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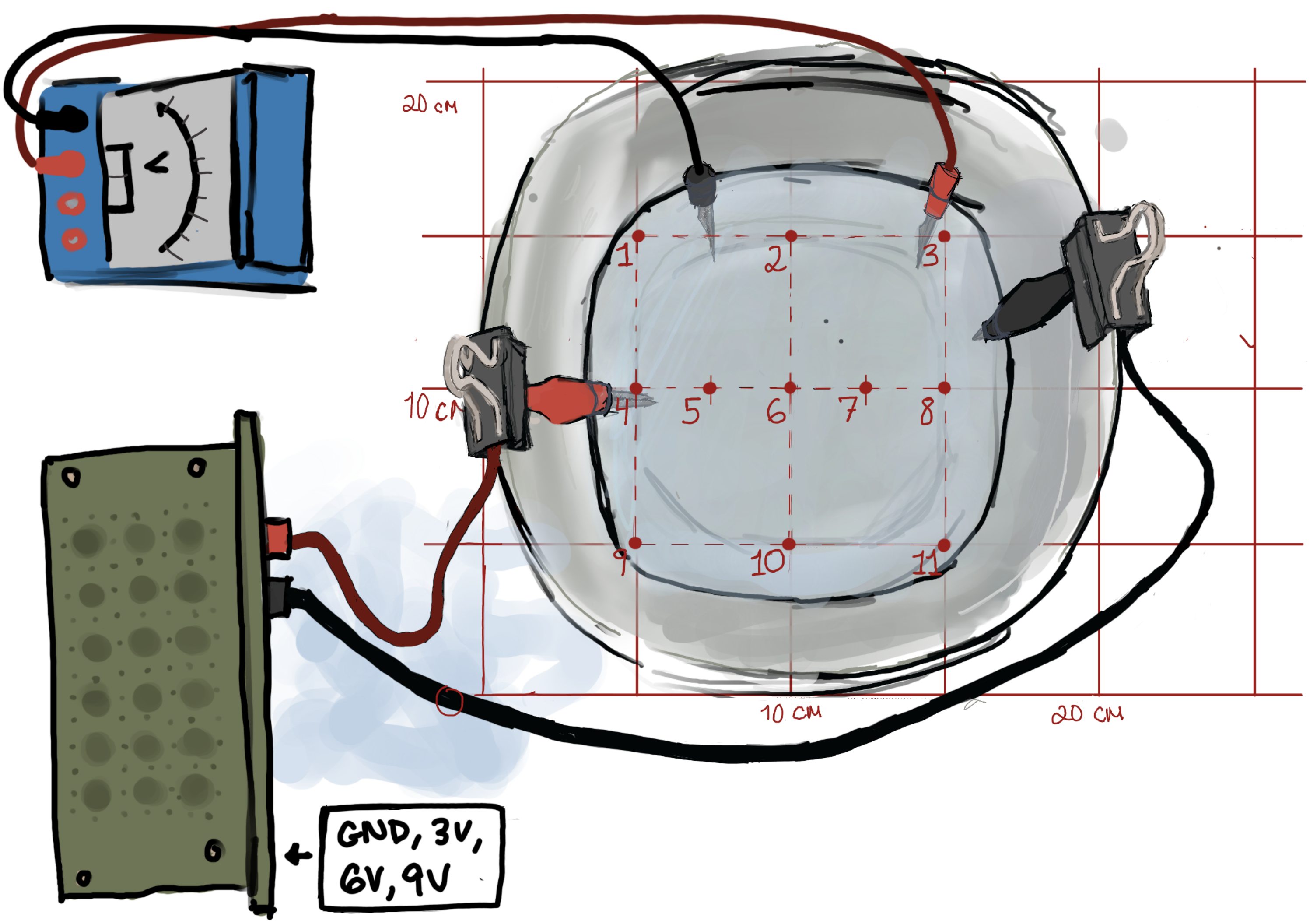

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From the cover: The electric potential, a scalar quantity, can be visualized by drawing equipotentials; isolines or level curves in which potential is a constant. The electric field, a vector field, points in a direction perpendicular to the equipotentials, down the gradient. These physics concepts might be important to consider when designing equipment that makes use of electric fields, such as in a low-cost gel electrophoresis rig. Here, researchers consider this problem. Electrophoresis is a technique where molecules can be sorted according to their charge and size. By characterizing the field and equipotentials within a prototype device, one could eventually predict the movement of various biomolecules of interest, such as fragments of DNA cut into parts at specific nucleotide sequences by restriction enzymes. *Cover image: Pooja Thaker.*

Equipotential
Square to the electric field
Charges move without work

Vikram Choudhury

Computational Mapping Analysis of Equipotential and Electric Field Lines in Gel Electrophoresis Rig

Saketh Ayyagari, Victoria Collemi, Krish Shah, and Kevin Tomazic

***Abstract*—Equipotential curves, also known as isolines, are lines of constant electric potential where a charged object does no work moving along them. These lines determine the direction of an electric field (represented by a vector field) as the direction of the field at a point will be perpendicular to an equipotential line. To simulate these equipotential lines, we used two oppositely charged hex nuts to observe the relationship between potential and electric fields. After measuring the potential at every point on a 6 x 6 cm plane, we used Matplotlib to generate graphs of both equipotentials and predicted electric field lines. These experimental findings can help predict the path DNA molecules will take through a gel electrophoresis rig.**

***Index Terms*—electric potential, equipotential lines, electric field visualizations, saline conductive medium, electrostatics, electric field mapping, data visualization in electrostatics, gel electrophoresis, electric field dynamics**

I. Introduction

THE ELECTRIC potential V of a particle can be described as the amount of electrical potential energy per unit coulomb of charge. This can be expressed by the following equation:

$$V = \frac{U_E}{q} = k\frac{Q}{r}, \tag{1}$$

where U_E is the electric potential energy between a charge Q and a small test charge q, and r is the distance from the point of interest to the location of the charge Q [1]. Multiple points along a plane where the potential V is equal can be represented by equipotential lines. Using these equipotential lines, the electric field $\vec{E}$ generated by the charge Q can be described as:

$$\vec{E} = -\vec{\nabla}V, \tag{2}$$

where $\vec{\nabla} = \frac{\partial}{\partial x}\hat{x} + \frac{\partial}{\partial y}\hat{y}$ and $\vec{\nabla}V$ is the gradient of the scalar potential function $V(x, y)$ [1], [2]. (1) and (3) indicate that a larger electric potential difference with respect to a particular direction results in a larger magnitude of the electric field antiparallel to that direction. This implies that the electric field will always point in the direction of decreasing electric potential and be perpendicular to the isolines. In this experiment, we analyze the equipotential regions and their relationship associated with the electric fields generated by different electrode configurations in a saline medium. Such analyses have practical findings when designing gel electrophoresis rigs as an electric field can predict the path a negatively charged DNA molecule will take when moving from the negatively charged region to a positively charged one [1], [3].

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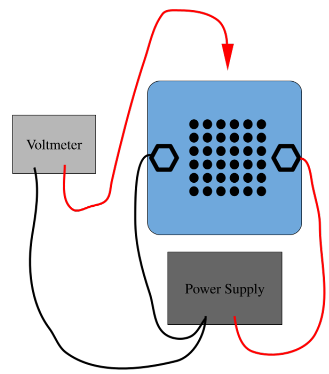

Fig. 1. Diagram of the experimental setup. Measurements were taken in a 3-cup polypropylene food storage container with a pre-marked $6\,\text{cm} \times 6\,\text{cm}$ grid. The container was energized using negative and positive electrodes connected to a power supply. For each point, potential difference was measured with respect to the negative electrode.

II. Methods and Materials

To measure the voltage, we used the setup diagrammed in Fig. 1, consisting of a 3-cup polypropylene food container (EasyFind; Rubbermaid; Atlanta, GA), laminated graphing paper, a Buck Engineering Lab-Volt 187 power supply, two M10 metal hex nuts, a DM 1800 digital multimeter, four leads, and a smartphone camera. We filled our container with ordinary tap water to approximately $1\,\text{cm}$ in depth and added a pinch of sea salt to create a weak saline solution. Power supply voltage was $8.89\,\text{V}$. We then attached two leads to connect the power supply to the hex nuts, which were placed on opposite sides of the container. On the graph paper, we marked 36 equally spaced points in a $6\,\text{cm} \times 6\,\text{cm}$ square grid to measure the voltage, which was placed under the container so the center of the square was under the center of the container. Using our smartphone, we took pictures of each measurement. After the first trial, we rotated the orientation of the hex nuts $90°$ clockwise, with the positive lead at the top of the container and the negative lead at the bottom. We repeated the same measurement process from the first trial in the second.

After collecting our data, we utilized the Numpy [4] and Matplotlib [5] libraries in Python to generate visuals of the equipotential and electric field lines. To generate coordinate pairs for our system, we used Numpy's `meshgrid()` method [5], which takes in lists of x and y coordinates where the

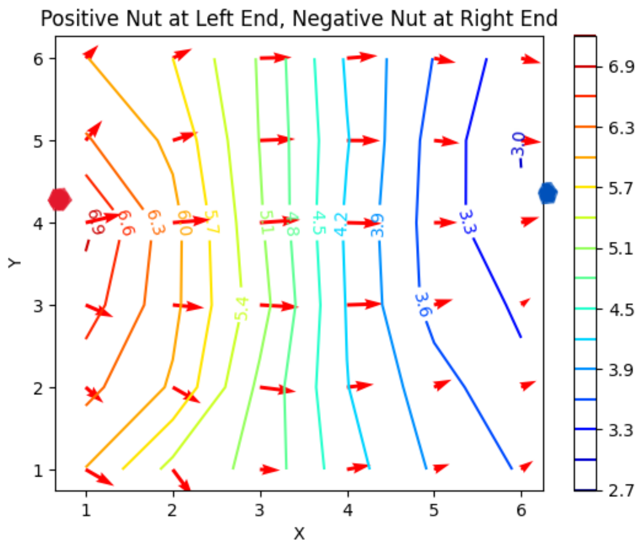

Fig. 2. Equipotential lines and electric field in the first configuration. The red and blue hexagons represent the positive and negative nuts, respectively

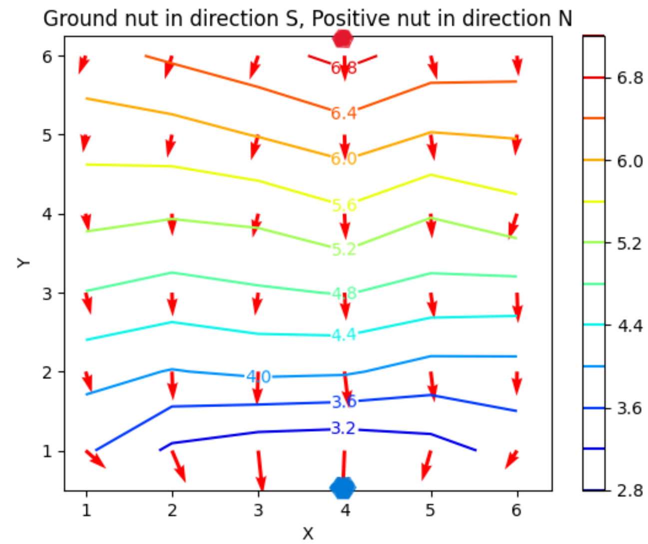

Fig. 3. Equipotential lines and electric field in the second configuration. The red and blue hexagons represent the positive and negative nuts, respectively

voltage was measured and returns arrays representing a mesh. For equipotential lines, we used Matplotlib's `contour()` method [5], which takes in the two arrays returned by the `meshgrid()` function along with a z value at each point. We also used the `colorbar()` method to show what color line represents which quantity of potential. To generate the electric field, we first approximated the partial derivatives of the potential with respect to the x and y directions, resulting in a vector at each point perpendicular to the level curve. We then used Matplotlib's `quiver()` method [5], which takes the outputs of the `meshgrid()` function along with matrices containing the components of the vector at each coordinate to generate a vector field.

III. Results

A. Positive Nut (Left), Negative Nut (Right)

For the first trial, the negatively charged nut was placed on the left and the positively charged nut on the right. Our power supply applied a measured voltage of $8.89\,\text{V}$ to our experimental system.

As seen in Fig. 2, equipotential lines of larger magnitude were closer to the positively charged nut and those of lower potential were closer to the negatively charged nut. Between the y-coordinate values of $3\,\text{cm}$ and $4\,\text{cm}$, we interpolated the experimental value of the equipotential line approximately equidistant to the two oppositely charged nuts to be $\frac{4.8+4.5}{2} = 4.65\,\text{V}$. In addition, as the position moved from the location of the positively charged nut to that of the negatively charged nut, the line density of the equipotentials decreased. To obtain an average rate of change of the electric potential in the direction of decreasing potential for this trial, we used the following equation:

$$-\frac{\Delta V}{\Delta s} = -\frac{V_{maxneg} - V_{maxpos}}{d}, \tag{3}$$

where ΔV is the potential difference between the maximum electric potential near the negatively charged nut and the maximum electric potential near the positively charged nut, and d is the straight line distance between the two nuts. Referencing Fig. 2 for the electric potential values, $V_{maxneg} = 3.3\,\text{V}$ and $V_{maxpos} = 6.9\,\text{V}$. To determine the value of d, we can treat the charged nuts as point charges, so d is the straight-line distance between them since there were six points of measurement separated by approximately $0.01\,\text{m}$ (or approximately 0.4 inch): $d = 5 * 0.01 = 0.05\,\text{m}$. Therefore, we can substitute the experimental values for V_{maxneg}, V_{maxpos}, and d to find that the average rate of change of the electric potential in the direction of decreasing potential, i.e. the electric field strength, is $72\,\text{V}\,\text{m}^{-1}$.

B. Positive Nut (Top), Negative Nut (Bottom)

For the second trial, the positively charged nut was placed on the top (North) and the negatively charged nut was placed on the bottom (South). Our power supply applied $8.46\,\text{V}$ to our experimental system.

As seen in Fig. 3, equipotential lines of higher electric potential were closer to the positively charged nut and those of lower electric potential were closer to the negatively charged nut. Between the x-coordinate (Fig. 3 is rotated $90°$ clockwise compared to Fig. 2) values at $3\,\text{cm}$ and $4\,\text{cm}$, we calculated the experimental value of the equipotential line approximately equidistant to the two oppositely charged nuts to be $\frac{5.2+4.8}{2} = 5\,\text{V}$. In addition, as the position moved from the location of the positively charged nut to that of the negatively charged nut, the line density of the equipotentials decreased.

To obtain an average rate of change of the electric potential in the direction of decreasing potential for this trial, we can use (3) from Trial 1. Referencing Fig. 3 for the electric potential values, $V_{maxneg} = 3.2\,\text{V}$ and $V_{maxpos} = 6.8\,\text{V}$. Since the value of d is the same for both trials, we can substitute the experimental values for V_{maxneg}, V_{maxpos}, and d to find that the average rate of change of the electric potential in the direction of decreasing potential is $72\,\mathrm{V\,m^{-1}}$. This value is the same rate of change of the electric potential as the first trial, demonstrating consistency across both a change in charge orientation (rotating the nuts' locations by $90°$) and the potential difference.

IV. Discussion

Based on the applied voltages from Trials 1 and 2, the theoretical value for the equipotential line equidistant to the two oppositely charged hex nuts is $4.45\,\mathrm{V}$ and $4.23\,\mathrm{V}$, respectively, since they are expected to be exactly half of the total voltage supplied to each system (Trial 1: $8.89\,\mathrm{V}$; Trial 2: $8.46\,\mathrm{V}$). To determine the percent error of our observed voltage values, we can use the percent error equation:

$$\delta = \frac{v_a - v_e}{v_e} \times 100, \tag{4}$$

where δ is the percent error, v_a is the experimental voltage, and v_e is the expected voltage. Substituting in the proper values, we found that δ_1 = 4.49%, indicating that our experimental voltage was close to the expected value for Trial 1. In contrast, we found that δ_2 = 18.20%, indicating that our experimental voltage was not as close to the expected value for Trial 2.

According to theory, the electric field points in the direction of decreasing electric potential (1) and is perpendicular to the equipotential lines. To be consistent with the equipotentials in Figs. 2 and 3, the electric field must point in the direction of decreasing electric potential. In addition, the magnitude of the electric field at a point in space should be higher in regions where the equipotential lines are more densely packed together (near the positively charged nut) and lower in regions where they are more spaced out (near the negatively charged nut).

In Figs. 2 and 3, as the position moves down the gradient of electric potential, the density of the isolines decreases. This is consistent with the direction of the experimental average rates of change in electric potential found for Figs. 2 and 3 ($-72\,\mathrm{V\,m^{-1}}$ for both). This implies the presence of an electric field in both trials since the overall vector field direction is consistent with the behavior predicted by (1). In addition, the regions in Figs. 2 and 3 where the magnitude of the electric field vectors (represented by the vector length) is at a maximum is consistent with the isoline density distribution in both equipotential maps, where areas of higher equipotential line density correspond to regions of high electric field strength. The observed consistency of the electric field vectors and isoline orientation and densities in Figs. 2 and 3 indicate the validity of using our measuring setup for a device governed by electrostatic principles. Our measurement techniques could be applied to devices similar to the electrophoresis rig we tested, including capacitor designs and electric field sensors.

Any outlying values of all experimentally determined quantities and the discrete nature of our equipotential lines across experiments are most likely due to the limited number of points measured and measurement errors (e.g. not measuring at the exact point, oscillating voltage values on the voltmeter). Across both experiments, data was collected at only 36 points for each trial, a very small dataset. This may have contributed to the straight, discrete nature of the equipotential lines since there was not enough data to generate curved, smoother lines. In addition, more configurations of the two-nut system should be tested to observe how the isolines and voltage values change with respect to the orientation of the system.

V. Conclusion

This experiment illustrated the relationship between theoretical knowledge of electric fields and their practical visualization through equipotential lines in salt water. By mapping these regions, we validated the fundamental relationship between electric potential and electric fields as described by electrostatic theory. The consistency of electric field vectors and equipotential line directions corroborates that our experimental setup can simulate electrostatic phenomena in other engineering applications, including capacitors, electric field sensors, and devices like electrophoresis setups where accurate electric field mapping is essential. Next time, we could also try different electrode configurations to visualize different cases and collect more data points to get smoother equipotential curves. In future experiments, we could develop electrostatic simulations to observe the effects of measurement on the electric potential in the electrophoresis rig. Through the fusion of theory and application, this work provides a solid ground to apply electrostatics to new engineering solutions.

VI. Acknowledgement

We thank several anonymous reviewers whose comments helped our manuscript. SA contributed to the abstract, methods description, and data visualization components. VC contributed to the introduction, results, discussion, and paper formatting. KS and KT were responsible for data collection and the experimental setup. KT also contributed to the methods section along with creating the setup diagram.

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Demonstrating a Method to Create a Low-cost Electrophoresis Rig Solution

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***Abstract*—We observed and analyzed the potential and electric field in a saltwater solution with conducting wires that could be used for a low-cost electrophoresis rig. Specifically, we inspected the formation of equipotential regions in the saltwater solution because they are especially important for the functions of an electrophoresis rig in organizing particles by charge and mass. To do this, we measured the potential difference (compared to a common point) at various set points in the saltwater solution, for various voltages. We expected to have equipotential regions that are able to be represented with elliptic curves and to have a non-constant electric field. We found that solution is a good low-cost substitute for electrophoresis rig solution as it creates equipotential regions suitable for the electrophoresis rig's applications.**

***Index Terms*—electric potential, equipotential lines, electric field visualizations, saline conductive medium, electrostatics, electric field mapping, data visualization in electrostatics, gel electrophoresis, electric field dynamics**

I. INTRODUCTION

DIFFERENT PARTICLES will settle at different regions in a solution based on their size and charge (negative charged particles will rest at higher potential regions and positive charged particles will rest at lower potential regions). An electrophoresis rig separates particles based on size and charge by having equipotential regions that different particles will settle at. A solution that is very conductive is needed to create a good separation between different particles. Salt (NaCl) dissociates into its ions (Na^+ and Cl^-) in water, allowing for a high conductivity as the ions are free to carry charge in the aqueous solution. This allows for a higher current density by the equation $\vec{J} = \sigma\vec{E}$, where $\vec{J}$ is current density, σ is conductivity of the material (very high for saltwater), and $\vec{E}$ is the electric field, which allows for clearer voltage differences across the rig as a higher current means a higher voltage by Ohm's law.

Placing a fixed positive charge (The positive terminal of a power supply) and a fixed negative charge(The ground terminal of a power supply) into this saltwater will create an electric field. This field will not be constant(it will be maximized close to each charge and minimized at the point exactly between them) and will never be zero between the two charges (both charges' electric fields are never in opposition in the region between them). Since $V = \int \vec{E} \cdot d\vec{s}$, there will be a potential gradient (since $\vec{E}$ is never 0) and this potential gradient will change inconsistently (as $\vec{E}$ is not constant in the solution).

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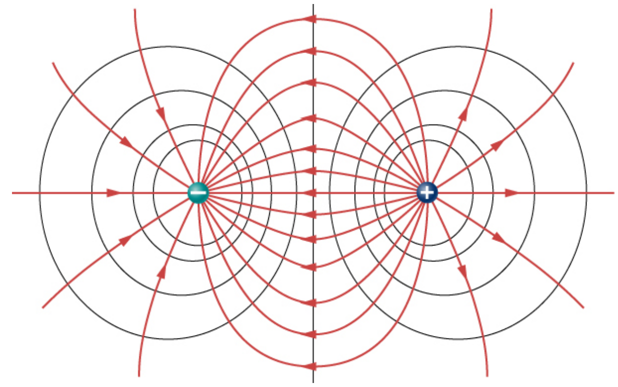

Fig. 1. Electric field (red) and equipotential (black) lines for a dipole configuration with positive and negative charges spaced by a short distance. From [1].

Certain points in this gradient will have the same potential, these points are considered to have equipotential. A region of these points is called an equipotential region and will run perpendicular to the net electric field. In this case, they should follow the pattern shown in Fig. 1. For our purposes, we can measure the potential difference from a set point to a number of points in a region to check if that area is an equipotential region(or line).

II. METHODS AND MATERIALS

We used a clear 3-cup polypropylene food container (EasyFind; Rubbermaid; Atlanta, GA), $500\,\mathrm{mL}$ of tap water, and a pinch of salt to create an aqueous solution with sufficient conductivity for experiments. Voltage was applied using a power supply and two alligator leads, clipped to the side of the container using large size binder clips in the positions shown in Fig. 2. A $20\,\mathrm{cm} \times 20\,\mathrm{cm}$ measurement grid was then drawn on a whiteboard placed beneath the container, with dots marking 11 measurement points within a $10\,\mathrm{cm} \times 10\,\mathrm{cm}$ area, as shown in Fig. 2. With the power supply adjusted to provide $3\,\mathrm{V}$ applied voltage, we measured the potential at each of the 11 measurement points. This was repeated for applied voltages $3\,\mathrm{V}$, $6\,\mathrm{V}$ and $9\,\mathrm{V}$. For our measurements, we took the vertical midline (points 2, 5, and 8) as ground $(0\,\mathrm{V})$.

To estimate electric field in the x direction along the horizontal midline, we took finite differences between measurement points 4–8, using $dx = 2.5\,\mathrm{cm}$ between each, e.g.:

$$|E_{x,4-5}| = \frac{V_5 - V_4}{dx} \tag{1}$$

and similarly for points 5-6, 6-7, and 7-8.

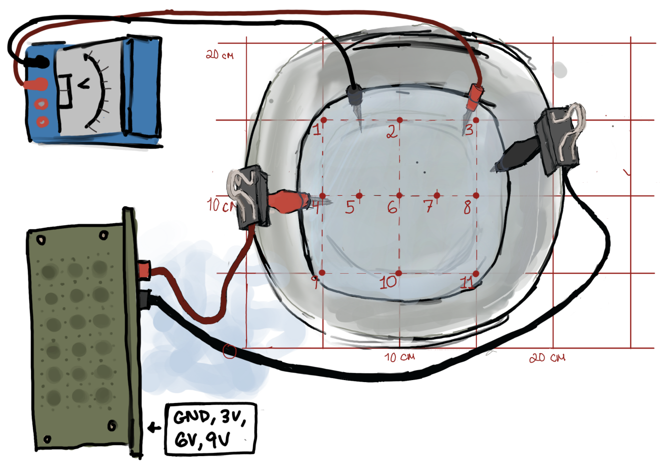

Fig. 2. Experimental setup. Tub of water depicted on right, voltmeter (blue/white) and power supply (green) on the left. Vertical midline points 2, 6, and 8 were taken as ground while horizontal midline points 4–8 were used to compute the electric field strength using finite differences, (1).

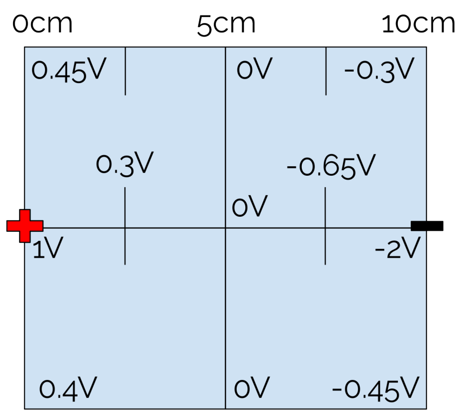

Fig. 3. Measured potentials for 3 V applied voltage shown at each test point. The test points are numbered 1–11 in Fig. 2. Positive and negative electrodes are located at the red plus and black minus signs, respectively.

III. Results

Figs. 3 to 5 show the measured potentials for three different applied voltages, 3 V, 6 V and 9 V. Table I and Fig. 6 show our estimates of the electric field along the center path between the positive and ground terminals obtained from points 4–8 using the finite difference method of (1).

Fig. 7 shows the electric fields at each point and the equipotential lines.

IV. Discussion

The electric field for this saltwater can be defined by $E = kQ(\frac{0.1}{x^2} + \frac{0.1}{0.1-x^2})$. Between $0\,\mathrm{m}$ to $0.1\,\mathrm{m}$, the distance between the two terminals, the maximum values for this equation are found at $x = 0\,\mathrm{m}$ and $x = 0.1\,\mathrm{m}$; one denominator will be 0 so $|E| = \infty$ at the (singularity) points. The minimum value is found at $0.05\,\mathrm{m}$, when the denominators are maximized. Thus

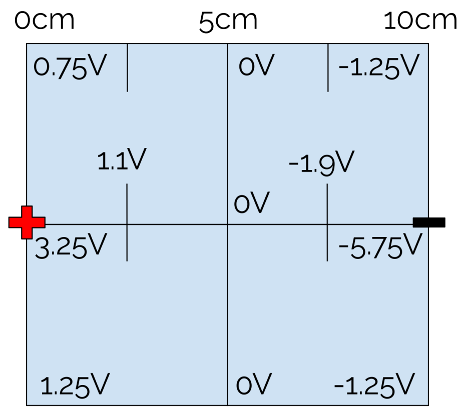

Fig. 4. Measured potentials for 6 V applied voltage shown at each test point.

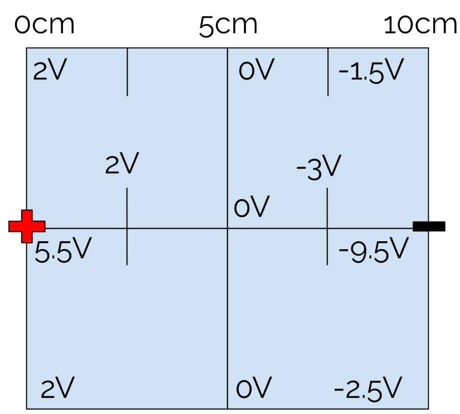

Fig. 5. Measured potentials for 9 V applied voltage shown at each test point.

TABLE I
Estimates of Electric Field Strength from the Gradient of Potential Along the Center Path Using Finite Differences for Measurement Points 4–8, (1).

	E_x, (V cm^{-1})			
V_a, (V)	points 4-5	points 5-6	points 6-7	points 7-8
9	1.40	0.80	1.20	2.60
6	0.86	0.44	0.76	1.54
3	0.28	0.12	0.26	0.54

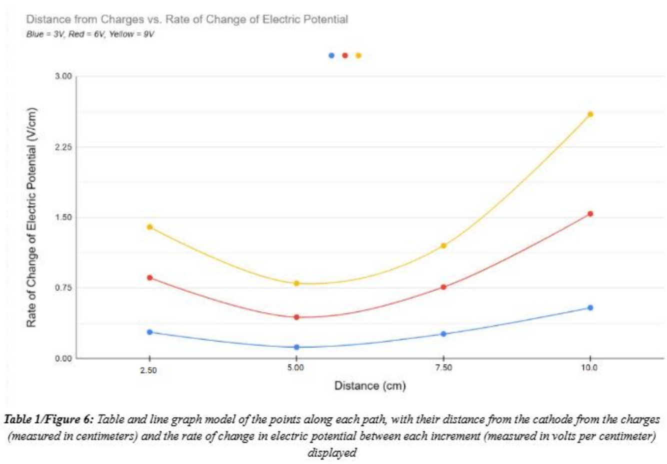

Fig. 6. Estimates of electric field strength from the gradient of potential along the center path using finite differences along measurement points 4–8, (1). Data from Table I.

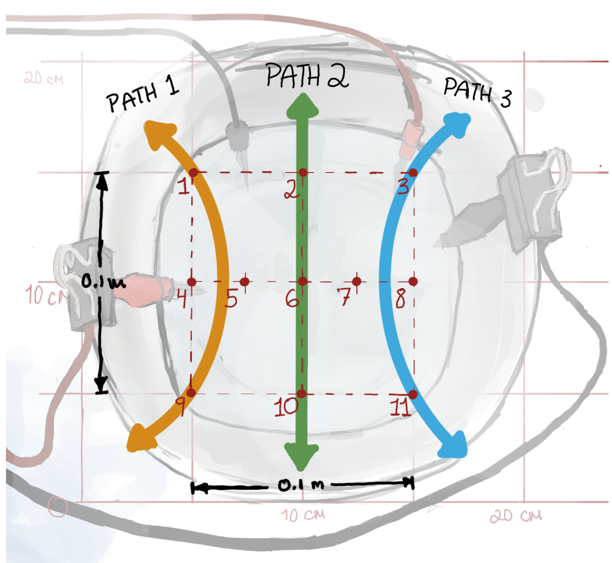

Fig. 7. Model of the tub overlaid with the observed equipotential lines and electric field lines for each point. Equipotential lines are carried in three paths (orange, green, and blue) while the electric field lines are shown as yellow arrows.

the gradient of potential observed in Table I and Fig. 6 makes sense as it follows that type of pattern, though it is odd that the rate of change seems to higher at the negative terminal than it is at the positive terminal ($9\,\mathrm{V}$ data in Table I and Fig. 6). This is likely due to a combination of human error and errors with the system. The terminals moved around a bit while we worked, which may have changed the distance between certain points and the terminal, causing odd values. Additionally, the salt in the water may not have dissolved evenly and congregated closer to the negative terminal, increasing the relative electric field in that region since the water would be more conductive.

The equipotential lines sketched in Fig. 7 loosely match the shapes predicted for a dipole as shown in Fig. 1. We can see that, with a small margin of error, the top and bottom left points for each of the different voltages are the same. These form an equipotential line which makes sense as both have the same distance to the positive and ground terminals, so they will both be affected by the terminals electric fields in the same way. This goes for the top and bottom right points and the center line between the terminals for each voltage as well. We can also see that as the left clasp gave off a positive charge and the right clasp gave off a negative charge, the electric fields at each point pointed away from the cathode and gradually started to point more toward the anode as they got closer to it, following the path of electric fields from positive to negative. Though some of the potential values were a little different between supposed equipotential regions, this can be explained by human error. For the same reasons why the tested rate of change for potential was a little off.

By analyzing the data, we observed that the electric field strength (e.g. see Fig. 6) follows what is essentially an inverse quadratic function that has approached infinity at $x = 0\,\mathrm{m}$ and $x = 0.1\,\mathrm{m}$ and has a minimum in the middle. This observation aligns with what we expected from theory, as the electric field is the derivative of potential and this is the same form as the electric field for two-point charges. We also identified three equipotential lines located along the paths between the top and bottom right, the top and bottom left, and directly between the two charges. We had a few errors that skewed our data, but did not entirely reject our hypothesis as the areas where we did not make significant errors were extremely consistent with our expected results. These errors mainly had to do with the terminals of the power supply shifting around in the water and possibly with the salt not dissolving evenly in the water, Ideally, the experiment would be conducted with the terminals of the power supply affixed onto the container, as opposed to just being clamped down, and with the water stirred well so that the salt would be fully and evenly dissolved into it. Also a voltmeter with higher precision would be useful, since more exact data is better data. Despite the lack of optimization, this experiment shows that saltwater is a reasonable low cost solution for an electrophoresis rig as it can properly construct equipotential regions.

V. Acknowledgement

We thank several anonymous reviewers whose comments helped our manuscript.

VK set up and performed experiments, and worked on introduction, formatting, and revisions. SB set up and processed and plotted results from the experiment, and worked on abstract and conclusions. PT set up and performed experiments and worked on abstract and conclusions. DA set up the lab and plotted results, and worked on abstract and materials and methods. NM set up and performed experiments, plotted results, and worked on the results section.

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Visualizing Electric Potential: Mapping Equipotential Lines in a Conductive Water Tray

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Nirvik Patel, Dilan Gandhi, and Nathan Gershteyn

***Abstract*—The goal of this experiment was to study the distribution of electric potential around conducting wire configurations and identify the corresponding equipotential regions. Using a water tray with a saline solution as the conductive medium, we measured the potential difference at defined points on a coordinate grid by connecting the wires to a power supply and using a multimeter to record voltages at various locations. Our observations indicated that equipotential regions were centered somewhat equidistantly between the voltage sources, with a mostly consistent rate of potential change along paths parallel to the sources. Some discrepancies between expected and observed values were noted, likely due to limitations in the measurement equipment and procedural inconsistencies. Despite these challenges, the experiment successfully demonstrated the properties of electric potential and equipotential lines, providing a clear visual representation of their relationship with the electric field.**

***Index Terms*—electric potential, equipotential lines, electric fields, saline solution, conductive medium, voltage mapping, potential gradient**

I. Introduction

ELECTRIC FIELDS arise from the presence of electric charges and describe the force that a charge would experience within the region of influence [1]–[3]. The strength of the electric field is determined by the magnitude and distribution of charges, as well as the distance from the source. Electric potential, on the other hand, represents the potential energy per unit charge at a point in the field and is related to the electric field through the equation [1]:

$$V = -\int E \cdot dr. \tag{1}$$

(1) shows that electric potential is the integral of the electric field along a path, with the negative sign indicating that electric potential decreases in the direction of the field. Equipotential lines are defined as contours where the electric potential remains constant. These lines are always perpendicular to electric field lines, reflecting the fact that no work is required to move a charge along an equipotential surface. This property makes equipotential mapping a useful tool for visualizing the distribution of electric fields and potential in various setups.

In this experiment, we used a polypropylene container filled with a saline solution as a conductive medium to simulate the behavior of electric potential and field in a simplified, accessible environment. Salt was added to enhance the conductivity of the water, ensuring a stable field for measurement. By placing conducting wires connected to a power supply in the tray, we created an electric field and measured the potential at various points using a multimeter. This allowed us to map the equipotential regions and explore their relationship with the electric field. The results gave us insights into how equipotential lines and their relationship to electric fields are critical in applications such as designing capacitors, grounding systems, and electrical shielding.

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II. Methods and materials

To study electric potential and equipotential regions, we used a 3-cup polypropylene food container (EasyFind; Rubbermaid; Atlanta, GA) containing approximately $500\,\mathrm{mL}$ of a weak saline solution prepared using ordinary tap water plus a pinch of sea salt. The polypropylene container acted as a prototype simulating the final electrophoresis rig. The aqueous salt solution acted as a stable conductive medium for electric field visualization, allowing the electric field to propagate more effectively and improving the consistency of voltage measurements across the tray. Container dimensions were approximately $15\,\mathrm{cm} \times 15\,\mathrm{cm}$, ensuring sufficient space for accurate mapping of the potential. A small amount of blue food coloring (about five drops) was added to the water to improve visibility during the setup and ensure uniform distribution of the solution.

Voltage was applied using a $12\,\mathrm{V}$ DC power supply (model PS-28A), and the potentials were measured using a digital voltmeter (model HSPE-051 AC). A piece of graph paper beneath the container allowed for repeatably locating the measurement points, which were on $1\,\mathrm{cm} \times 1\,\mathrm{cm}$ grid squares. The circuit was set up by attaching one alligator lead to the positive terminal of the power supply and submerging it at one end of the tray, while the other was connected to the negative terminal and submerged at the opposite end. This configuration created an electric field across the tray. We placed the wires parallel to the graph paper's grid lines for consistency in measurements. Points of measurement (labeled 1 through 9) were marked at specific coordinates on the grid, spaced uniformly to facilitate data collection.

Using a multimeter set to measure voltage, we started at a reference ground point ($0\,\mathrm{V}$) and systematically recorded the voltage at each grid intersection, moving outward from the ground point. Measurements were taken at incremental voltage settings of $3\,\mathrm{V}$, $6\,\mathrm{V}$, $9\,\mathrm{V}$ and $12\,\mathrm{V}$ adjusted at the power supply. This allowed us to observe how potential varied across the tray for different input voltages. Data collected at these points were

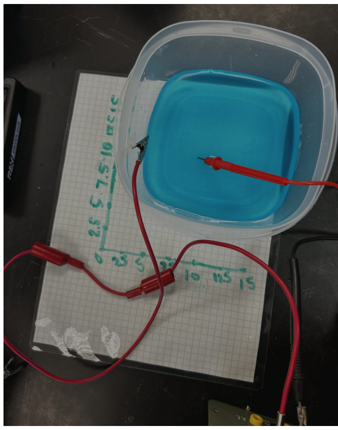

Fig. 1. Image of experimental setup

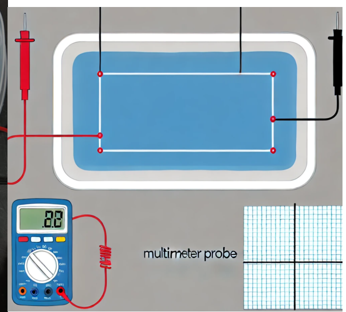

Fig. 2. Diagram of experimental setup

TABLE I
RECORDED VOLTAGE (V) AT DIFFERENT POINTS

	measurement point								
V	1	2	3	4	5	6	7	8	9
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.53	1.02	1.35	0.28	1.05	2.95	0.63	0.98	1.48
6	2.02	3.27	4.48	2.08	3.28	8.97	2.48	3.29	4.55
9	3.47	5.52	15.2	3.63	5.57	18.9	3.45	5.47	7.87
12	4.79	7.78	9.47	5.12	7.72	21.15	4.55	10.2	10.53

used to plot a 2D map of the tray using the Matplotlib library in Python [4], [5].

III. Results

As shown in Table I, the data collected at input voltage levels of 3 V, 6 V, 9 V and 12 V consistently showed an increase in potential as the distance from the ground point increased. For example, at 3 V, the potential ranged from 0.53 V at Point 1 to 1.48 V at Point 9. At 9 V, the potential rose from 3.47 V at Point 1 to 7.98 V at Point 9. However, there were outliers, such as a value of 15.2 V at Point 3. This suggests either variations in field uniformity or higher concentrations of salinity in that region. It is also unclear how we observe voltages higher than the power supply output (e.g. point 6).

The data from Table I are plotted in Fig. 3, which visually represents the regions of equal electric potential across the water tray. Though Fig. 3 does not depict level curves of equal potential, we hypothesize that equipotential lines are more tightly packed near the electrodes, indicating steep potential gradients and stronger electric fields. As the distance from the electrodes increases, the equipotential lines become more widely spaced, reflecting weaker electric fields and more gradual potential changes.

IV. Discussion

The potential changes most rapidly near the electrodes, where the electric field strength is highest. This is evident in the tightly packed equipotential lines close to the voltage sources in Fig. 3. Farther from the electrodes, the potential

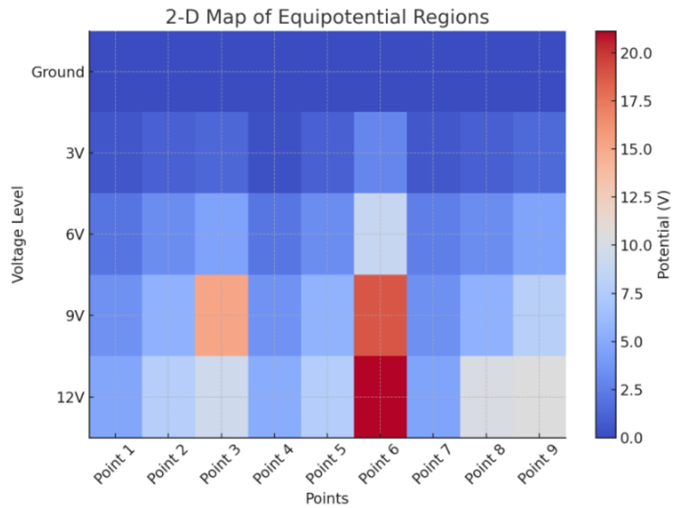

Fig. 3. Equipotential map of data in Table I

change becomes more gradual, as reflected in the broader spacing between lines. This indicates a diminishing electric field strength as distance from the source increases.

The electric field radiates outward from the positive terminal and converges at the negative terminal. The regions with steeper potential gradients correspond to stronger electric fields, while flatter potential regions indicate weaker fields. This relationship reflects the fundamental correlation between electric fields and the rate of change of potential. From our observations, we infer that electric field lines would radiate outward from the positive terminal and converge at the negative, crossing equipotential surfaces perpendicularly. This pattern aligns with the theoretical relationship [1], [3] between electric fields and equipotentials.

V. Conclusion

The experiment effectively demonstrated the idea of equipotential lines. The electric potential along a theoretical equipotential line stayed somewhat constant, proving how electric potential is the same along an equipotential line. Even with this, the experiment could have been improved. The voltmeter at some points seemed to not be very precise, and the power supply may have been supplying a slightly incorrect voltage due to wear and tear. In addition, human error in terms of correct probe placement would have caused some incorrect readings with the voltage. If this experiment were to be conducted again, more modern technology could be used, along with more precise measuring.

VI. Acknowledgement

We thank several anonymous reviewers whose comments helped our manuscript. All authors did data collection. RC did data analysis and wrote the discussion. SM wrote the conclusions. JH plotted the results. EH wrote the introduction. NP plotted the results and wrote materials. DG analyzed results and wrote the abstract. NG wrote the methods.

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Electric Field Mapping for Cost-Effective Gel Electrophoresis Applications

Ryan Edwards, Cameron Karabin, Chloe Li, Krish Patel, and Jake Schatz

***Abstract*—In this experiment, we tested the functionality of a low-cost electrophoresis rig by utilizing two electrodes, a battery, and a voltmeter, to map the electric field and equipotential lines formed by a positive and negative charge placed in the rig. After placing a positive charge on the origin and a negative charge on the positive y-axis of the coordinate system in the electrophoresis rig (saltwater tub), we took voltage measurements across various chosen points in the container. Using these measurements, we drew the equipotential lines by identifying regions of equal voltage and then calculated/drew electric field lines. We hypothesized that equipotential lines would have a higher concentration closer to the origin, the voltage would be high near the positive charge and decrease as we move away and toward the ground, and the electric field would point away from the positive charge and toward the ground. Ultimately, our results aligned with our hypotheses, demonstrating the viability of this rig as an educational tool for biology students to use in an electrophoresis lab.**

***Index Terms*—equipotential lines, vector field, electric potential, saltwater conductivity**

I. Introduction

A. Theory

When two or more charges are in the same vicinity, they exert a force on each other, either repulsive or attractive depending on whether the charge is positive or negative [1]. As a result, an electric field is formed surrounding the electrical components, demonstrating the amount of electric force per unit charge exerted on a test charge in a certain region of space. Electric potential is the negative of the rate of change of the electric field with respect to position [1]. Similar to the relationship between forces and the electric field, the electric potential (otherwise known as voltage) at a point is equal to the electric potential energy per charge at a point in space [1]. Drawing equipotential lines is often significant because they indicate areas where electric potential is equal [2], [3].

B. Hypotheses

Since the electric potential is inversely proportional to the distance to a charge, we hypothesized that these equipotential lines would have a higher concentration closer to the origin, near the positive charge. Furthermore, we hypothesized that the voltage would be high near the positive charge and decrease as we move away and toward ground since the electric potential is directly proportional to the charge. Lastly, we hypothesized that the electric field would point away from the positive charge and toward ground since positive charges repel positive test charges, and negative charges attract positive test charges. To test the validity of our hypotheses, we found the electric potential at multiple points in the first quadrant at various distances from the origin and mapped both the electric field lines and equipotential lines. After analyzing our data and results, our findings supported these hypotheses, aligning with theoretical predictions.

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II. Materials and Methods

A. Materials

We used two steel nuts, water, salt, a $370\,\mathrm{mL}$ polypropylene food container (EasyFind; Rubbermaid; Atlanta, GA) to simulate a low cost electrophoresis rig [4]. A whiteboard and a marker were also used to locate measurement points on a laminated piece of graph paper.. We recorded measurements using a multimeter, alligator clip leads, and a $15\,\mathrm{V}$ power supply.

B. Setup

To set up this experiment, we sketched an xy-plane on a laminated piece of grid paper as seen in Fig. 1. This plane would be used to find equipotentials at various points throughout the electric field. We plotted 25 points, each roughly three grid boxes away from each other, which we set to be separated by one unit of measurement.

To create a conductive electric field to measure electric potential, we filled a small Tupperware container with water (roughly $1\,\mathrm{cm}$ depth of water). Then, we added a pinch of salt to create the weak saline solution, providing a conductive medium for our electric field. After creating this solution, we placed the polypropylene container over the laminated plane, so that the measurement grid would be easily visible during measurements (see Fig. 2).

C. Measurements

Incorporating the electrical portion of the experiment, we acquired both a voltmeter and a power supply. The power supply would introduce charge into the aqueous solution and the voltmeter would be the means of measuring potential throughout the electric field. For the two poles of the power supply, we attached nuts to the end of them to act as electrodes. The positive and negative poles were then placed at the origin and point (0,4), respectively. We then applied $15\,\mathrm{V}$ to the saltwater system at the electrodes. The setup is shown in Fig. 3. Then, we placed the negative (black) terminal of the

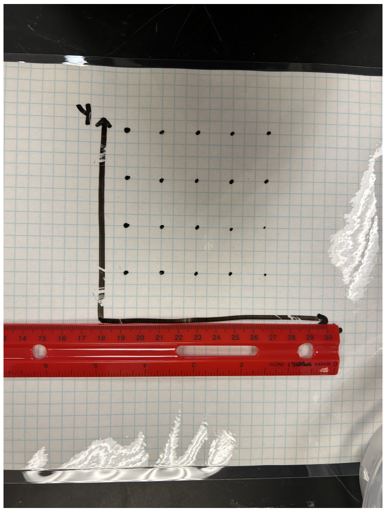

Fig. 1. The grid of points. Each square is 0.25 inch (0.635 cm). Measurement grid points are 3 grid squares (1.905 cm) in x and 4 grid squares (2.54 cm) in y.

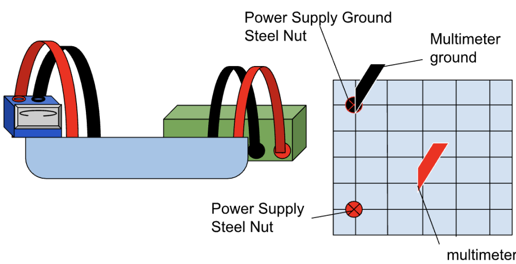

Fig. 2. Diagram of the setup

multimeter at point (0,4). The positive (red) terminal was then placed at each of the plotted points. For each point the positive terminal was placed at, the electric potential in relation to ground was tracked in a spreadsheet.

D. Analyses

To create the equipotential lines, we graphed the voltage along the xy plane and drew lines where the voltage is similar. Again due to the electric field, the highest concentration of equipotential lines should be closest to the charge.

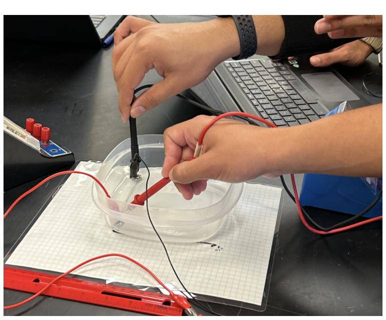

Fig. 3. Collecting the voltages with the multimeter

TABLE I
POTENTIAL VALUES IN V AT ALL 25 MEASUREMENT POINTS

	x (cm)				
y (cm)	0	1	2	3	4
4	0.8	2	3	3.4	3.8
3	2.5	3.5	4.5	4.7	5
2	5	6.5	6.6	6.5	6.3
1	8.5	8	10.5	8.2	7. 5
0	15	12.7	11	9	7.7

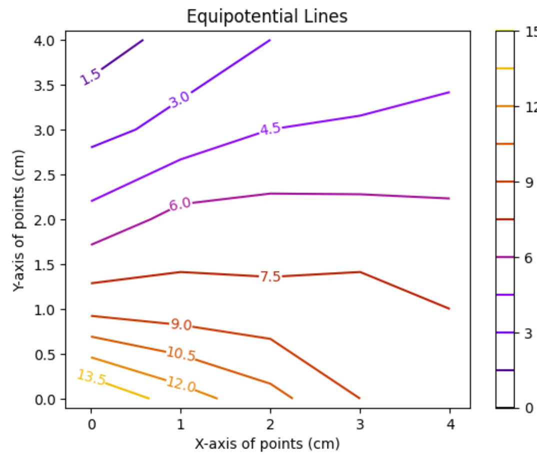

Fig. 4. The equipotential lines from the points in the experiment. Data from Table I.

To obtain electric fields, we calculated the gradient of the measured potential V to evaluate gradient of the potential [1]–[3], [5]:

$$\vec{E} = -\nabla V = \left(-\frac{\partial V}{\partial x}, -\frac{\partial V}{\partial y}\right) \quad (1)$$

By taking the partial derivatives of voltage with respect to the x and y directions, we get the electric field vectors at any specific point, which can then help visualize the change in potential.

To compute and graph the lines, we utilized Python with the NumPy [6] and Matplotlib [7] libraries. Partial derivatives were calculated numerically using a central difference method implemented in Python. The source code and raw data used for these computations is available on Google Colab at https://colab.research.google.com/drive/1tGvBPIV3KCg6DGzSNkJwY9w86lo38hpc?usp=sharing for reproducibility.

III. RESULTS

Table I shows the potential of all 25 points in the experiment in a 1 cm square grid pattern, where the positive charge is at (0,0), and the furthest measured point was 4 cm right and 4 cm above it. The data of Table I are plotted in Fig. 4, which shows the equipotential curves that result.

Fig. 5 shows us how the potential changes as it gets further from the charge. The electric field closer to the origin has a greater magnitude and it exponentially decreases as it gets

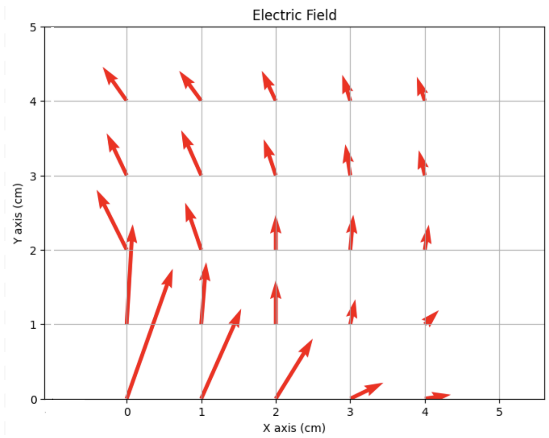

Fig. 5. The electric field vectors from the experiment

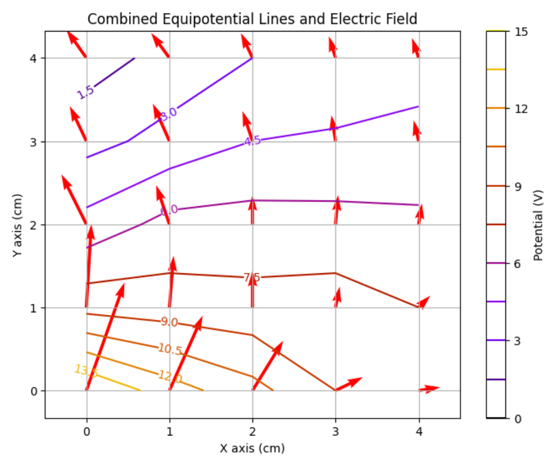

Fig. 6. The equipotential and electric field lines

further away. The change in potential will have the same magnitude but the opposite sign, which means it increases exponentially as it gets closer to the origin.

By overlaying the electric field with the equipotential lines in Fig. 6, it further confirms how along the equipotential lines the potential will be equal in magnitude and that the potential will change according to the electric field. The electric field vectors are also perpendicular to the equipotential lines, which confirms that there is no potential difference along the region and that no work must be done to move along it.

IV. Discussion

Examining these equipotentials, vector fields, and overall methodology of this experiment lead to a multitude of questions about both the lab setup and findings.

Starting with the lab setup, one may want to understand the necessity of salt as part of the aquatic solution. As shown by Fig. 7, salt proves to be a necessary solute in this system because water is not electrically conductive on its own. It lacks ionic particles that carry current. However, salt (NaCl; often split into Na^+ and Cl^- ions) carries current throughout the system [4]. In order to measure electric potential, the electrophoresis rig must be of a conductive substance.

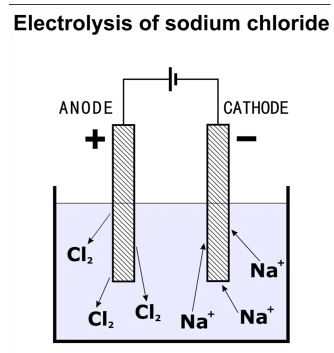

Fig. 7. The movement of charged NaCl particles in solution

Moving on, there is a significant relationship between the derivative of the change in potential with respect to the distance away from the centered point ($\frac{dV}{dr}$). As depicted by Table I, when the distance from the centered point (0,4) increases, the rate of change of the potential changes at a slower rate. Furthermore, the equipotential lines, lines that show equivalent electric potential, demonstrate this relationship, getting closer together as the distance from point (0,4) increases.

We believe that we successfully achieved our goal in our expedition to create a low-cost electrophoresis rig. However, our rig and the results it produced were affected by some external complications. One major source of error was the reliance on manual measurements of electric potential at the points, which could have led to inconsistencies in readings due to slight misplacements of the probes. Additionally, the salt concentration in the solution may not have been perfectly uniform, potentially impacting conductivity and introducing slight variations in electric field measurements.

To improve this experiment, we could use a digital voltmeter, which would ensure precise voltage readings. Additionally, a standardized solution with carefully measured salt concentration could guarantee uniform conductivity. Conducting the experiment in a controlled environment free from any other external variables would further improve the reliability of our results.

V. Conclusion

Analyzing the electric fields and potentials across the low-cost electrophoresis rig along with the plotted equipotential lines, the results support our central hypotheses that stated both the potential, measured in voltage, would be greater closer to the origin (positive charge) as well as the increase in the concentration of equipotential curves. By mapping voltage readings at various points, we observed that equipotential lines concentrated near the positive charge, reflecting the strength and direction of the electric field. Despite minor limitations in measurement precision and setup stability, our results were consistent with expected behavior, highlighting both the effectiveness of our experimental approach and the fundamental properties of electric fields and potentials.

VI. Acknowledgement

We thank several anonymous reviewers whose comments helped our manuscript. JS was responsible for drafting the abstract and contributing to the introduction. CK conducted data collection, contributed to the experimental design, and assisted in drafting the abstract. RE contributed to the introduction, methods, discussion, and conclusion sections. KP analyzed and graphed the data, drafted the results section, and contributed to the discussion. CL contributed to the methods and conclusion sections and assisted with data collection. All authors reviewed and approved the final paper.

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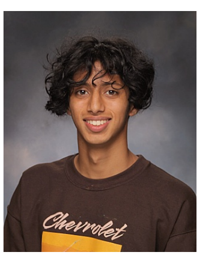

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Mapping Electric Potential and Electric Field Distribution in Saltwater and Investigating the Effect of Distance from Source

Aadarsh Kumar, Steven Perkins, Nareshsanjay Muthukumar, Henry Villaseñor, and Anirudh Khanna

***Abstract*—When two opposite point charges are placed near each other, the equipotentials of the system are roughly circular around the charges, roughly linear in between the charges, increase in magnitude closer to the positive point charge, and run perpendicular to the electric field lines between the two charges. To simulate two point charges near each other in a conductive medium and test if this hypothesis is true, we placed two leads in saltwater and measured the voltage at a predetermined set of points. Our results confirmed the hypothesis, showing a gradual decrease in electric potential with distance and the formation of consistent equipotential lines. This experiment demonstrates how the principles of electric fields and conservation of energy apply in a physical system, providing a hands-on understanding of how electric potential behaves in different regions of space.**

***Index Terms*—equipotential, electric field, mapping**

I. Introduction

ELECTRIC POTENTIAL, the ability of an electric field to do work on a charge, is a fundamental concept in electromagnetism [1] with applications in fields such as electronics, telecommunications and biomedical devices. In this experiment, we explored the distribution of electric potential around conducting wire configurations submerged in a saltwater solution, with the goal of mapping equipotential lines. We hypothesized that the electric potential and its rate of change would decrease as the distance from the source increased, creating distinct equipotential regions. Using a polypropylene container filled with saltwater, a power supply, and a multimeter, we measured the voltage at various points on a coordinate grid to construct a two dimensional (2D) map of the potential.

II. Methods and materials

The procedure involved the following materials: a 3-cup polypropylene food container (EasyFind; Rubbermaid; Atlanta, GA), two wires with alligator clips (designated as positive and negative), two bolts, an 830B Multifunctional LCD Digital Multimeter with probes, a Lab Volt 197P power supply, graph paper, and a marker. The experimental setup included placing the polypropylene container on a flat surface with the two bolts connected to the negative lead of the power supply, serving as the reference points for potential measurements. The container was filled to a depth of 1 cm with a weak saline solution consisting of tap water with a pinch of sea salt.

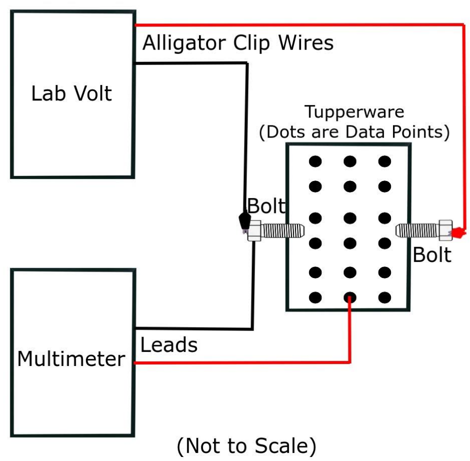

Fig. 1. The experimental setup consisted of a small polypropylene container containing a saline solution, positive and negative electrodes, and a grid marking the 6×3 array of test points to be measured. The system was energized with a Labvolt 197P power supply set to 3.7 V. Measurements of the potential between each point and the negative electrode were made using a digital multimeter.

To measure electric potentials, a 6×3 grid array representing 18 measurement points was established beneath the container's surface. The grid's coordinates were defined such that the y-axis corresponded to three rows of dots, spaced 2.25 cm apart, with $y = 0$ defined at the row nearest the positive lead. The x-axis was marked by six columns of dots, spaced 1 cm apart, with $x = 0$ at the leftmost column of the grid. For each measurement, the positive lead of the multimeter was placed at the desired measurement point, and the negative lead was connected to the bolt.

Voltage measurements were taken at each grid point, and from these measurements, equipotential lines were constructed. These lines were plotted using MATLAB (Mathworks; Natick, MA) via the `countour()` command, and the electric field was derived from the negative gradient of the potential via the `gradient()` and `quiver()` commands. The MATLAB code used for this analysis can be provided upon request.

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TABLE I
POTENTIAL MEASUREMENTS AT EACH TEST POINT, IN V

	x (cm)					
y (cm)	0	1	2	3	4	5
0	3.11	3.21	3.60	3.70	3.68	3.50
2.25	2.65	2.70	2.75	2.80	2.65	2.70
4.5	2.30	2.25	2.00	2.10	2.22	2.40

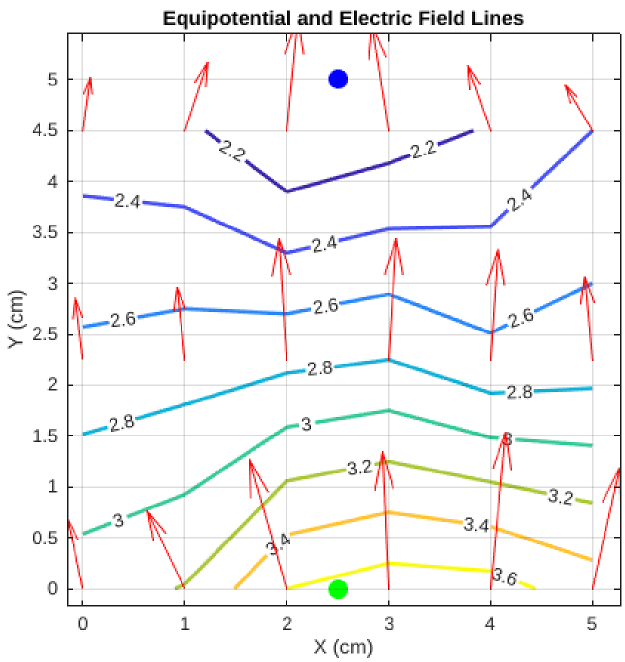

Fig. 2. Results of Table I plotted. Positive electrode shown as green dot (bottom); negative electrode shown as blue dot (top). Equipotential lines labeled with the potential value in V; electric field lines shown as red arrows.

III. Results

The potential measurements at each test point are shown in Table I and Fig. 2. Fig. 2 also shows the resulting equipotential curves and the electric field.

IV. Discussion

Based on our mapped equipotentials, our measured voltages decreased as the locations at which they were measured were farther away from the source positive electrode. This means that as we moved away from the source, the potential decreased. These results are to be expected because of what we can determine about electric field from Fig. 2. Equipotentials appear linearly distributed along the midline path from positive to negative electrode, as expected.

When equipotential lines are closer together, the magnitude of the electric field in said region is greater than if the equipotential lines are farther apart. In Fig. 2, as we moved farther away from the midline path, the equipotential lines are farther away from each other. Thus, we can determine that the magnitude of the electric field decreases as we get farther away from the source.

We can determine the behavior of the rate of change of potential using the relationship between electric field and potential [1], [2].

$$\vec{E} = -\vec{\nabla}\phi, \tag{1}$$

$$= -\frac{\partial V}{\partial x}\hat{x} - \frac{\partial V}{\partial y}\hat{y} - \frac{\partial V}{\partial z}\hat{z}. \tag{2}$$

We can conclude from (2) that the rate of change of potential decreases as we move farther away from the source. These results support our hypothesis, and affirm the principles of electromagnetism we wanted to test through this experiment.

V. Conclusion

Our procedure supports our hypothesis that the electric potential will decrease as the distance from the source increases, creating observable equipotential regions. The experiment procedures are sufficient to demonstrate accurate measurements. The results could have been improved to have more precision by using a tub with precise divots at the coordinate points and having a more controlled salinity. Precise divots would allow measurements to be made at the exact points needed for the experiment, reducing the chance of human error and missing the desired coordinate. Because conductivity increases with salinity, using a controlled amount of salt and using the TEOS-10 function [3] to determine the conductivity our solution would allow more informed and more accurate results. Confounding variables like unstable hand movement, movement of the water, and contaminants in the water reducing conductivity may have altered our results. Further studies could explore different electrode configurations and conductance conditions to deepen the scientific community's understanding of electric fields in various mediums.

VI. Acknowledgement

We thank several anonymous reviewers whose comments helped our manuscript. AK generated the equipotential and electric field graphs, SP wrote the procedure and took measurements, NM wrote the abstract and took measurements, HV completed the conclusion and formatting, and AK wrote the discussion and data.

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