H320 Biophysics Final Report: Congealed Eel’s Fields

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1.0) Abstract

The investigation aims to map the equipotential lines and electric field around an electric eel as it bends from a straight line into a U shape- which eels often do to bring the poles of their organs closer together and therefore increase the effectiveness of their voltage volleys that they deliver to induce muscle paralysis. An electric eel was simulated by using a series of eight 3V coin cell batteries in series set in salted gelatin. The model gelatin eel was placed in ionic pond water and the electric field around the eel was mapped out in 4 different configurations of the eel. The eel was created with Calcium and Sodium ions to match the dielectric constants of the eel’s body to the gelatin used in the model. The pond water was also created using distilled water with Sodium and Calcium ions and a recommended water conditioner, so it maintains the conductivity of real pond water. The eel was placed (in a shallow tub of pond water) in a straight line (180 degree angle), with a 135 degree angle, at a 90 degree angle and in a U shape (0 degree angle). The equipotential lines around the eel were mapped out using a voltmeter with ground placed at a fixed point in the tank. Finally, a java simulation was used to place point charges in the shape of the eel for each configuration, and the electric field lines and equipotential lines were mapped out. The equipotential lines from the java simulation and the experiment were roughly of the same shape, showing how the model for the eel accurately recreates the electric field from an electric eel.

2.0) Introduction

The electric eel can produce a voltage of over 500V outside water and therefore makes it nature’s most proficient organism when it comes to manipulating electromagnetic fields. The goal of the experiment is to measure the electric fields around an electric eel, which are formed due to charge separation in its three organs. (Hunters, Main and Sach’s Organs.) Eel’s organs have different field distributions depending on their orientation or how they are bent, and so it is not enough to measure the field while the eel lays flat. To truly understand the Electric Eel’s field, we must measure and observe how it changes as the eel bends into different positions.

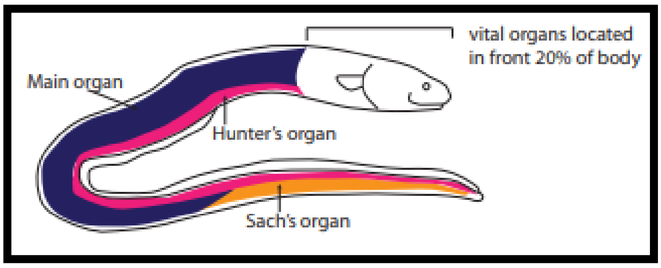

Figure 1: Showing the placement of the 3 organs of the eel in its body[1]

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[1] Emery, James, and Brian Gratwicke. “Electric Eels - University of Western Australia.” *Fact-Sheet- Electric Eels*, 2015, https://www.uwa.edu.au/study/-/media/Faculties/Science/Docs/Electric-eels.pdf.

Electric eels have 3 voltage generating organs which each contain about 70 columns of electrocytes. Each electrocyte (10000 per column) has a slight positive charge on the outside compared to the inside. A neurotransmitter is released by a nerve fibre on one side of the electrocyte to induce a pathway of low resistance on one side of the cell, drawing electrons outwards due to the charge difference. This creates a concentration of Na+ ions on one side of the electrocyte and a dipole voltage difference across the cell which, when linked in series, is the voltage source of the cells. [2]

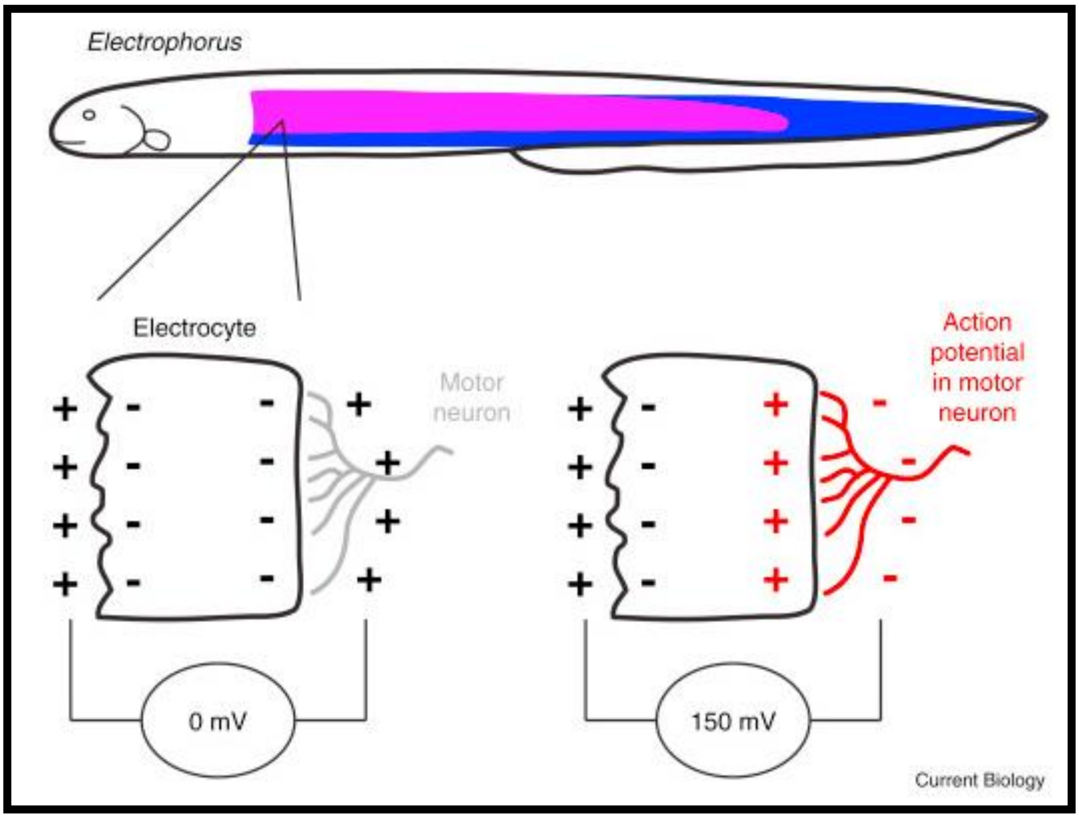

Figure 2: Showing how an electrocyte creates a voltage difference[3]

Eels can use their electricity to repeatedly deliver voltage volleys that cause muscle contractions in their prey at frequencies up to 100 Hz, causing involuntary muscle fatigue. [4]The Sach's organ also emits a lower amplitude of voltage that causes twitching and reveals prey. This is called electrolocation, where eels sense their prey's muscles firing.

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[2] Catania, Kenneth C. "The Astonishing Behavior of Electric Eels." *Frontiers*, Frontiers, 1 Jan. 1AD, https://www.frontiersin.org/articles/10.3389/fnint.2019.00023/full.

[3] Catania, Kenneth C. "The Astonishing Behavior of Electric Eels." *Frontiers*, Frontiers, 1 Jan. 1AD, https://www.frontiersin.org/articles/10.3389/fnint.2019.00023/full.

[4] KC;, Catania. "Electric Eels Concentrate Their Electric Field to Induce Involuntary Fatigue in Struggling Prey." *CB*, U.S. National Library of Medicine, 2015, https://pubmed.ncbi.nlm.nih.gov/26521183/#:~:text=These%20results%20reveal%20a%20unique,by%20inducing%20involuntary%20muscle%20fatigue.

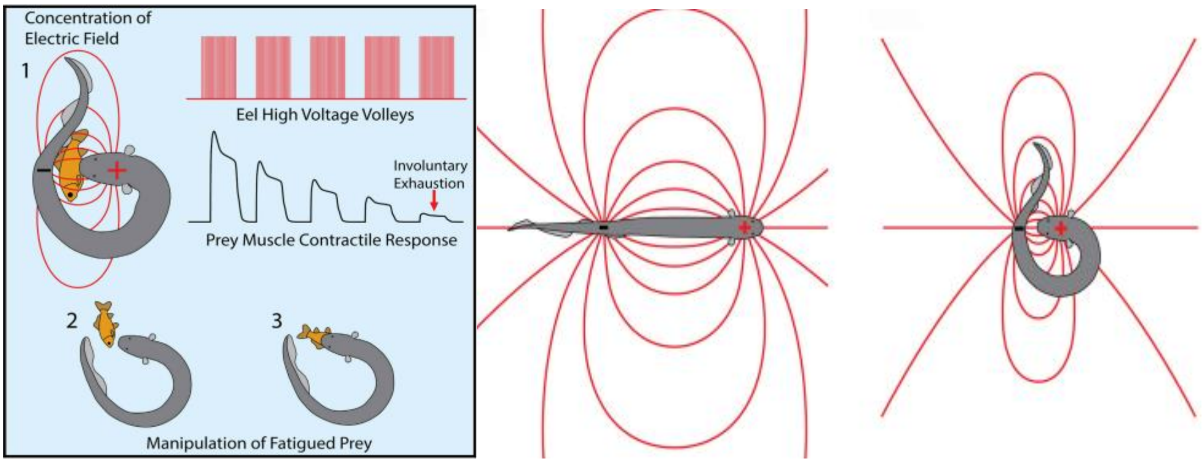

Figure 3: Showing how eels bend to induce muscle paralysis in prey by strengthening their electric field.[5]

The relative dielectric constant of most of the eel's body ranges from 80-90, while its skin is somewhat less conductive at a relative dielectric constant closer to that of the pondwater in which it lives[6]. The pondwater in which the eel lives is rich in Na+ and Ca+ ions, which provides outlets for the eel's voltage volleys. If the eel strikes above water, it can provide a more concentrated and higher amperage as there are fewer outlets for the electrons in air relative to ionic pondwater. (Eel's often do this when striking.) Finally, another mechanism that eels use to increase their effectiveness is bending. Since eels' organs have a positive charge and one end and a negative charge at another, they can bend to move the poles of their organs closer to each other and concentrate their electric field. This can allow them to deliver a strong series of shocks in extremely quick succession, which is useful when they strike larger prey whose muscles require a higher frequency of voltage volleys to induce muscle paralysis.

3.0) Methodology and Materials

First, we will go into how the eel and its environment were constructed, and then delve into how voltages were measured, and electric fields/equipotential lines were mapped out at different orientations of the eels body.

3.1) Creating Pond Water

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[5] KC;, Catania. "Electric Eels Concentrate Their Electric Field to Induce Involuntary Fatigue in Struggling Prey." *CB*, U.S. National Library of Medicine, 2015, https://pubmed.ncbi.nlm.nih.gov/26521183/#:~:text=These%20results%20reveal%20a%20unique,by%20inducing%20involuntary%20muscle%20fatigue.

[6] Xu, Jingjing. "A Fully Differential Switched-Capacitor ... - Wiley Online Library." *Nano-Dielectrics in Biosystems*, 2021, https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/cds2.12014.

Following the Cold Harbor Spring protocols[7], recreating pond water in which eels live is fairly simple.

1. For a 5L sample of pondwater, 12.5 g of NaCl along with 1g of $NaHCO_3$ are used to add Sodium ions.
2. Another 7g of $CaCl_2$ were mixed to add the Calcium ions
3. Finally, a water conditioner (55 mL) was used as recommended by CSHP.

This allowed us to recreate the eel's ionic environment.

3.2) Casting the Eel- Alginate and Gelatin

Sodium alginate was the first gel used to build the body of the eel, but it would not hold the batteries and fell apart outside the water. Since it holds Calcium ions, it has a dielectric coefficient similar to that of the eel's skin.

Gelatin was used and the concentration of the powder was varied until the conductivity matched that of the Sodium alginate trials. The temperature at which it was set was also varied to make sure it was as flexible as possible while still being solid. We ended up using about 1.2g of Gelatin powder per 100 mL of distilled water, along with some added $CaCl_2$ to make the conductivity match that of the Sodium Alginate gel. The gelatin was set in a refrigerator (not freezer) overnight.

Figure 4: Salted Gelatin with a dielectric close to that of the eel's body.

3.3) Building the Eel's skeleton

To recreate the eel's electrocytes, we used a series of coin cell batteries soldered together in a row. The eel was built in two segments as one icetray was too short to fit all the batteries. 8 holders were soldered together with jumper wires to provide flexibility. 8 3V (24V total) coin

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[7] Anonymous. “Artificial Pond Water.” *Cold Spring Harbor Protocols,* 1 Jan. 1970, http://cshprotocols.cshlp.org/content/2019/4/pdb.rec104992.full?text_only=true.

cell batteries were linked in series and covered in heat shrink to prevent the mechanism from affecting the gelatin from setting. Finally, the mechanism was set in two icetrays(4 cells in each tray) filled with gelatin in a refrigerator overnight.

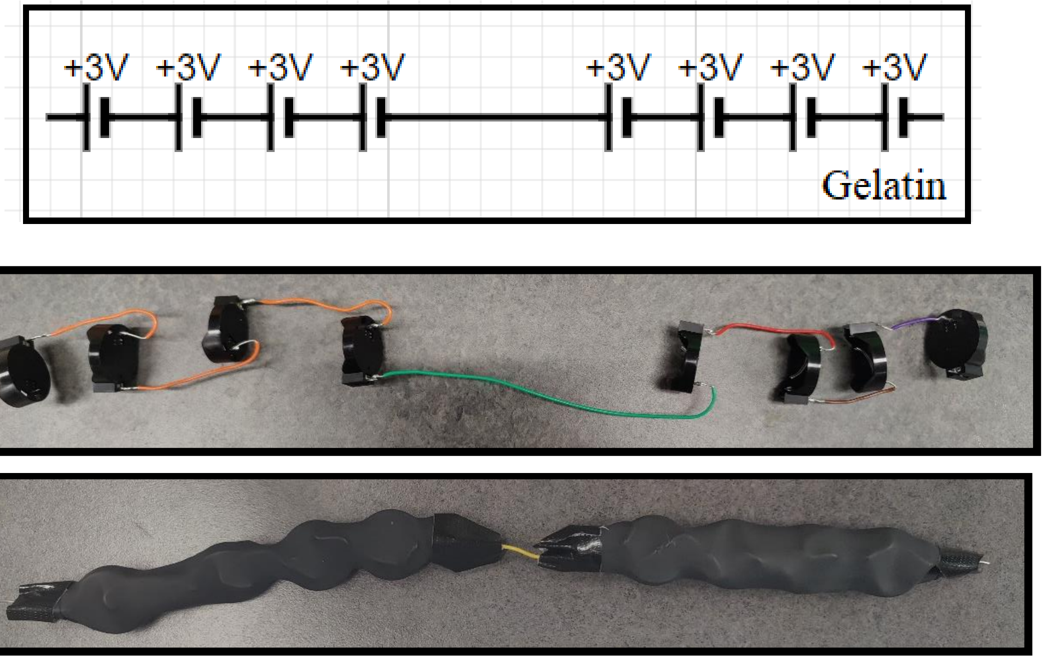

Figure 5: a) The circuit diagram for the eel; b) the cells for the eel soldered together; c) the eel wrapped in heat shrink with a little exposed wire at each end. [8]

3.4) Measuring the Equipotential Lines/Field Lines

The gelatin filled with 8 batteries in series were put inside 5L of pond water. Then the negative terminal of the voltmeter at a point in the water, and the positive terminal was moved around to take voltage measurements at many points in the water.

The eel was set in 4 different states.

1. Completely flat (180 degrees between the two segments)
2. Bent at 135 degrees between the two segments
3. Bent at 90 degrees
4. U shaped (almost 0 degrees between segments)

For each state, at least 5 separate equipotential lines were noted, which at least 3 or 4 points used to plot each equipotential line. Measurements were noted on a piece of conductive paper placed below the tank of water as shown below.

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[8] “CircuitLab.” *Circuit Diagram*, https://www.circuit-diagram.org/.

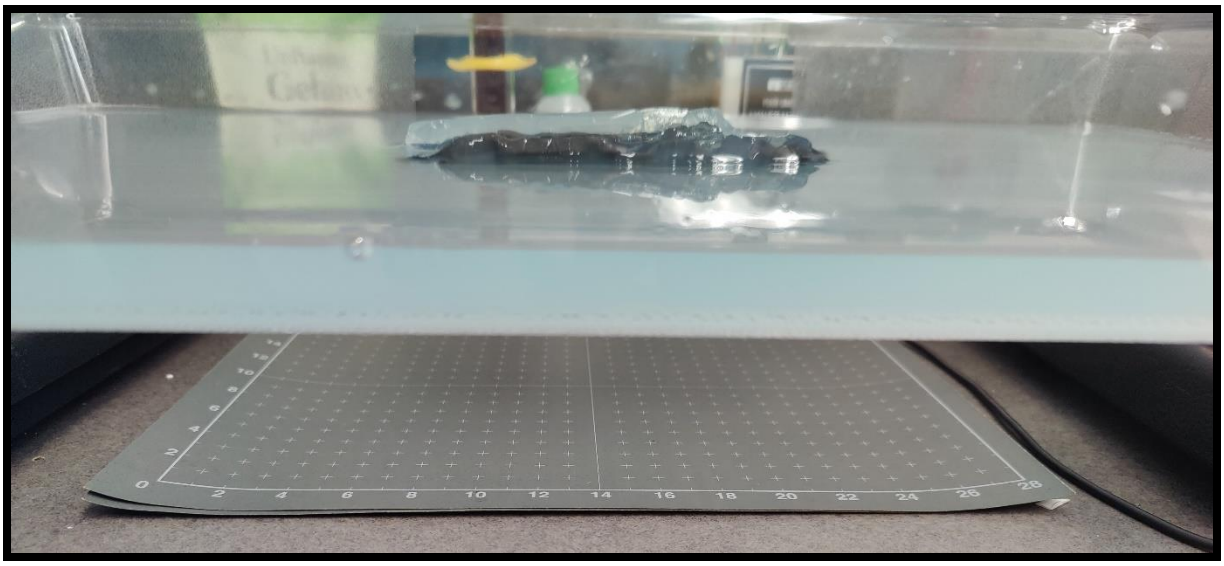

Figure 6: Showing the piece of paper under the tank on which measurements of the equipotential lines were noted.

3.5) Creating a simulation

To simulate the eel's organ's electric field, the organ was represented by a large concentration of positive ions at the front, a few positive ions till the halfway point, a few negative ions till the end and finally a large concentration of negative ions at the end.

These changes were plugged into a java simulation for the electric field and the equipotential lines were noted and compared to the ones measured above. Only the general shapes were compared, as we did not measure the specific values for the charges in each cell in the organ.

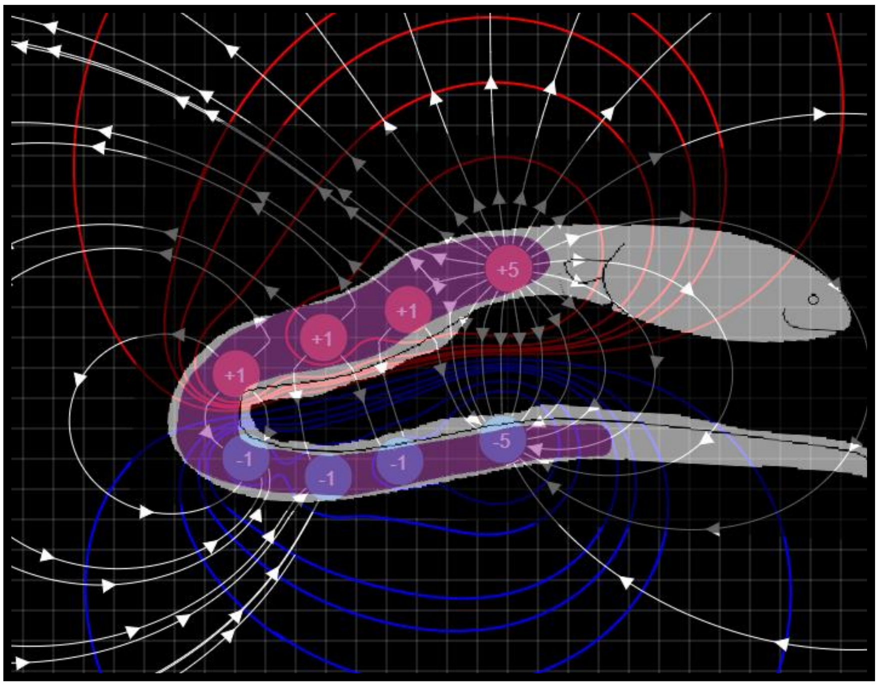

Figure 7: Showing an example of how the eel (from Figure 1) was modelled using test charges in a simulation, with Electric Field lines(white) and Equipotential lines (red and blue)[9]

4.0) Results (Status)

So far, the eel was set in 4 different positions, one as a straight line, with a 135-degree angle, with a 90-degree angle and almost completely bend in a U. The equipotential lines were mapped out for each trial.

4.1) Experimental Measurements

The field lines were mapped out below. Attached below are images for the experimental setup along with the results for each trial. The voltage of each equipotential line is marked on the line itself.

Figure 8: Showing the setup for the 4 trials. A) 180 degrees, B) 135 degrees, C) 90 degrees, and D) 0 degrees

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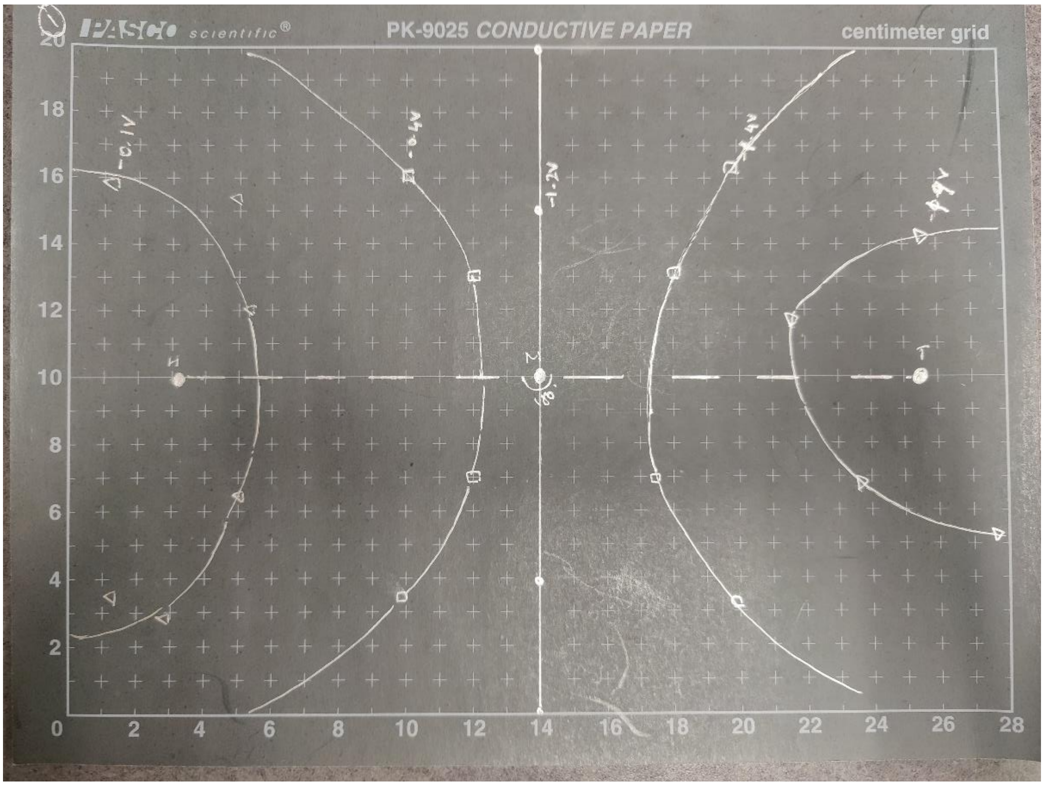
[9] College, Ithaca, and Ted Mburu. “Java Version- Electric Field Plotter.” *Point Charges Electric Field*, 2020, https://icphysweb.z13.web.core.windows.net/simulation.html.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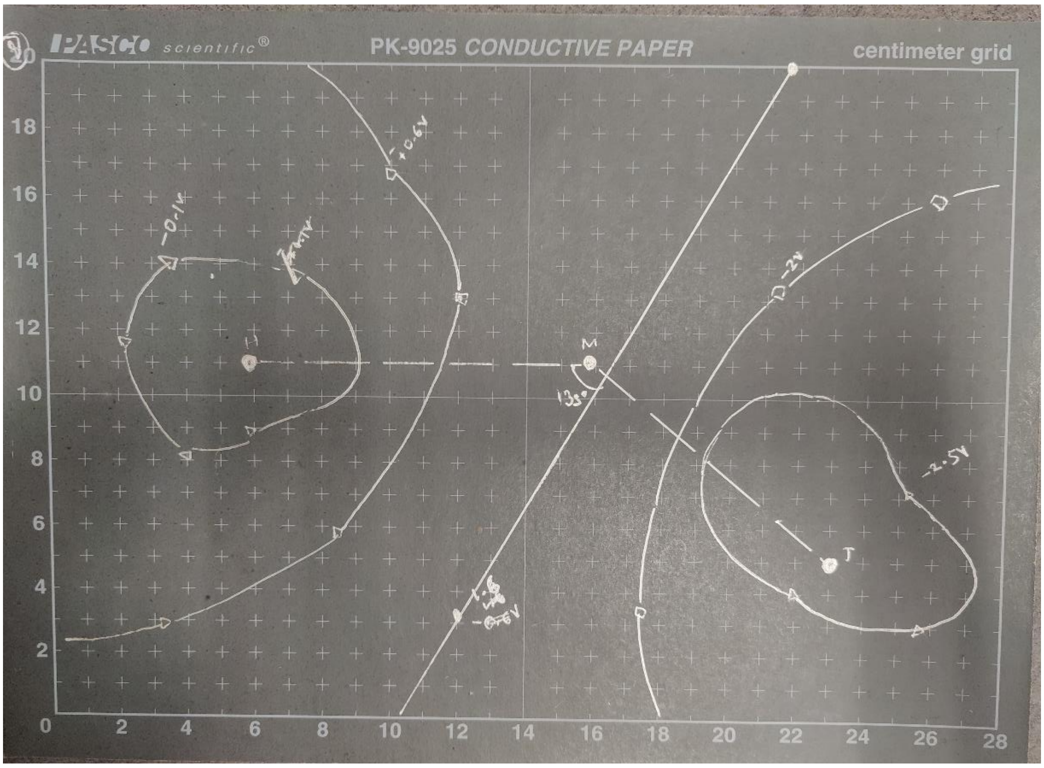
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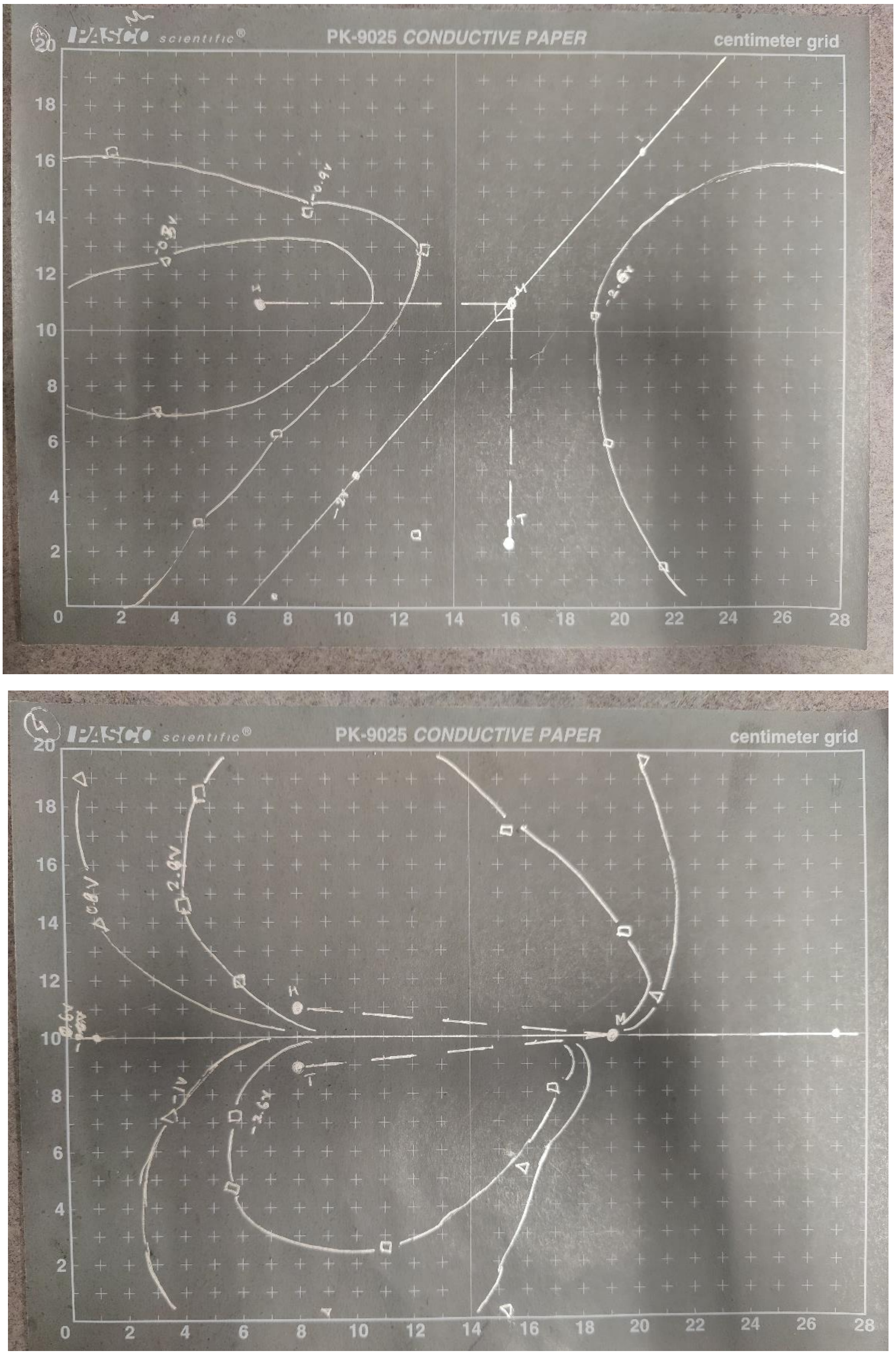

Figure 9: Showing the mapped Equipotential lines for A) 180 degrees, B) 135 degrees, C) 90 degrees, and D) 0 degrees.[10]

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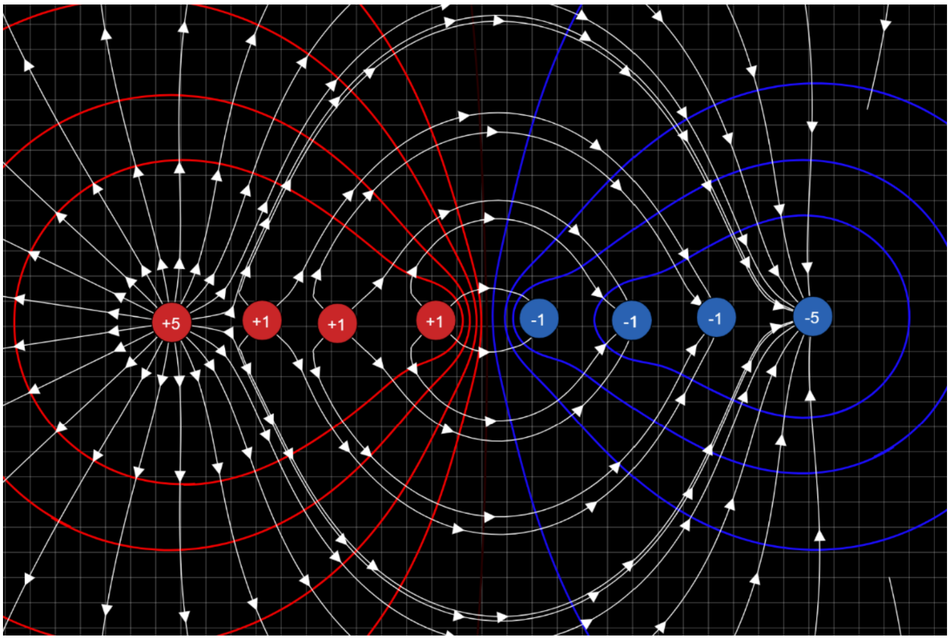
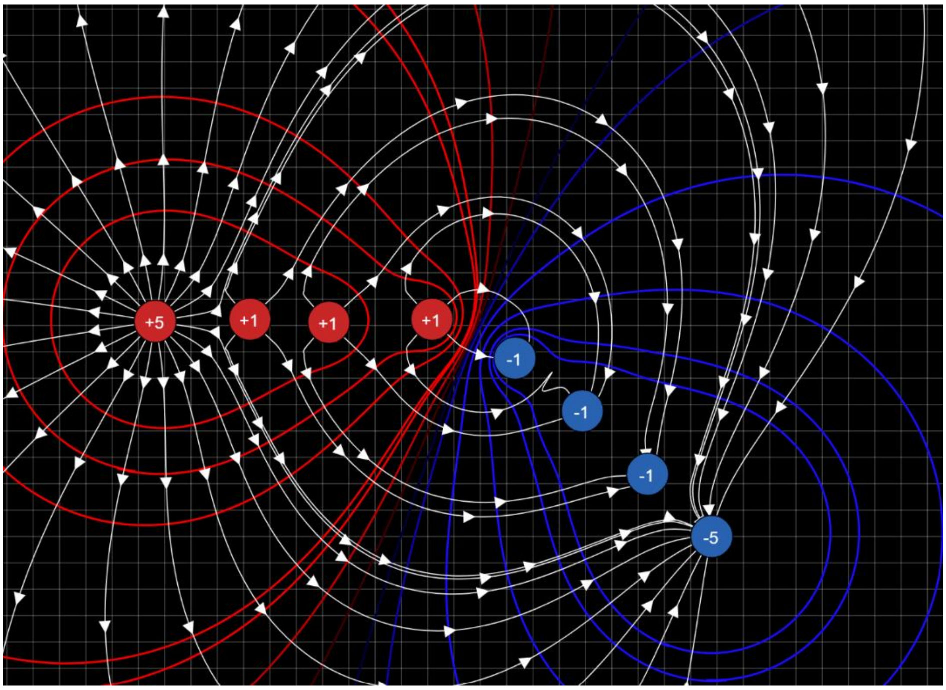
[10] In the images above, the marking H marks the Head of the eel (positive charge), M marks the middle and T marks the tail (negative charge). The head, middle and tail of the eel are marked with dotted lines and the equipotential lines are marked with solid lines.

As can be seen above, the field's magnitude close to the eel seems to increase (as expected) as the eel bends and brings the poles of the organ closer together. The highest line marked in the first trial is close to 1.9V whereas the last trial has an equipotential line at 2.9V.

4.2) Theoretical Measurements and comparisons

A java program (from Ithaca University) was used to place point charges in the shape of the eel, with positive charges near the head (largest at the head) and negative charges at the tail (smallest at the tail). This configuration allowed for the simulation's equipotential lines to match the experimental lines quite accurately.





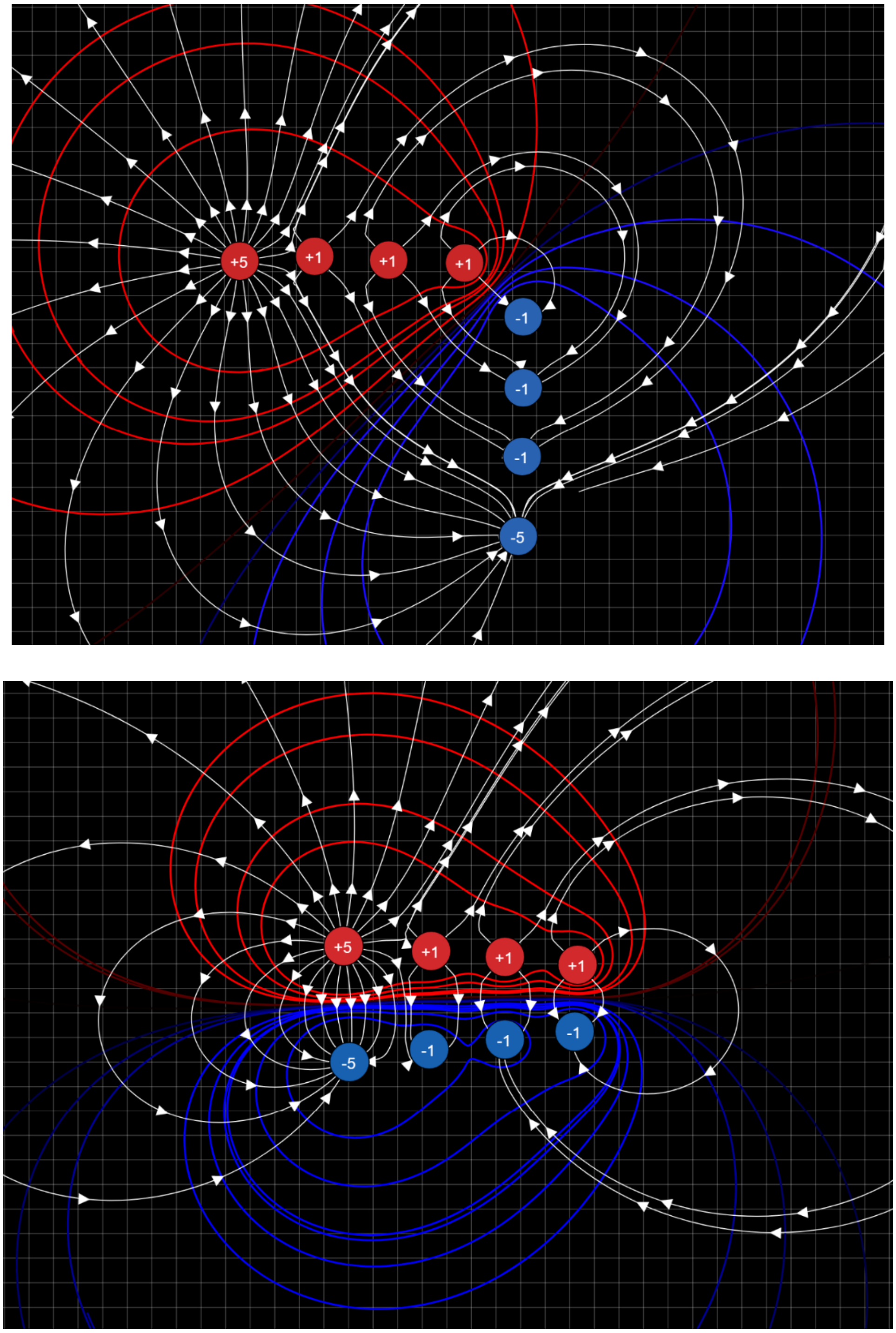


Figure 10: Showing the simulation of the electric field around the eel for A) 180 degrees, B) 135 degrees, C) 90 degrees, and D) 0 degrees with Electric Field lines(white) and Equipotential lines (red and blue)[11]

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[11] These images taken in the same configurations as the experiment was in image 9.

In the above images, Figure 10 a should be compared to 9 a, and so on. This makes it clear that the simulation’s equipotential lines match the experimental results quite well, especially in the first and last case (180 and 0 degrees).

Additionally, the reason I chose to place smaller positive charges along the first end of the eel and smaller negative charges along the second end was to recreate the gradient of charge that an eel creates. When the acetylcholine is released near one side, it provides a low resistance pathway for electrons to pass out of their sodium atoms leaving sodium ions behind. Sodium atoms, however, are distributed rather evenly through the electrocyte, and so when acetylcholine is released at one end, the atoms closer to that end are mostly converted into ions as the electrons move out of the electrocyte.

As those electrons move out, the positive charge that draws electrons out of the electrocyte reduces (as negative charge moves out)- so as we go deeper into the cell, fewer and fewer sodium atoms are converted into ions, and the positive charge distribution becomes less and less concentrated. So, the charge distribution is not a simple dipole- rather, it is a complicated gradient of charge. We can clearly see the similarity between the equipotential lines from our model and this version of the simulation.

5.0) Discussion

5.1) Comparing the simulation to the experimental measurements

After comparing the equipotential lines from the experimental measurements to the simulations, we can see that they are very similar, which means that the charge distribution from the batteries and in the simulations is similar to the charge distribution created by the electrocytes of the eel. This also means that the field lines from the simulations are what the electric field around the eel would look like.

In general, the technique of matching the charge configuration of the simulation to the experiment by matching their equipotential lines is a useful way to map out electric fields of complicated mechanisms. (As opposed to mapping out the equipotential lines and then the field lines both by hand.)

Additionally, as the eel bends, it is also clear that its field lines come closer together, and therefore its voltage volleys are more potent- which is the case in real eel attacks.

5.2) Using sausages instead of gelatin

Hydrogels and gelatin are extremely useful for reconstructing biological mechanisms that involve magnetic or electric fields because of their variable dielectric constants. Another idea for recreating the eel's body (or any other biological body) would be to use fish sausages inside a sausage casing. The meat of fish has a dielectric constant close to the body of an electric eel. This was not done as it would be considerably messier than using gelatin, but it might be interesting to see how using sausages affects the equipotential lines.

When casting the gelatin, we were forced to cover the batteries in heat shrink (to allow the gelatin to bind) which limited the flexibility of the eel greatly. The sausage mold would allow for much better flexibility, like a real eel.

5.3) Improving the gelatin mold

The gelatin mold also might benefit from more salts (they were sprinkled lightly over the ice tray used to set the gelatin). More salts would mean better conductivity, which might make it easier to distinguish between equipotential lines of the eel. Additionally, it would be great to use a larger icetray that can create a larger body around the batteries, so it becomes easier to wield without breaking/tearing.

5.4) Simulating the Electric Field

The simulation was not completely accurate for a few reasons. Firstly, the relative dielectric constants of the water and the eel are similar, but not the same. Freshwater can have a relative dielectric constant between 78 and 85, and the eel's body usually ranges between 80 and 90[12]. A simulation that could account for this would be more accurate than the one we have.

Additionally, the charges along the length of the body were estimated, and the real eel might have more (or less) charge along the length of its organ relative to its poles. One would need to measure this to be sure, but this was impossible for the gelatin mold because the batteries had to be covered in heat shrink so that the gelatin would set properly. (The sausage mold might help fix this.)

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[12] Xu, Jingjing. "A Fully Differential Switched-Capacitor ... - Wiley Online Library." *Nano-Dielectrics in Biosystems*, 2021, https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/cds2.12014.

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