Integrating electrostatics with demonstrations and interactive teaching

Wheijen Chang
Physics Teaching and Research Center, Feng-Chia University, 100 Wen-Hwa Road, Taichung 407, Taiwan

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Teaching electrostatics is challenging due to its complexity and high degree of abstraction. To facilitate students’ understanding of the meanings and relations of the key terms, this paper describes a series of demonstrations and conceptual questions based on an interactive teaching approach. The context was an introductory university physics course for engineering and science students in Taiwan. Features of the teaching intervention include the utilization of a series of demonstrations for repeated practice applying the important concepts, the incorporation of derivations of equations and verbal elaboration of concepts, and the engagement of students in thinking and discussing. Data show that the teaching intervention benefited the students’ academic performance and their satisfaction with the learning achievement. © 2011 American Association of Physics Teachers. [DOI: 10.1119/1.3533342]

I. INTRODUCTION

Electrostatics is challenging to teach in part because key terms such as electric field, electric flux, and electric potential are not commonly used in everyday life. The concepts are not independent but are closely related. Each quantity may be derived in multiple ways, depending on the given information. For example, the electric field can be derived from charges, electric flux, electric force, or electric potential. The selection of appropriate equations may be challenging for students when solving problems. The provision of many contextualized questions is necessary for many students to overcome the abstractness and complexity of the topic.

In recent decades we have learned that treating students as passive receivers of knowledge is ineffective for learning physics. Students need to engage cognitively to comprehend the meanings and usages of the key concepts.

This paper describes a series of demonstrations and conceptual questions in the context of an interactive teaching approach. The goal is to facilitate students’ understanding of the meanings and relations of the key terms and to help them gain an overall understanding. Assessment of the outcomes of the intervention is discussed, as are the features of the teaching design.

II. LITERATURE SURVEY

The literature suggests four main difficulties in learning electrostatics: (1) The concepts of electricity are more abstract than mechanics, for example, and the required mathematics is more complicated. Students often confuse field lines, equipotential lines, and trajectories. (3) Students are likely to overlook the electric field. For example, many students identify the electric field $\mathbf{E}$ with the electric force $\mathbf{F}$. In addition, students tend to ignore the field model perhaps because of the similarity between the forces between two charges and two masses. (4) Many students are unfamiliar with the limits of the application of Gauss’ law and Coulomb’s law.

The use of demonstrations must be coupled with an understanding of contemporary learning theories to achieve the desired outcomes. The conceptual change model states four conditions for achieving conceptual change, that is, the intelligibility, plausibility, and fruitfulness of the new model and dissatisfaction with the existing concepts. Demonstrations may help students to encounter cognitive conflict and trigger a shift from their preconceptions toward scientific models. Real-life examples usually comprise multiple principles and provide an opportunity to students to integrate the related ideas and strengthen their conceptual framework.

Based on a sociocultural view, scientific tools, including cognitive tools (for example, words, symbols, and diagrams) and physical tools (for example, equipment), are mostly either new to the students or discrepant in meaning or usage compared with everyday life. University instructors are often unaware that the meanings of these tools are not readily understandable by students from their everyday experiences. Understanding of university physics needs to be illuminated by multimodal scaffolding, for example, language, images, apparatus, and mathematics, and repetitive practice is necessary for students to become fluent in the disciplinary discourse. Vygotsky claimed that higher mental functioning and human action are mediated by cultural tools. Scientific tools are not merely for facilitating cognition but entail thinking. They serve as the essential “vehicle of thought.” To comprehend and apply scientific knowledge, students are required to become acquainted with these tools and grasp scientific ways of thinking. Kuhn suggested that scientific tools can be acquired by students by exposing them to examples of their use rather than by symbolic definitions. While discussing demonstration phenom-
ena, students may gradually become acquainted with the meanings, functions, and relations of the scientific tools. Demonstrations should not only engage students and provide entertainment but should also help students to visualize, focus, and think about the physics. A spiral structure is suggested, allowing students to repeatedly revisit the ideas in different contexts to distinguish the similarities and differences among related terms, concepts, and formulas.

The goal of enhancing understanding via demonstrations may be difficult to achieve. Students may be unaware of the key phenomena that the teacher wants to illustrate in the demonstration and that the students may be confused by the representational tools that the teacher adopts for explanation. Demonstrations are usually perceived as interesting but irrelevant to the “official” learning agenda. Some students completely ignore the anomaly that the instructor has demonstrated and use only equations to interpret their conceptions, which implies isolation between “real-life” demonstrations and school physics. Demonstrations should provide instruction on the scientific tools and highlight the signals for students to undertake effective reasoning, encompass questions in demonstrations to engage thinking and discussion, and show the direct links of demonstration questions to official learning tasks, such as solving textbook problems and examination questions.

Examples related to electrostatics are far fewer than for other topics such as mechanics and optics. Guibert has introduced the technique of constructing a plasma globe, verbally explaining the principles of why it glows, and a few tricks that teachers can show in class, “just for fun.” Doty et al. introduced a lightning machine to illustrate the relevance and difference of the electric field and the electric potential and to show that the ionization of air is due to rather than . Some studies describe attempts to facilitate students’ visualization of key concepts, such as , mainly through computer simulations. Sokoloff and Thornton devised interactive lecture demonstrations to engage students in observation, thinking, and discussion, confronting anomalies, and triggering conceptual development. Designing questions to engage thinking and discussion is not easy because it requires instructors to continuously modify the question statements according to the responses of the students.

### III. METHODOLOGY

This study included the design of the teaching intervention, including a series of demonstrations involving a plasma globe and other equipment, the implementation of the teaching sequence, and an evaluation of the outcomes. The study was conducted over 2005–2007, which allowed for ongoing modifications. We will present the design and outcomes of the most recent implementation, along with a brief discussion of the modifications.

During the three years, the author taught the unit six times in an introductory physics course for science and engineering students at a large university in Taiwan, with about 2000 students enrolled in the course each year. The course structure is similar to that in the U.S., and American versions of the calculus-based textbooks are commonly adopted. In the intervention class, the distribution of teaching time was 65% lecturing, 10% assessment, and 25% discussion. Given the same number of teaching hours as traditional classes, the intervention adopted two strategies to reallocate time for in-class discussions. The intervention reduced the time spent solving problems, which was compensated by quizzes (to reinforce the students’ commitment to practicing problems outside of class). The use of handouts saved the time usually spent copying notes. The teaching style adopted by the author was the same during the entire academic year, so that students would perceive that learning electrostatics was similar to learning other physics topics.

Both the students’ academic achievements and their perceptions of the course were investigated. The assessment tools, the participants, the timing of evaluations, and the types of analyses are tabulated in Table I.

Academic achievement was evaluated by a written examination consisting of nine questions with 15 subquestions in total, which were either written by the author or modified from the resources such as textbooks and the standardized Conceptual Survey of Electricity and Magnetism (CSEM) test. The academic achievement test devised by the author was given 2 weeks after the unit was completed and served as a quiz. The experimental class included 60 students taught by the author, and the control class had 83 students taught by another instructor. A one-tailed t-test and test were applied to examine differences between the two groups. The Pearson product-moment correlation was adopted for analysis of the subquestions between the two groups to evaluate the reliability of the academic achievement test. The two instructors did not discuss the test questions prior to the assessment.

Most students in Taiwan are placed according to the Unified Entrance Examination and are allocated to a specific department of a university. For the introductory physics course, students in the same class have the same major.

### Table I. The assessment tools, participants, time of evaluation, and method of data analysis to evaluate the outcomes of the teaching design.

<table>
<thead>
<tr>
<th>Assessment tools</th>
<th>Experimental group</th>
<th>Control group</th>
<th>Timing of evaluation</th>
<th>Data analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic test</td>
<td>(N=60)</td>
<td>(N=83)</td>
<td>2 weeks after the unit</td>
<td>Quantitative</td>
</tr>
<tr>
<td>Open-ended survey</td>
<td>(N=52)</td>
<td>Not applicable</td>
<td>1 week after the unit</td>
<td>Qualitative</td>
</tr>
<tr>
<td>Closed-form survey</td>
<td>(N=40)</td>
<td>(N=41)</td>
<td>4 months after the end of the semester</td>
<td>Quantitative</td>
</tr>
</tbody>
</table>

### Table II. Content structure and time allocation of the control and experimental classes in electrostatics.

<table>
<thead>
<tr>
<th>Classes</th>
<th>Topics</th>
<th>Coulomb’s law (h)</th>
<th>Gauss’ law (h)</th>
<th>(V) and (U) (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>4</td>
<td>4</td>
<td>4 h</td>
</tr>
<tr>
<td>Experimental</td>
<td></td>
<td>3</td>
<td>3</td>
<td>Integrating the 3 units: 6 h</td>
</tr>
</tbody>
</table>
some popular departments, students with the same major are randomly allocated to two to three classes. To ensure a similar background between the two groups, students in the control class all had the same major as the experimental class, that is, electrical engineering, in the most recent implementation (2007). The average scores (standard deviations) in the physics entrance examination of the experimental and control groups were 37.1 (8.8) and 36.1 (10.5), respectively. A two-tailed t-test showed no difference between the two groups on the entrance examination.

IV. DESIGN OF THE TEACHING SEQUENCE

Electrostatics usually consists of discussions of Coulomb’s law, Gauss’ law, electric potential, and potential energy. Key concepts include the electric charge \( q \), the force \( \mathbf{F} \), the field \( \mathbf{E} \), the electric flux \( \Phi_E \), the electric potential \( V \), and the potential energy \( U \). Understanding the definitions and meanings of each concept and the relations among them is a major goal of learning electrostatics. Equations can be effective tools for defining concepts and linking their relations. The key relations, following the usual sequence, include

\[
\begin{align*}
E &= kq/r^2, \\
\text{definition of electric field by electric force,} & \quad \mathbf{E} = \mathbf{F}/q, \\
\Phi_E &= q/e_0, \\
\text{flux } \Phi_E \text{ due to charge } q \text{ (Gauss’ law),} & \quad \oint \mathbf{E} \cdot d\mathbf{A} = \Phi_E = q/e_0, \\
\Delta U &= -\int \mathbf{F} \cdot d\mathbf{r}, \\
\text{definition of potential energy difference,} & \quad \Delta U = -\int \mathbf{F} \cdot d\mathbf{r}, \\
\Delta V &= \Delta U/q, \\
\text{definition of electric potential difference } \Delta V \text{ by } \Delta U, & \quad \Delta V = \Delta U/q, \\
V &= kq/r \text{ (assuming zero potential at } r = \infty), \\
\text{electric potential due to a point charge,} & \quad V = kq/r, \\
\text{relation between } \mathbf{E} \text{ and } \Delta V, & \quad \Delta V = -\int \mathbf{E} \cdot d\mathbf{r}, \\
& \quad \mathbf{E} = -\frac{dV}{dr}. 
\end{align*}
\]

Following a brief introduction of Eqs. (1)–(3) and the solution of a few related problems, the teaching sequence presented in this paper was adopted. This sequence serves not only to introduce \( V \) and \( U \) but also to review Coulomb’s and Gauss’ laws. About 12 teaching hours (4 weeks) were devoted to electrostatics for both the control and experimental classes, of which the teaching sequence took 6 h.31 The distribution of the teaching hours used in each group is compared in Table II, which shows that the control class adopted the three topics of electrostatics with a unidirectional approach and the experimental class adopted a spiral structure allowing for the review and integration of the three topics.

The teaching intervention starts with three demonstrations aimed at introducing the meanings, functions, and relations of \( \mathbf{F}, \mathbf{E}, \Delta U, \) and \( \Delta V \). Then, with the guidance of the instructor, the students assemble a “formula diagram” to further consolidate the conceptual relations of the four terms. Details of how to assemble the formula diagram are discussed later. When the formula diagram is completed, more questions are needed to help the students to further comprehend the terms, formulas, and concepts associated with the formula diagram. Small group discussions were then undertaken with a series of demonstrations involving the plasma globe.

A. Initiating key terms: Three demonstrations

The three demonstration examples are conducted through whole-class discussion, during which the instructor poses the questions and recruits students to answer. Instruction and dialog are flexibly interchanged in the three examples.

The first demonstration utilizes Wimshurst’s electrostatic generator to introduce the concepts of charge, potential field, force, and potential energy and the relations between them. As shown in Fig. 1, Wimshurst’s electrostatic generator has

![Fig. 1. A Wimshurst generator is used to illustrate the five key terms of electrostatics, including \( q, V, U, E, \) and \( F \), to illustrate the meaning of each term and to link relations among them.](image)
wheels attached to leather plates, which rub against the metal brushes while rotating. Electric charges are thus separated and then accumulated on the two metal poles. The questions and answers (including formula derivation and verbal descriptions) are as follows, along with some typical student’s responses.

**Question 1.** Why does the electrostatic generator spark when the wheel is rotated? Answer: Rotating the wheel allows the materials to rub, separating charges. The charges gradually accumulate and result in intense electric fields between the poles.

Common student responses indicate the causality of rub→charging→high $V$→sparking. The inappropriate link between high $V$ to sparking was similar to the finding of Doty et al. This question highlights the critical role of $E$ (rather than $V$) to trigger sparks.

**Question 2.** If the sparks do not appear after rotating, how can they be subsequently created? How can this discharging phenomenon be explained using the relations and concepts of electrostatics? Answer: This question highlights the critical role of $E$ and $V$. This question can be answered as follows: (a) Reducing the distance $\Delta r$ between the two poles increases $E$ because $E = \Delta V / \Delta r$; $E \propto 1 / \Delta r$ when $\Delta V$ is fixed. (b) Because the potential $V$ depends only on the amount of charge $+q$ and $-q$ accumulated on each spherical pole ($\pm V = \pm kq/r$), $\Delta V = V_+ - V_-$ is fixed when the charge $q$ of the two poles is fixed. (c) The electric force exerted on the ions within the two poles increases when the electric field $E$ increases ($F = qE$, which implies that $F \propto E$), which can trigger sparks when the magnitude of the field is greater than the threshold of ionizing air.

A few students were able to answer with “shortening the poles,” but most could not invoke the electric field by linking $V$ using $E = \Delta V / \Delta r$. Wimshurst’s electrostatic generator is a popular demonstration in Taiwan; thus, students may recall the phenomenon from high school but fail to grasp the key underlying concepts.

At this stage in the sequence, the term “dielectric strength” is introduced. For dry air, the dielectric strength (referred to as the breakdown threshold) is $E = 3 \times 10^6$ N/C.

**Question 3.** If sparks have not yet appeared, the electric potential remains very high. How could a high potential difference $E$ of electrostatics? Answer: This question highlights the critical role of $E$ and $V$.

The purposes of this sequence include showing that the electric potential is determined by the accumulation of charge ($V \propto q$), the distance $\Delta r$ between the two points with potential difference $\Delta V$ plays a significant role in linking $E$ and $\Delta V$ ($\Delta V = \Delta U / q$), $E$ is different from $F$, charge serves as the vehicle to transport energy ($\Delta U = q\Delta V$), and the role of $E$ is highlighted by the breakdown threshold. Equations and verbal explanations are tightly incorporated to clarify the concepts. Because the concepts are demanding, two more demonstrations and questions are given to students after they have worked on a few traditional problems.

**Question 4.** (a) Why does the stun gun (shown in Fig. 2) produce sparks? Stun guns produce an electric potential difference from 200 to 300 kV, which can momentarily disable a person with an electric shock. (b) To estimate the minimum electric potential of the stun gun, which quantity of the gun should be measured, and how can you calculate the electric potential? Answer: (a) To create sparks the electric field $E$ needs to exceed the breakdown threshold. Because $\Delta V$ of the stunner is very high, the value of $E$ between the poles is high ($\Delta V = E\Delta r$). (b) The distance between the two poles needs to be measured ($\Delta r = 3.6 \text{ cm}$). The dielectric strength of dry air ($E \approx 3 \times 10^6 \text{ V/m}$) can be utilized to estimate the minimum electric potential of the equipment, $\Delta V \approx E\Delta r = 1.1 \times 10^3 \text{ V}$.

Although the students applied the same ideas in Question 2 a few days earlier, Question 4 is very challenging. The students tend to link high $V$ to sparking and fail to use $\Delta V = E\Delta r$.

**Question 5.** An electric insect eliminator (shown in Fig. 3) is composed of parallel metal wires. Each neighboring pair of wires possesses a potential difference of a few kilovolts, which delivers high electrical power to eliminate insects, such as mosquitoes. (a) Explain why this potential can eliminate insects. (b) Why cannot an electric insect eliminator produce sparks in the same way a stun gun does? (c) How can we trigger sparks between neighboring wires without connecting them to conductors? (d) If the potential difference between the neighboring wires is 5000 V, estimate how close they should be to trigger sparks. Answer: (a) While the insects get an electric shock, the transferred energy $\Delta U$ (or electrical power $P$, which is the transferred energy rate, $P = \Delta U / \Delta t$) determines the level of harmfulness. The electric potential between the two wires results in insects, which behave as conductors with a small resistance $R$, receiving a fatal electric shock ($P = V^2 / R$). (b) The potential difference of Fig. 2. A stun gun is used to illustrate the dielectric strength of air and to use the relation between $E$ and $V$.

Fig. 3. An electric insect eliminator is used to illustrate to distinguish the concepts of $E$ and $V$ and to highlight the key role of $E$ in determining sparking.
a few kilovolts is insufficient to give the breakdown threshold \( E = \Delta V / \Delta r \approx 10^3 / 10^{-2} - 10^5 \text{ V/m} \). (c) The key to triggering sparks is the electric field, which can be increased by decreasing the distance between the wires \( E = \Delta V / \Delta r \); \( E \approx 1 / \Delta r \) for fixed \( \Delta V \). (d) From the threshold of dry air and \( E = \Delta V / \Delta r \), the gap between the gates must be \( \Delta r = \Delta V / E = 1.7 \times 10^{-3} \text{ m} \). A photo can be provided to confirm this estimate (see Fig. 4).

The purposes of Questions 4 and 5 include reinforcing the concept of \( E \) in electrostatics and distinguishing between \( E \) and \( V \) and the relations between them. Immediately after Question 4, many students were able to answer Questions 5(c) and 5(d). Repeated practice is required to help the students’ conceptual understanding and reinforce their confidence in learning electrostatics.

B. Structuring key terms and relations: Assembling the formula diagram

After the definitions and relations of the four key terms of electric force \( F \), electric field \( E \), electric potential energy \( U \), and electric potential \( V \) have been introduced and practiced, the instructor guides the students to draw a “formula diagram” (see Fig. 5), which can serve as a way to activate students in their thinking and interactions. To draw the formula diagram, the students were guided by the instructor by the following three steps: (1) locate the four terms: the instructor placed \( F \) in the upper left corner and \( U \) in the lower left, then asked the students to locate \( E \) and \( V \) in the two right corners, respectively, based on their relations; (2) select a formula to connect each pair of key terms in the corners; and (3) modify the formulas to improve their precision and sophistication. For example, replace \( \Delta V = E \cdot \Delta r \) by \( \Delta V = -\int E \cdot dr \); clarify the meanings of the terms and formulas, for example, \( q \) means the source of \( E \) in Eq. (1) but a detector of \( E \) in Eq. (2); and add the reverse formulas, for example, \( F = qE \) implies \( E = F / q \).

While assembling the formula diagram, common difficulties faced by the students are the equations linking \( F \) and \( \Delta U \) and \( E \) and \( \Delta V \). These relations were less recognized than those linking \( F \) and \( E \) and \( \Delta U \) and \( \Delta V \). Also the relations \( E = F / q \) and \( \Delta V = \Delta U / q \) were more frequently adopted than their reverse, for example, \( F = qE \). Inadequate causal assertions were made, for example, attributing \( q \) as the cause of \( E \) in \( E = F / q \), and the forms of some expressions were incomplete.
C. Further practice: Demonstration of plasma globe

After completing the formula diagram, a demonstration involving a plasma globe was included in the teaching.23 The questions are assembled into a worksheet for small group (three to four students per group) discussion. After a brief introduction of the questions by showing demonstrations, the instructor gave the students about 40 min to work on the worksheet. The questions, answers, and students’ responses are provided in Appendix A, comprising Questions 6–11, along with Figs. 6–11.

V. MODIFICATIONS AND PEGADOGICAL PURPOSES

Major modifications included adding more questions, explicitly addressing key variables in the questions or giving more hints, shifting questions from requiring explanation to problem solving, and merging derivations and verbal elaborations in answering the questions.

Extra questions were added to correspond to the identified learning difficulties. For example, because Question 11 (in Appendix A) (indirectly lighting up the tube) was very challenging, the task of extinguishing the fluorescent tube (Question 10) was added. Both questions are aimed at overcoming the same pitfall, that is, confusing the potential V with the potential difference ΔV. During early implementations, a popular invalid strategy to light up the tube (Question 11) suggested by students is letting the other hand of the second (left) person touch the globe to form a “closed loop” (see Fig. 10). Although the strategy reflects the notion of “current appears in a closed circuit only,” the strategy is incorrect due to the zero potential difference. After adding Question 10, the students become more capable of solving Question 11. When seeing the tube successfully lit up, as they predicted, they usually cheer out loud, providing a thrilling ending to the unit.

Information was supplemented by the instructor to facilitate discussions as well as to strengthen the integration of related principles. For example, explanations of the pattern and colors of the glow of the plasma globe (shown in Fig. 6) were initially given as two separate questions, which were difficult and irrelevant. Question 7 is now aimed at connecting the pattern and colors of the glow to help link the electric flux Φ_{E} and potential energy difference ΔU by showing the glow to help visualize Φ_{E}, explicitly relating phenomena to...
the key terms. In other words, the pattern of the glow illustrates the distribution of the electric field $E$, and the colors indicate the energy difference $\Delta U$. A follow-up task is to guide students to connect $E$ and $\Delta U$, which is (pattern $\rightarrow \Phi_E \rightarrow E \rightarrow F \rightarrow$ work $\rightarrow \Delta U \rightarrow$ color variations).

In addition to the usual questions asking students to explain why specific phenomena occur, I modified two questions from requiring explanation to problem solving, including extinguishing the tube (Question 10) and indirectly lighting up the tube (Question 11). Problem solving questions are beneficial to stimulating curiosity and engaging cognition, as is discussed later based on the students’ comments.

The role of incorporating equations and verbal interpretations in explaining the demonstrations was promoted. During the modifications, the students were asked to incorporate the two tools of derivations and verbal elaboration to answer Questions 6–11. The formula diagram was added to illustrate the relations of the key terms. The formula diagram serves as mediated scaffolding to facilitate the effectiveness of small group discussion.

In summary, the modifications were done mainly to provide more guidance in terms of specifying the required scientific tools and identifying the key phenomena, which are essential for effective reasoning.

The pedagogical purposes of the complete demonstrations/questioning teaching sequence aim at highlighting the significance of $E$ (rather than $V$) as the direct threshold of the conducting dielectrics; illustrating the notion of potential difference $\Delta V$ rather than $V$ in determining both the electric field $E$ and electrical energy $\Delta U$; and demonstrating the meanings, functions, and uses of Eqs. (2)–(7), for example, the pattern of the plasma glow (Fig. 6) helps students visualize the meanings of $\Phi_E$ and $E$ and the relation between them and the meanings of Eq. (3); Questions 4(b) and 5(d) help relate $E$ and $\Delta V$ in Eq. (7).

A summary of how the demonstrations and questions repeatedly reflect each pedagogical purpose/principle is presented in Table III, which shows that most pedagogical purposes are addressed and practiced repeatedly with questions in different contexts. For example, the relation between $E$ and $\Delta V$ [Eq. (7)] is used five times with five different phe-

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**Table III. Summary of the demonstrations and questions and their pedagogical purposes.**

<table>
<thead>
<tr>
<th>Pedagogical purpose/principle</th>
<th>Demonstrations</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (rather than $V$) as the threshold</td>
<td>Figures 1, 2, 10, and 11</td>
<td>2, 4, and 11(a)</td>
</tr>
<tr>
<td>$\Delta V$ (rather than $V$) in determining $E$ and $\Delta U$</td>
<td>Figures 9–11</td>
<td>10 and 11(b)</td>
</tr>
<tr>
<td>Equation (2): $F=qE$</td>
<td>Figures 1 and 6</td>
<td>2(a), 7(a), and 7(b)</td>
</tr>
<tr>
<td>Equation (3): $E=\Phi_E/q$</td>
<td>Figure 6</td>
<td>7(b)</td>
</tr>
<tr>
<td>Equation (4): $\Delta U=-\int F_r \cdot dr$</td>
<td>Figures 6 and 8</td>
<td>6(b), 7(b), and 9(a)</td>
</tr>
<tr>
<td>Equation (5): $\Delta V=\Delta U/q; \Delta U=q\Delta V$</td>
<td>Figures 1 and 7</td>
<td>3 and 8</td>
</tr>
<tr>
<td>Equation (6): $V=kq/r$</td>
<td>Figure 1</td>
<td>2(b)</td>
</tr>
<tr>
<td>Equation (7): $\Delta V=-\int E \cdot dr$</td>
<td>Figures 1–3, 6, 10, and 11</td>
<td>2(c), 4(a), 5(c), 6(a), and 11(a)</td>
</tr>
</tbody>
</table>

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**Table IV. Percentages of correct response to each question and $\chi^2$ test of the experimental and control groups.**

<table>
<thead>
<tr>
<th>Question</th>
<th>Experimental group (N=60)</th>
<th>Control group (N=83)</th>
<th>$\chi^2$ test</th>
<th>Significance</th>
<th>Learning demands$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85.0</td>
<td>66.2</td>
<td>15.7</td>
<td>$^b$ (7)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>56.7</td>
<td>49.4</td>
<td>2.11</td>
<td>n.s.</td>
<td>CC</td>
</tr>
<tr>
<td>3(a)</td>
<td>86.7</td>
<td>88.5</td>
<td>0.10</td>
<td>n.s.</td>
<td>CC</td>
</tr>
<tr>
<td>3(b)</td>
<td>38.3</td>
<td>8.4</td>
<td>116</td>
<td>$^b$ (5)</td>
<td></td>
</tr>
<tr>
<td>3(c)</td>
<td>65.0</td>
<td>10.8</td>
<td>303</td>
<td>$^b$ (4)/(2 and 7)</td>
<td></td>
</tr>
<tr>
<td>4(a)</td>
<td>75.0</td>
<td>68.7</td>
<td>1.86</td>
<td>n.s.</td>
<td>RF</td>
</tr>
<tr>
<td>4(b)</td>
<td>63.3</td>
<td>26.5</td>
<td>69.6</td>
<td>$^b$ (2)</td>
<td></td>
</tr>
<tr>
<td>5(a)</td>
<td>63.3</td>
<td>39.7</td>
<td>23.2</td>
<td>$^b$ (7)</td>
<td></td>
</tr>
<tr>
<td>5(b)</td>
<td>80.0</td>
<td>43.3</td>
<td>54.6</td>
<td>$^b$ RF(5)</td>
<td></td>
</tr>
<tr>
<td>6(a)</td>
<td>30.0</td>
<td>8.4</td>
<td>60.2</td>
<td>$^b$ (5)</td>
<td></td>
</tr>
<tr>
<td>6(b)</td>
<td>66.7</td>
<td>33.7</td>
<td>48.5</td>
<td>$^b$ (6)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>75.0</td>
<td>56.6</td>
<td>13.7</td>
<td>$^b$ RF(5)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>51.7</td>
<td>45.8</td>
<td>1.39</td>
<td>n.s.</td>
<td>CC</td>
</tr>
<tr>
<td>9(a)</td>
<td>91.7</td>
<td>50.6</td>
<td>67.5</td>
<td>$^b$ (7)</td>
<td></td>
</tr>
<tr>
<td>9(b)</td>
<td>75.0</td>
<td>44.6</td>
<td>37.5</td>
<td>$^b$ (2)</td>
<td></td>
</tr>
</tbody>
</table>

$^a$The learning demands entail conceptual clarification (CC), representational familiarity (RF), and invocation of the equations in Sec. IV.

$^b$Significant at probability < 0.001; n.s.: not significant at probability=0.10.
omena. In addition, the integration of multiple principles is required to explain many demonstrations, for example, integration of Eqs. (2)–(4) and (7) to explain the patterns and colors of the glow in Fig. 6.

VI. OUTCOMES OF THE TEACHING INTERVENTION

Two questionnaire surveys were administered to investigate the participants’ opinions about the teaching intervention. One week after the completion of the unit, an open-ended questionnaire was distributed to the experimental group. The students were invited to anonymously comment on the equipment, question design, and features and quality of the teaching performance, what and how well they learned from the unit, how university and high school learning in electrostatics compare, and suggestions for modifying the teaching intervention. There were 52 students (out of 60) who completed the questionnaire. The students’ comments were qualitatively categorized in terms of cognitive outcomes, affective outcomes, and learning engagement. (Affective outcomes mean the students’ subjective judgment of their emotional feeling about the nature of the teaching and their own learning, such as feelings of interest, usefulness, confidence, and effectiveness.)

Three months after the end of the semester, an anonymous closed-form survey was administered to both the experimental (N=40) and control (N=41) groups. The instructor’s competency and the students’ learning achievements were investigated. The questions were devised by the author and used a five-point Likert scale, ranging from “strongly agree” (five points) to “strongly disagree” (one point). The average score and two-tailed t-test were used to examine the significant differences between the degrees of satisfaction of the two groups.

<table>
<thead>
<tr>
<th>Table V. Evaluation of instructor’s teaching: Average score in a five-point Likert scale and probability of t-test.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental (N=41)</strong></td>
</tr>
<tr>
<td>1. Solid knowledge in physics</td>
</tr>
<tr>
<td>2. Lucid instruction</td>
</tr>
<tr>
<td>3. Introduces real-life examples</td>
</tr>
<tr>
<td>4. Enthusiastic about teaching</td>
</tr>
<tr>
<td>5. Integration of formulas</td>
</tr>
<tr>
<td>6. Monitors learning outcomes</td>
</tr>
<tr>
<td>7. Promotes in-class interaction</td>
</tr>
</tbody>
</table>

A. Academic performance

The test was designed to encompass the major pedagogical purposes of the intervention design, summarized in Table III, involving conceptual clarification, representational familiarity, and use of formulas. Appendix B and Table IV present the test, the demands of each question, the percentage of correct responses, and the chi-square test between the experimental and control groups.

The results of the experimental group were found to be significantly superior to those of the control group on the test. For example, students were required to determine the direction of the electric field given a pattern of equipotential lines [Question 5(b)], for which 80% of the experimental group answered correctly compared to 43% of the control group. The average scores (standard deviation) of the experimental and control groups were 66.9(18.5) and 42.6(18.5), respectively. A one-tailed t-test yielded $t=4.46$, indicating that the experimental students outperformed their counterparts at a significant level of $p<0.001$. In addition, the order of difficulty of individual questions with respect to each group was evaluated, and the Pearson product-moment correlation $r$ was adopted for the difficulty order between the two groups. The correlation coefficient is $r=0.753$, indicating consistency among the questions for the two groups. Thus, the superiority of the experimental group as measured by the average score can be attributed to the outperformance of most questions rather than excellence in particular questions.

The $\chi^2$ test was utilized to analyze the difference for each subquestion between the two groups. The experimental group performed significantly better at $p<0.001$, in 11 out of the 15 subquestions. Three out of the four questions that showed insignificant differences asked for conceptual clarifications only. Questions 2, 3(a), and 8 require a qualitative understanding of individual concepts, that is, the meaning of

<table>
<thead>
<tr>
<th>Table VI. Students’ self-evaluation of learning achievements: Average scores in a five-point Likert scale and probability of t-test.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental</strong></td>
</tr>
<tr>
<td>1. Understanding of physics concepts/principles</td>
</tr>
<tr>
<td>2. Cultivates thinking/reasoning ability</td>
</tr>
<tr>
<td>3. Enhances mathematical ability</td>
</tr>
<tr>
<td>4. Adoption of flexible learning strategies</td>
</tr>
<tr>
<td>5. Solidifies foundation for advanced courses</td>
</tr>
<tr>
<td>6. Promotes interest in learning</td>
</tr>
<tr>
<td>7. Enriches knowledge of applications</td>
</tr>
</tbody>
</table>
F, E, V, and U, where use of formulas and integration of multiple concepts is unnecessary. Although both groups appear to perform equally well in terms of conceptual clarification, the teaching intervention seems to benefit the tasks of invoking key formulas and familiarity of representation. The performance of the control group was slightly better than their peers in the U.S. for the questions from CSEM.\textsuperscript{33}

B. Results of closed-form survey

The experimental group (N=40) responded significantly more positively than the control group (N=41) in evaluating the teaching competency and their own learning achievements on the closed-form questionnaire survey (see Table V). The strengths of the instructor/teaching were significant in introducing real-life examples and promoting interactions (Questions 3 and 7), reflecting the key strategies that the teaching intervention adopted. The students’ praise of the teaching competency was consistent with their satisfaction with their learning achievement, as shown in Table VI. The experimental group ranked higher in learning achievement in all aspects. Outcomes were found to be particularly significant in terms of cultivating thinking/reasoning ability, conceptual understanding, informing application knowledge, and promoting interest, while mathematical ability was not sacrificed.

C. Responses to open-ended survey

The open-ended survey showed that 83\% of the experimental group self-reported positive cognitive outcomes, affective outcomes, and learning engagement, reflecting the goals of the teaching design. For example,

“Super! Exploring the (plasma globe) experiment can help us understand many concepts in electricity and learn how to apply the four key formulas (of the formula diagram).” (S1)

“I have a better understanding of the principles and their application. High school (physics) only teaches us to recite many formulas, which become very confusing. Whereas now, due to the understanding, (I can) adopt the formula I need by reasoning.” (S2)

“Compared with high school, (university physics) is no more suffering with lots of cold formulas; rather, (I have) practiced many real-life questions, (and) come to understand electricity step by step.” (S3)

“The plasma globe has made electric field visible, and I can sense that electric field really causes electric force.” (S4)

These quotes imply that the students understand the concepts by means of reasoning (S2), revisiting (S3), and visualizing (S4) the ideas, and an understanding of the concepts helps them to grasp the meanings and functions of using the key formulas (S1 and S2). Their comments reflect the strategies of the teaching intervention, which is effective in facilitating understanding and becoming acquainted with the scientific tools. In addition, meaningful learning was found, in contrast with the “confusing” and “suffering” experience in high school.

In addition, 62\% of the students commented on the affective outcomes of the innovation teaching. For example,

“The atmosphere in the class is active. I feel happy learning, and I have learnt a lot.” (S5)

“The relaxed way of teaching relieves my stress (with physics), helping me learn more, and recover my confidence.” (S6)

“The concepts that we have learnt in electrostatics will be very useful for (our) advanced courses, such as circuit design.” (S7)

When students responded to the affective outcomes of the teaching intervention, some of them linked it with their satisfaction with either their current learning achievement or as a foundation for advanced courses. Reinforcing the value of the course and cultivating a supportive classroom atmosphere are both critical ingredients for promoting learning motivation.

71\% of the participants commented that they were highly engaged in thinking and discussing the questions proposed by the instructor. For example,

“Everyone tried so hard to think about and discuss how to (indirectly) light up the tube. Every group was highly engaged in the discussion. During the break time, many of us crowded around the equipment to try out our methods. That was really fun!” (S8)

“Amazing equipment, engaged everyone to think deeply. But I feel sorry that there is only one set (of the plasma globe), so that I can’t explore it by myself.” (S9)

These quotes suggest that the combination of appealing equipment and inspiring questions effectively engages the students in thinking and discussion.

In summary, appealing equipment and demonstrations, relevant and inspiring questions, and a friendly classroom atmosphere all contribute to facilitate learning engagement and benefit learning outcomes.

Despite the positive comments regarding the teaching intervention, 28\% of the experimental group expressed their need for more guidance/information. For example,

“I wish that the questions can provide more hints, because, for students like me with little imagination, we often don’t know in which direction to start thinking.” (S10)

This quote suggests that conducting effective discussion is not easy. Although the teaching unit has been modified many times over the three years of implementation, mainly by add-
ing more hints to the questions, further guidance is still required for some students. Despite the repeated practice of each principle (illustrated in Table III), most of the students still perceive the questions as very challenging, and none of them complained about the repetition.

VII. CONCLUSION

To help students understand electrostatics, we introduced a teaching intervention involving a series of demonstrations and questions. The positive learning outcomes may be due to three features of the intervention. First, the intervention integrates everyday phenomena via demonstrations with official learning tasks, such as understanding the principles and solving examination questions. This connection helped to highlight the status of demonstration in physics classes. Second, while explaining the questions included in the demonstrations, verbal clarifications was given along with mathematic derivations. Formulas serve as tools to enhance the precision, consistency, and sophistication of verbal interpretations, and the latter helps to shape the meanings of the formulas. Third, while the teaching strategy aims at engaging students in thinking and discussion, guidance by the instructor, such as initiating the required scientific tools or identifying the key features, was not overlooked. Before posing questions to students, instructors need to ensure that the students are equipped with the tools (for example, terms, principles, and formulas) and mathematical abilities sufficient for effective thinking and discussion.

This study illustrates how demonstrations can facilitate physics teaching. Demonstrations were found to help the students visualize abstract and novel concepts, such as the electric flux and field. A combination of demonstrations and questions was found to be effective in engaging thinking and promoting interaction. In addition to conventional questions asking for explanations of the observed phenomena, we found that problem solving questions (for example, Questions 10 and 11) are especially effective in engaging thinking and discussion (commented on by S8 and S9). Providing equipment for each group to allow hands-on work is recommended (corresponding to S9’s request) if the time constraints are not too tight. The demonstrations were found to include several physical principles (commented on by S1), agreeing with Ref. 3. While explaining a phenomenon, students practice the connections of the related principles and distinguish their differences. Lastly, by means of a series of demonstrations, multiple opportunities were provided for students to practice and revisit the concepts/formulas (shown in Table III), which helped them to clarify the meanings and uses and to highlight the functions and significance of the key concepts, such as E, V, and the related formulas. That is, multiple opportunities to practice in different contexts facilitate the students to become acquainted with the key tools.

Although this study describes the positive outcomes of the intervention, the author does not intend to provide a "prescription" for physics instructors to directly copy the sequence. The feasibility and outcomes of the teaching design may vary due to different contexts. A mature teaching sequence design may not be obtained until after several years of implementation and modifications. Grasping the appropriate level of difficulty of the questions to suit the students can be challenging. Continuous modifications by instructors based on the evaluations of prior implementations are necessary. Saving a few minutes before the end of the class to ask the students to write down their questions and suggestions is highly recommended.

ACKNOWLEDGMENTS

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APPENDIX A: QUESTIONS, ANSWERS, AND STUDENTS’ RESPONSES OF THE DEMONSTRATION OF THE PLASMA GLOBE

Question 6. The technology required to make a plasma globe glow (see Fig. 6) includes (a) high V at the center to conduct the glow and (b) low gas pressure (of Ne or Ar) to allow glowing. Select appropriate formulas and use both a mathematical derivation and verbal description to explain this technology. Answer: (a) Based on \( E = \nabla V / \Delta r \), high \( \Delta V \) allows strong \( E (E \propto \Delta V) \), which reaches the breakdown threshold and thus makes the plasma globe conduct. (b) Low gas pressure implies low density of the gas, which allows large distances for acceleration of gas particles between collisions. In the “free” acceleration region (\( \Delta r \)), the electric potential energy \( \Delta U = F \Delta r \) is transformed into kinetic energy, which leads to the emission of photons with visible wavelengths \( \Delta U = E_k > U_{\text{photon}} \).

Question 7. The glow (see Fig. 6) indicates the path of the free electrons, which illustrates the pattern of the electric flux \( \Phi_E \) in the globe. (a) Derive the electric field as a function of \( r \), where \( r \) is the distance from the center of the globe. (b) According to the dependence of \( E \) on \( r \), explain the colors of the glow. Why is the inner part purple and the outer part red? Answer: (a) The path of the free electrons is determined by the electric force, which is parallel with the direction of the electric fields (when the initial velocity is negligible). Here,

\[
r = \frac{1}{2} \frac{2}{3} a r^2 = \frac{1}{2} \left( \frac{q (F/m) a^2}{r^2} \right).
\]

Therefore, the path of the glow (r) is parallel to the electric field (E). Because the pattern of the glow shows a radial dependence, \( E \) (the density of flux) gradually weakens along the radial direction and the relation between \( E \) and \( r \) is

\[
E = \frac{\Phi_E}{A} \propto \frac{1}{r^2} \Rightarrow E \propto \frac{1}{r^2}.
\]

(b) By connecting electric force and electric field,

\[
F = qE \Rightarrow F \propto \frac{1}{r^2}.
\]

The glow of the globe is “stimulated light” based on the photon theory of light \( U_{\text{photon}} = hf \) (h is Planck constant and f is the frequency). Due to the electric force, the free electrons are accelerated, accumulate kinetic energy, and then transfer the kinetic energy to emit a photon (\( U_{\text{photon}} \)).

\[
U_{\text{photon}} \leq |\Delta U| = \int F \cdot dr \Rightarrow U_{\text{photon}} \propto F.
\]

From Eqs. (A3) and (A4),
After instruction, the students raised two questions: If we wait longer, will the bulb accumulate enough heat to radiate visible light? Is not glass an insulator? How could an electric current pass through glass to the tube? Accordingly, further explanation was provided on the quick balance between the electrical power and the rate of dissipation of bulb filaments and the inappropriate separation of conductors and insulators. That is, for strong electric fields, insulators such as glass or air can become conductive.

**Question 9.** How can a plasma globe (a) light up a fluorescent tube (see Fig. 8) but (b) fail to light up a bulb? Answer: (a) A fluorescent tube is based on the nature of photons. The energy of a photon \( U_{\text{photon}} = hf \) is transformed from the kinetic energy of the colliding free electrons, that is, free electrons are accelerated by the electric force, accumulating their kinetic energy, which can be transformed to a photon while stimulating the gas atoms,

\[
U_{\text{photon}} \leq E_k = \int \mathbf{F} \cdot d\mathbf{r} = U_{\text{photon}} \propto F.
\]  

To light up the tube, \( \mathbf{E} \) needs to be strong enough to ionize the mercury vapor. The high \( \Delta V \) of the globe refers to sufficient \( \mathbf{E} \) \((E=\Delta V/\Delta r)\). (b) The light of the bulbs is due to the thermal radiation of the filament, which needs sufficient electrical power \((P=IV)\) to be heated to \(\sim 10^2\) °C to radiate visible light. The current of the globe is too low to obtain the required power.

After instruction, the students raised two questions: If we wait longer, will the bulb accumulate enough heat to radiate visible light? Is not glass an insulator? How could an electric current pass through glass to the tube? Accordingly, further explanation was provided on the quick balance between the electrical power and the rate of dissipation of bulb filaments and the inappropriate separation of conductors and insulators. That is, for strong electric fields, insulators such as glass or air can become conductive.

**Question 10.** How can one extinguish the tube without moving the tube away? Answer: Reducing the potential difference is a way to extinguish the tube. This reduction can be achieved by touching the globe with the left hand, that is, increase the potential of the right end to reduce the potential difference of the two ends \((E=\Delta V/\Delta r=\Delta V=V_{\text{left}}-V_{\text{right}})\) (see Fig. 9). The task of extinguishing the tube highlights the significance of the potential difference \(\Delta V\) and the potential \(V\).

**Question 11.** If the tube is not touching the globe but is being held by two people, where the person on the right is touching the globe (see Fig. 10) and what strategies can help light up the bulb? What are the principles (formulas) underlying the strategies? Answer: To indirectly light up the tube, \( \mathbf{E} \) between the two hands on the tube needs to be increased. Possible strategies include shortening the gap between the two hands \((E=\Delta V/\Delta r)=(E)\) or increasing \(\Delta V\) of the two hands by “isolating” the person touching the globe. A method of isolating is jumping. With careful trials (including selection of appropriate shoes), both strategies can be effective.

**APPENDIX B: THE QUESTIONS AND ANSWERS OF THE ACHIEVEMENT TEST**

1. The dotted lines show the equipotential lines of the electric field, as shown in Fig. 12. What is the magnitude of electric field at \( B \) for the three cases?
   - (a) \( I>III>II \)
   - (b) \( I>II>III \)
   - (c) \( III>I>II \)
   - (d) \( II>I>III \)
   - (e) \( I=II=III \)
   **Answer:** (d) \((E=\Delta V/\Delta r=1/\Delta r)\).

2. Point \( a \) is at the center between the two charges \(\pm Q\) and point \( b \) is anywhere between point \( a \) and \( +Q \), as shown in Fig. 13. Determine whether the electric field \( E_a \) and potential \( V_a \) are zero.
   - (a) \( E_a=0 \) and \( V_a=0 \)
   - (b) \( E_a=0 \) but \( V_a \neq 0 \)
   - (c) \( E_a \neq 0 \) but \( V_a=0 \)
   - (d) \( E_a \neq 0 \) and \( V_a \neq 0 \)
   **Answer:** (c) \( E_a \) is vector sum; \( V_a \) is scalar sum.

3. As shown in Fig. 14, a proton is at rest at the center of a parallel-plate capacitor, and the potentials on each plate and distance between the plates are given. (a) What is the direction of the electric force exerted on the proton? (b) Evaluate the kinetic energy of the proton when colliding with the plates (neglect \( F_p \)). (c) Determine the magnitude of the electric force on the proton during the acceleration.
   **Answer:** (a) Upward; (b) \( E_k=|\Delta U|=e\Delta V=25 \text{ eV} \)
   (c) \( F_e=|\Delta E|=e(\Delta V/\Delta r)=2.67 \times 10^{-15} \text{ N} \).
4. A charged particle of \( m = 3 \times 10^{-6} \) g, \( q = 25 \) nC is at rest due to the uniform electric field and gravitational field. The particle is in equilibrium when the inclined angle to the vertical axis is \( \theta = 30^\circ \), as shown in Fig. 15. (a) Draw the free-body force diagram on the charged particle. (b) Evaluate the electric field of the space.

Answer: (b) \( E = \frac{Fe}{q} = 0.679 \) N/C.

5. The dotted lines show the equipotential lines in Fig. 16. Evaluate the electric field at the center dot, including (a) its magnitude and (b) direction.

Answer: (a) \( E = \frac{\Delta V}{\Delta r} = \frac{[200 - (-200)]}{2 \times 10^{-2}} = 200 \) \( \text{V/m} \); (b) pointing to the lower left, perpendicular to the equipotential lines.

6. As shown in Fig. 17, a ring with radius \( r \) carries a uniform positive charge, located at the \( y-z \) plane and centered at point \( o \). If the electric potential at point \( P \) is \( V_p \), (a) what is the change of potential energy when an electron is moved from infinite distance to point \( P \)? (b) Compare the electric potential between points \( o \) and \( P \).

Answer: (a) \( \Delta U = eV_p \); (b) \( V_o > V_p \) (\( V_o = kQ/r \times 1/r \)).

7. The dotted lines in Fig. 12 show the equipotential lines of electric field. A positive charge is moved from point \( A \) directly to point \( B \). How does the amount of work to move this charge compare for the three cases?

(a) Most work required in I. (b) Most work required in II. (c) Most work required in III. (d) \( I = II < III \). (e) \( I = II = III \).

Answer: (e).

8. As shown in Fig. 13, points \( a \) and \( b \) are located between the two point charges \( \pm Q \). When shifting an electron from \( b \) to \( a \), how does potential energy change?

(a) Increased. (b) Decreased. (c) Unchanged.

Answer: (a).

9. Fill in the blanks to form a unit of electric field: \( E = (b) \) \( \text{N} \).

Answer: (a) Volt; (b) N.


Level Tester. From a 1924 catalogue of the Gaertner Scientific Corporation of Chicago: An instrument used for the calibration and testing of levels. The screw has a diameter of 6 mm and a pitch of 0.5 mm; the divided head has 100 parts, one division corresponding to 3 seconds. The instrument is furnished with an iron base fitted with leveling screw. $50.00. The catalogue notes that for measuring small angles, a properly mounted level is often preferable to sensitive optical methods. This instrument is in the Greenslade Collection. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College.)