition to progress being made in modernizing the electroscope (Thompson, 2014), some developments have clearly demonstrated the different charges of rubbed PVC rods and glass rods (Cruz et al., n. d.; Hasan, 2021; Ünlü Yavaş & Karadağ, 2019) but they have not made it possible to estimate the amount of charge or accurately detect the neutral state.

Our development was inspired by Zátonyi (2014) and Davies (1974). In the latter, the effect of the electrostatic field was detected using an amplifier with high input impedance and a capacitor with known capacitance. If a parallel-plate capacitor is placed in an external electric field, a voltage can be induced between its plates due to that field. This is responsible for the creation of a potential difference. If the plates are connected to a voltmeter with high input resistance or a charge-sensitive amplifier, the voltage value and polarity can be measured (**Figure 1**).

The voltage U generated in the flat capacitor and the external electric field E_k are related as follows:

$$U = E_k \cdot d, \qquad (1)$$

where U is the voltage measured between the capacitor plates, d is the constant distance between the two plates, and E_k is the component of the external electric field in the direction perpendicular to the plates.

Although this solution did not yet use a digital display, its basic principle–the indirect measurement of electric fields–proved extremely useful to us. We took this concept as our starting point when we began designing a new, portable electroscope suitable for classroom demonstrations. Our goal was to combine the simplicity of the classic electroscope with the advantages of modern electronics and smart devices. We aimed to create an instrument that provides real-time digital feedback on the polarity and magnitude of the electric field created by nearby charges, while remaining inexpensive, easy to build, and reproducible. Based on the principle described in Davies (1974), we developed a system that measures changes in the electric field caused

✉ rszabo.elte@gmail.com ✉ pilath.karoly@trefort.elte.hu ✉ helena.franke@uni-leipzig.de **(*Correspondence)**

Contribution to the literature

- The paper introduces an innovative, low-cost, smartphone-connected electroscope that detects not only the presence and sign of electric charge but also quantifies the magnitude of the electric field of a nearby object, providing both qualitative and quantitative feedback in electrostatic education.
- The development details a reproducible, classroom-friendly design using 3D printing and accessible components, complemented by an open-source mobile app, thereby enhancing practical accessibility and adaptability for educational settings.
- Through student feedback and demonstrated experiments, the article shows that the tool significantly improves conceptual understanding, motivation, and inquiry-based learning in electrostatics compared to traditional electroscopes, highlighting its pedagogical effectiveness.

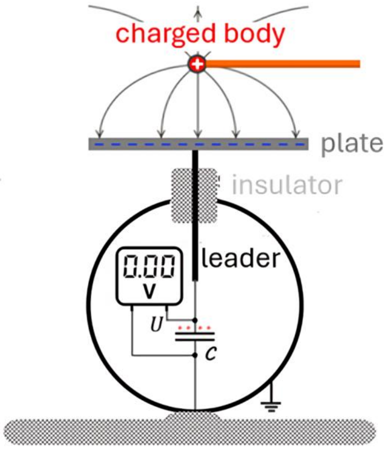

Figure 1. Principle of measurement (the parallel-plate capacitor has a plate separation d and is placed in an external electric field E_k & the component of the field perpendicular to the plates induces the voltage $U = E_k \cdot d$ between them) (Source: Authors' own elaboration)

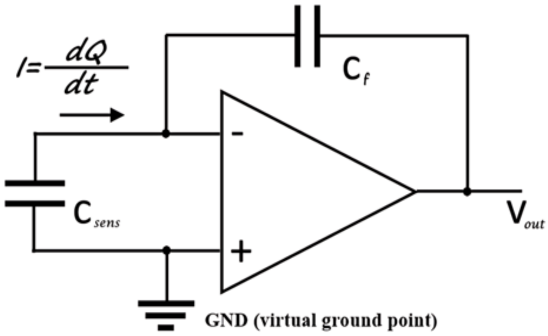

Figure 2. Schematic diagram of the charge amplifier (Source: Authors' own elaboration)

by nearby charges and transmits the data wirelessly via Bluetooth to a smartphone.

We used a special electronic circuit acting as a charge amplifier to measure the polarization-induced charge on the capacitor plates (Keim, 2018) used as sensors (**Figure 2**), which can convert the charge generated on the capacitive sensor into a voltage signal that can be evaluated by an AD converter.

The charge amplifier shown in **Figure 2** is essentially an integrator with high input impedance. The integrating action converts the charge into voltage, while the high input resistance ensures that the charge generated by the sensor–typically very small–is not lost through leakage currents. The sensor is read by a capacitive feedback charge amplifier. Ideally, the output voltage reflects the time integral of the input current, thus providing information not about the instantaneous current but about the total charge accumulated on the sensor:

$$V_{out}(t) = \frac{1}{C_f}\int_{t_0}^{t} I_{in}(\tau)\, d\tau = \frac{1}{C_f}\int \frac{dQ}{dt}\, dt = \frac{Q}{C_f}, \quad (2)$$

where C_f is the feedback capacitor, and $I_{\text{in}} = \frac{dQ_{\text{in}}}{dt}$ is the current associated with the Q_{in} induced charge at the sensor input. Under ideal charge amplifier conditions (negligible parasitic and leakage effects), the output voltage is largely independent of the capacitance C_{sens} of the sensor. In practice, however, small deviations may occur due to the presence of parasitic capacitance and leakage currents.

The operation of the device is fundamentally influenced by the reset and saturation limits, as well as noise and other non-ideal effects (e.g., drift). Its output only changes when the configuration of the external electric field changes; otherwise, it remains stable with slow drift.

DESIGN CONSIDERATIONS FOR THE MEASURING CIRCUIT

The capacitance of the feedback capacitor C_{sens} was dimensioned for the charge quantities expected in high school experiments (approximately 25 nC). The IC of the measuring circuit operates at a supply voltage of 12 V, so the output voltage can vary within a range of ±5 V relative to virtual ground point (GND). From this, the value of the feedback capacitor C_{f} can be calculated:

$$C_f = \frac{Q}{U_{IC,max,out}} = \frac{25 \cdot 10^{-9} C}{5\,V} = 5 \cdot 10^{-9} F = 5\, nF. \quad (3)$$

The feedback capacitor feeds the amplifier output back to the input; its main task is to convert the input charge into voltage. In the circuit diagram illustrating the measurement principle (**Figure 3**), we used a standard 4.7 nF capacitor (C4) instead of 5 nF in the measuring transducer we designed. In addition, the option of selecting a more sensitive measurement range

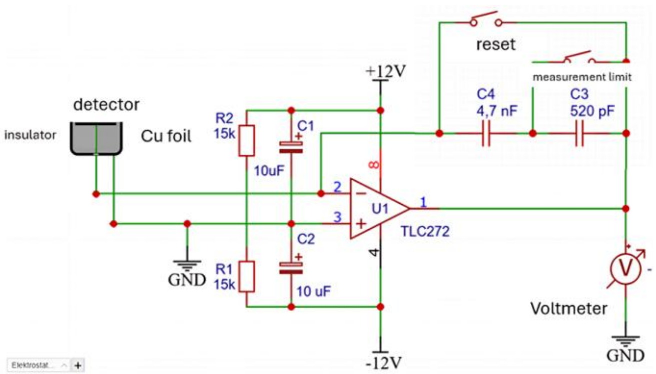

Figure 3. Schematic diagram of the integrator and measurement range switch circuit (the design was inspired by the charge amplifier concept described in Davies (1974) but the implementation is our own version adapted for educational purposes & the circuit was drawn using the *EasyEDA* online editor [EasyEDA, n. d.])

was included, for which we added a standard 520 pF (C3) capacitor into the integrator. The measurement range is switched by an electronic switch (DG444DJ), which allows C4 to be connected in series with C3, or, by short-circuiting C3, only C4 to be the integrating capacitor. When the 520 pF capacitor is short-circuited, the maximum detectable charge is 23.5 nC. When open, the total capacity of the two series capacitors is lower, so the integrator switches to a more sensitive measurement range of approximately 2.3 nC. The second unit of the DG444DJ switch also allows the integrator to be reset, which is essential for preparing the measurement.

SELECTING THE OPTIMAL OPERATIONAL AMPLIFIER FOR EDUCATIONAL PURPOSES

The electroscope sensor requires extremely high input impedance, so the current input of the operational amplifier must be as low as possible. The LMC6001 MOS input operational amplifier used in Zátonyi (2014) typically operates with an input current of 25 fA, ensuring virtually drift-free operation over long periods. During classroom experiments, where the measurement time is typically a few minutes, this level of precision is not necessary. In practice, a significantly cheaper TLC272 operational amplifier with an input current of approximately 0.6 pA may be an excellent choice.

The drift time constant can be estimated using the following relationship:

$$dt = \frac{dQ}{I} = \frac{C_f \cdot \Delta U}{I} = \frac{4{,}7 \cdot 10^{-9}\, F \cdot 0{,}1\, V}{0{,}6 \cdot 10^{-12} A} \sim 784\, s. \quad (4)$$

Calculated with a capacitance of $C_f = 4{,}7$ nF, this results in an output offset of only 0.1 V over 13 minutes, which is practically negligible on such a time scale. This period is sufficient to ensure that most high school measurements are not affected by any noticeable drift.

Designing the Electroscope

When designing the charge meter, our goal was to produce the device at the lowest possible cost (10 US dollars) while utilizing the latest technological possibilities. To this end, we produced the detector components using 3D printing. We used PLA plastic, which has good insulation properties and is now readily available to schools, for printing. The detector can be attached to the printed circuit board (PCB) of the measuring device with two M2 screws.

The printed detector consists of a solid PLA cylinder with a diameter of 20 mm and a height of 10 mm, with a through hole with a diameter of 2 mm in the center. We covered the cylinder's shell with self-adhesive copper foil, which acts as electromagnetic shielding connected to the GND of the measuring electronics (**Figure 4**). It was not necessary to shield the other electronic devices because their size is negligible compared to the sensor.

An 8.8 mm diameter, 1 mm thick disc is placed on top of the detector, the bottom and top surfaces of which are also covered with copper foil. A thin wire soldered to the center of the bottom foil connects to the inverting input of the electroscope IC through the central hole, ensuring electronic detection of charges. The design required for 3D printing the detector is available on the *GitHub* website (GitHub, n. d.a).

Signal Processing

The sensor signals are processed and transmitted by a microcontroller. We chose the *WEMOS Lolin32 Lite* device, which is based on the ESP32 microcontroller. This microcontroller has enough GPIO pins to handle the sensor and peripherals, is equipped with built-in Bluetooth and Wi-Fi modules, so it can easily establish wireless connections with smartphones or tablets, and supports energy-efficient operation, which is particularly advantageous for portable mobile devices. The program logic behind the application is quite simple, consisting of less than 20 visual blocks. The most important functions, such as reading data received via Bluetooth, updating the visual indicator, and sending the reset command, are implemented using these blocks. A timer ensures that the display updates regularly every 100 milliseconds.

We created the circuit diagram containing the microcontroller and measurement electronics based on the principles presented above. This was also used to create the PCB design, which allows for easy assembly and replication of the device. The circuit diagram shown in **Figure 5** shows that the TLC272 operational amplifier and the DG444DJ CMOS analog switch require a 12 V supply voltage to operate. This is provided by a built-in DC-DC converter from a lower voltage input supply.

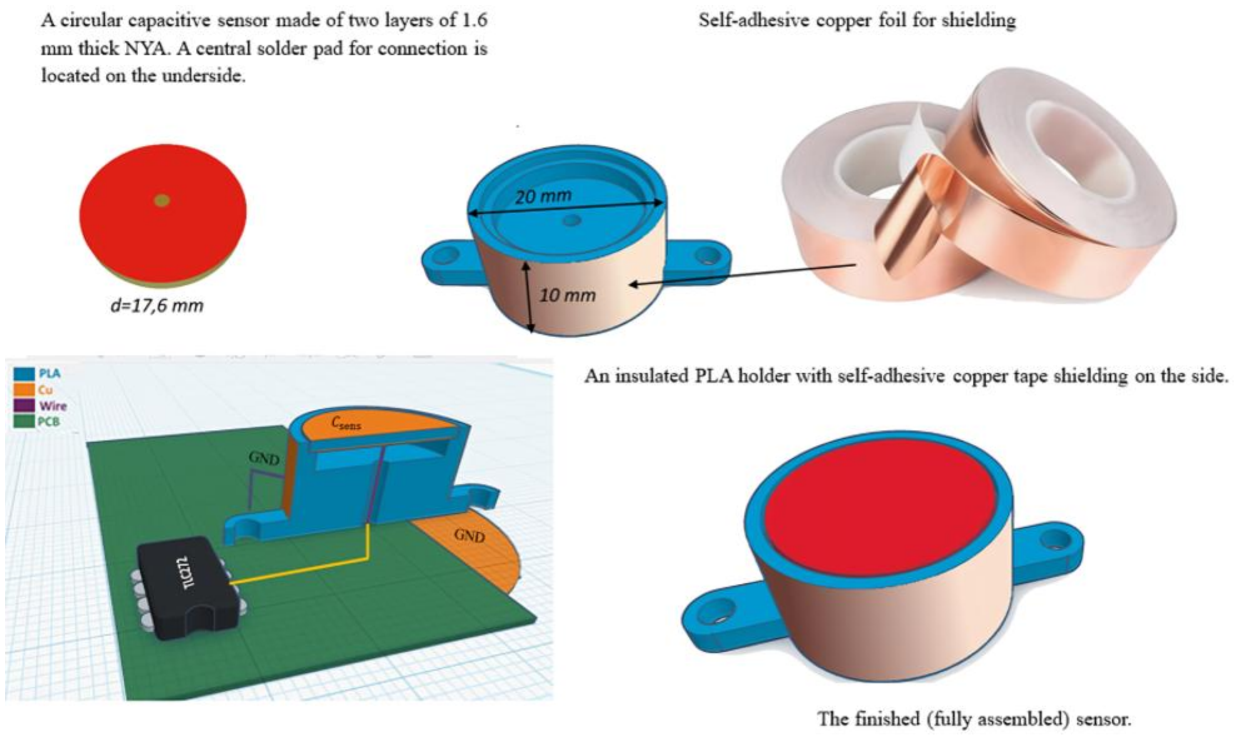

Figure 4. Components of the 3D-printed detector (Source: Authors' own elaboration)

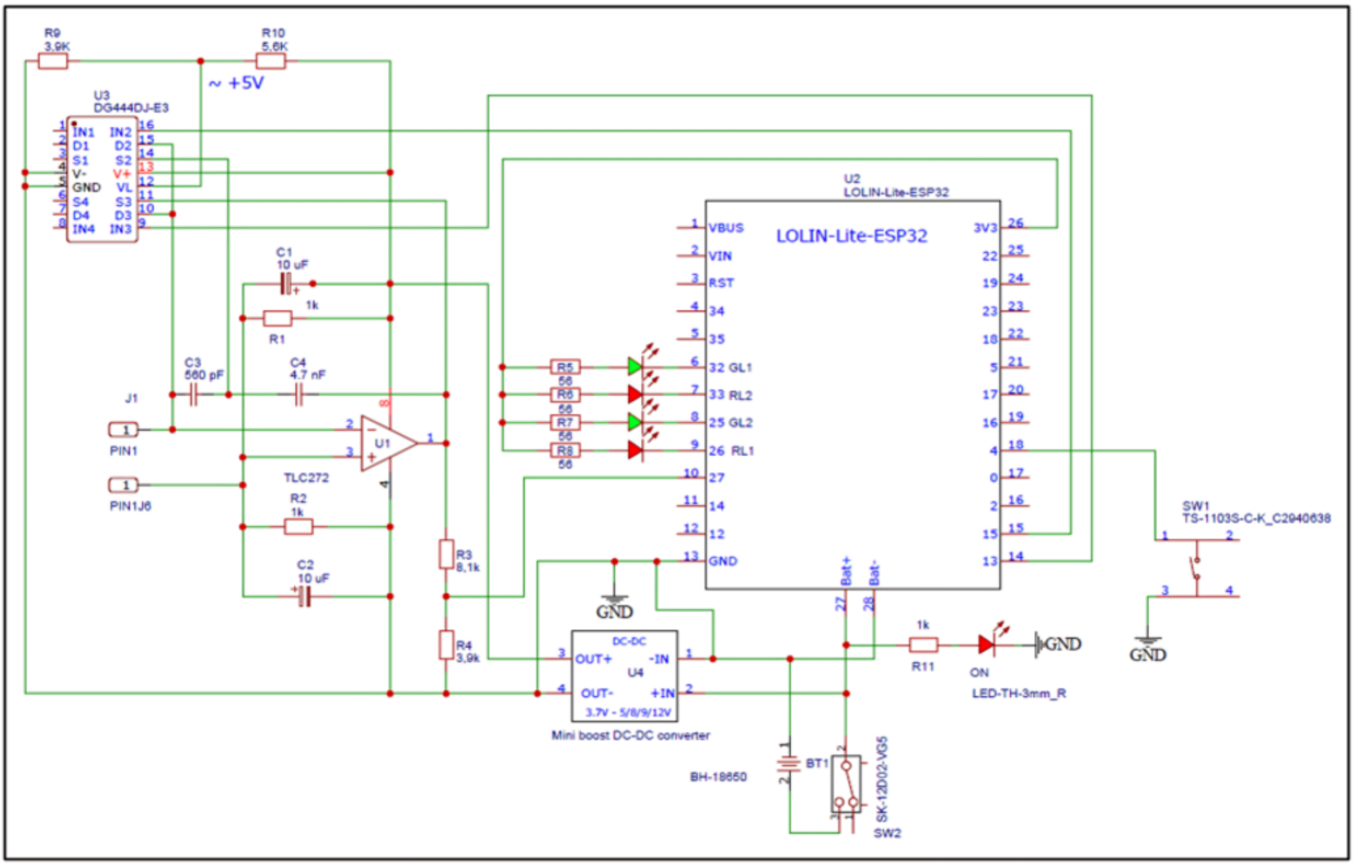

Figure 5. Detailed wiring diagram of the electroscope (Source: Authors' own elaboration)

The output voltage of the integrator IC (TLC272) is read by the GPIO27 pin of the ESP32 microcontroller. Since this input can accept a maximum of 3.3 V, a voltage divider (resistor R3 and resistor R4) has been incorporated to ensure safe operation. This divider ensures that even when the IC is fully driven, the voltage applied to the microcontroller does not exceed the 3.3 V limit. In addition, a second voltage divider (R9 and R10) provides the +5 V reference voltage for the DG444DJ to operate.

During the design process, one of our key objectives was to ensure that the device could also be used as a standalone visual indicator. The charge level and polarity are indicated by PWM-controlled LEDs: two red LEDs indicate a positive charge, while two green LEDs indicate a negative charge. Two LEDs are needed because this allows a wider range to be indicated: in the case of a small charge, only one is active, but its brightness is proportional to the small charge. When a certain threshold is exceeded, the other LED also turns on, further increasing the brightness. The brightness of the LEDs is proportional to the detected charge and inversely proportional to the square of the distance between the charged body and the sensor.

During operation of the system, it may often be necessary to redefine the zero-charge level. This so-called auto-zero operation can be performed in two ways: by pressing a button (connected to the ESP32 GPIO4 pin) or by sending a 'Z' command from the mobile application used as a display or via the com port.

In both cases, the microcontroller activates the DG444DJ CMOS switch, which creates a short circuit for a short time, thereby discharging the feedback capacitor C_f and setting the current state to zero charge.

After successful zeroing, the system enters a clearly recognizable state: none of the LEDs are lit, or if connected to a smartphone, a small gray disc is visible on its display, symbolizing the uncharged state, and the charge value measured at C_f displayed on the screen is also zero. This multi-level feedback ensures that the user receives a clear indication that the device is in a balanced state and ready to start a new measurement.

Signal Output

The detected charge value is displayed by the app with a colored disc: green indicates a negative charge, red indicates a positive charge. The radius of the circle is proportional to the magnitude of the charge. The charge value measured at C_f and the sign of the charge are also displayed numerically.

Based on the circuit diagram in **Figure 5**, we created the PCB for the electroscope using the *EasyEDA* design program. A detailed description of the device's operation and source code is available on the project's *GitHub* page (GitHub, n. d.c).

The measuring device can also communicate with an application running on an Android phone. The *Q_meter* app was created on the *MIT App Inventor* platform. This app communicates with the charging meter via a Bluetooth channel, serving as its real-time display. The interface (**Figure 6**) includes the following:

1. Charge indicator: A colored circle whose color and radius are proportional to the detected field strength.

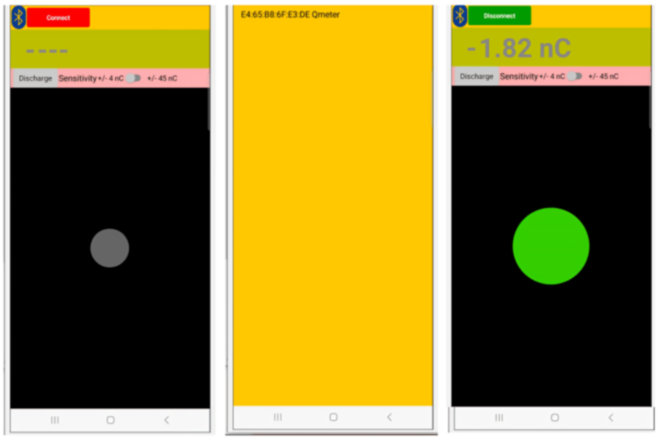

Figure 6. The application interface (Source: Authors' own elaboration)

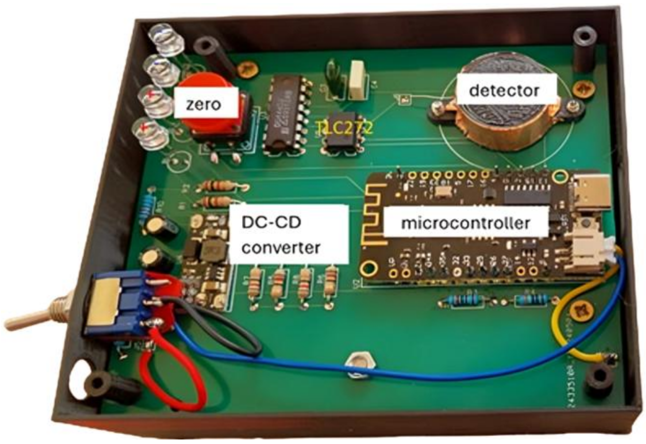

Figure 7. Photograph of the completed prototype (Source: Authors' own elaboration)

2. Numerical display: The current voltage value and charge level are displayed below the circle.
3. Control buttons: When connected, the list of paired Bluetooth devices opens and connects to the sensor module (*Smart Qmeter*). When set to zero, a 'Z' command is sent to remotely reset the integrator.
4. Status label to indicate the connection status and data transfer speed.

Both the compiled .apk installer and the editable. aia source files are available on the project's *GitHub* page (GitHub, n. d.b). Installation requires Android 6.0 or later; users must enable *Installation from unknown sources* and then open the .apk file. Alternatively, by importing the .aia file into *appinventor.mit.edu*, teachers or students can rebuild or modify the interface for classroom experiments.

Based on the installation diagram, we built a working prototype that fully reflects the planned layout. The device works stably and can also be successfully used in classroom demonstrations. **Figure 7** shows a photo of the completed circuit.

Figure 8. Displaying electrical conditions on the phone used as a display (Source: Authors' own elaboration)

Although we did not consider precise metrological calibration of the instrument necessary for educational purposes,[1] we verified its correct operation when testing the experimental model. We checked this as follows: we connected a small, known calibration capacitor (C_{cal}) in parallel to the input of the electroscope amplifier. By connecting the capacitor to a source of known voltage and then quickly switching it to the meter input, we fed a charge of $Q = C_{cal} \cdot U$ into the system. The instrument indicated an output voltage of $V_{out} = Q/C_f$, within a ±5% error margin. This method is known in the literature as 'known calibration capacitor injection' (James et al., 2020).

Demonstration of Electrostatic Experiments Using the Electroscope

Charge induction

The aim of this experiment is to demonstrate that rubbing two bodies together can transfer electric charge. We rub a PVC rod with a piece of wool fabric, then bring the rod close to the electroscope sensor. At this point, the grey disc indicating a neutral state on the mobile phone display turns green. The radius of the disc–for example, the measured charge–depends on the intensity and duration of the rubbing, as well as the distance between the rod and the sensor. It can be observed that the size of the disc does not decrease linearly with increasing distance, which draws attention to the spatial behavior of the electric field. The piece of wool fabric used to rub the rod shows a positive charge. In our experience, a sponge–unlike a traditional cotton or wool cloth–can retain its positive charge longer (**Figure 8**). This is probably due to the finer, smoother surface of the sponge, which reduces the likelihood of discharge to the negative ions in the air. As soon as the charged rod or piece of fabric is removed, the grey disc indicating zero charge reappears on the display. Similarly, if we rub a glass rod with a piece of leather, the glass becomes positively charged and the leather becomes negatively charged. The sign depends on the sign of the external charge.

Figure 9. Soft drink can charged by transfer (Source: Authors' own elaboration)

Charge transfer

If a pre-charged conductive body (for example, a metal ball) placed on an insulator touches the 'plate' of the electroscope, the display will not return to zero after the body is removed. Part of the charge is transferred to the measuring capacitor. The demonstration can be simplified by not touching the charged body directly to the plate. An aluminum soda can stand on an insulating surface that can be attached near the plate. By rubbing a pre-charged body (for example, a negatively charged PVC rod) against the can, its charge is transferred and can remain on it for a long time (**Figure 9**).

Since the can has a larger capacity than the plate, we can transfer a larger amount of charge to it by repeating this procedure.

[1] Like traditional electroscopes, the measured values may be influenced by environmental factors such as humidity, grounding conditions, or nearby conductive objects.

Figure 10. Metal body charged positively by electrical sharing (Source: Authors' own elaboration)

Electrical sharing

In this experiment, we create a charge by induction. We place a negatively charged PVC rod near a neutral aluminum soda can without touching it. The sensor detects the induced charge distribution (a green disc appears). Next, we touch the opposite side of the can with our finger, allowing the electrons to escape to the ground. When we remove our hand and then the rod, the can shows a positive charge, which is indicated by a red disc on the display (**Figure 10**).

Demonstration of the photoelectric effect

This experiment is particularly suitable for demonstrating the sensitivity and capabilities of the electroscope. Before the experiment, gently polish the concave base of an aluminum soda can. Then charge it negatively (for example, by touching it with a rubbed PVC rod). The can retains its charge for a long time, especially at low humidity–the negative charge can be detected stably for several minutes.

After charging, the bottom of the can is illuminated with a low-power UV light source with a wavelength of 254 nm (**Figure 11**).[2] Under the effect of the light, the box gradually loses its negative charge, which is clearly indicated on the display. It is important that the aluminum surface be free of oxidation, as the Al_2O_3 coating significantly inhibits or completely prevents electron emission. If the box is pre-charged to positive (for example, by electrical sharing), UV illumination does not cause a noticeable change in charge. This confirms that negative charge carriers (electrons) are emitted during the photoelectric effect, while positive ones are not.

Figure 11. Demonstration of the photoelectric effect (the UV light source is housed in a 3D-printed enclosure to prevent radiation from reaching the surroundings) (Source: Authors' own elaboration)

Examination of the time dependence of charge loss

The device can also be used to investigate how the charge on a negatively charged aluminum can decreases when exposed to low-power UV light with a wavelength of 254 nm. The observed phenomenon reveals the temporal course of the photoelectric effect: under the influence of light, electrons are emitted from the metal surface of the body, causing the negative charge to gradually decrease. The data collected by the electroscope can be displayed in real time using graphical evaluation software, such as *SerialPlot* v0.13, which can plot the values received via the COM port as a function of time. First, we charge the body with a negative charge, which can be achieved by rubbing a PVC tube with a sponge. The charge measurement is performed by collecting data in a series, with sampling intervals of 20 ms. The illumination began at approximately 250 ms: from this point on, we illuminated the top of the box with the UV lamp described earlier. The electroscope recorded the decrease

[2] The UV light source used in the photoelectric effect experiment is a low-power (1-3 W) 254 nm lamp placed in a 3D-printed housing that prevents lateral emission. During demonstrations, observers remain several meters away, so exposure is negligible, although direct viewing of the lamp should be avoided. The measuring electronics operate at low voltage (12 V) and are enclosed in an insulated case, making accidental contact unlikely. Under normal classroom supervision, the experiments can be performed safely.

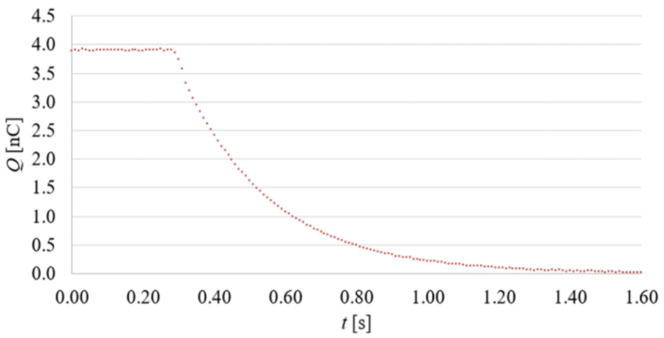

Figure 12. Decrease in charge over time in a negatively charged aluminum box exposed to UV light (Source: Authors' own elaboration)

in charge as a function of time (**Figure 12**), which confirmed that the process was indeed the result of the photoelectric effect.

Evaluation of the Educational Application of the Electroscope

The device was used in school lessons, on average two to three times, which allowed the students to gain a thorough understanding of its didactical benefits. To get direct student feedback, we created a Google Form, which was completed by 11th grade students (21 people). The students had to answer four closed and one open question; for the closed questions, they could choose from 1 to 5, where 1 was the worst and 5 was the best rating. Students had to formulate their own answers to the open-ended questions.

Most students found the device easy to use, and almost everyone found its use motivating and interesting. Compared to traditional electroscopes, student feedback shows a clear advantage for this digital tool. While nearly three quarters of respondents found the phenomenon much easier to understand with the tool, more than three quarters of students thought the measurement results were more spectacular. Its key advantage is that it makes abstract electrostatic phenomena tangible through quantitative and visual feedback. It was particularly significant that the magnitude and sign of the charge is visualized in real time: the vast majority of respondents rated this as helpful or very helpful. This direct feedback–the colored circle, whose size and color indicate the magnitude and polarity of the charge–was key to understanding the concepts, as the students emphasized in their open-ended responses. Comments such as 'much more spectacular,' 'clearly readable,' and 'easier to interpret' confirm that digital display supports conceptual understanding much more effectively.

From a pedagogical point of view, the tool enables active, inquiry-based learning. Students are not just passive observers, but can test their own hypotheses, receive immediate feedback, and discover physical laws for themselves. According to student responses, the tool was particularly effective in helping them understand the sign of charge, electrical sharing, and continuous observation of processes. In fact, some students specifically highlighted that they were able to understand previously incomprehensible phenomena (such as the specific behavior of charging materials) with the help of the real-time graph and display.

In summary, it can be said that the electroscope is not only a technical innovation, but also a truly effective pedagogical tool that promotes deeper conceptual understanding and increased interest in physics. Based on the extremely positive student feedback, the demonstrably better comprehensibility and visual appeal compared to traditional tools, and the promotion of research-based learning, the tool can be successfully integrated into high school experiments. In future educational use, special attention should be paid to the development of teaching aids (e.g., worksheets) and the consideration of development so that the full pedagogical potential of the tool can be exploited.

CONCLUSION

The development of the electroscope has made it possible to create a demonstration tool that not only indicates the presence and sign of charges invisible to the human eye but also indicates the magnitude of the electric field of a nearby body. For this reason, the device is not only student-centered but also spectacular, and the numerical values displayed in each experimental situation provide us with quantitative data. This makes further development of the device a logical next step. On the one hand, this could be done by making it suitable for further experiments. We plan to conduct a long-term study by monitoring the charge decay on electret-charged FFP mask material. In addition, the Faraday cage demonstration is suitable for the purpose: when placed inside a metal container (after auto-zeroing), the device does not indicate a charge when the container is charged from the outside. Finally, the slow decay of the charge can also be used as a qualitative humidity indicator. We have observed this in real conditions: in humid weather, it is difficult to detect the photoelectric effect because the charge of the aluminum box decreases rapidly even without UV light; in dry weather, however, the photoelectric effect is clearly observable. On the other hand, student feedback indicated that the digital charge meter significantly improves the understanding of and motivation for learning electrostatic concepts through its visual feedback, surpassing traditional tools. Therefore, it is also possible to continue the research by creating worksheets that facilitate the use and learning process for existing experiments, besides we plan to use the tool in teaching experiments to draw further conclusions.

Author contributions: RS: validation, formal analysis, writing – original draft; **KP:** resources, software; **HF:** supervision. All authors agreed with the results and conclusions.

Funding: On the one hand, this study supported by the EKÖP-KDP-24 University Excellence Scholarship Program Cooperative Doctoral Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund. On the other hand, the study is supported by the Open Access Publishing Fund of Leipzig University.

Ethical statement: The authors stated the highest practices in publication ethics have been followed throughout the study. The survey mentioned in the last part of the study was conducted anonymously. The responses provided by the students will be stored accordingly.

AI statement: The authors stated that the work was completed without the use of Generative AI or AI-based tools for content creation. All analysis and writing were undertaken by the authors.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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