PHY 224: Millikan Oil Drop Experiment

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Abstract

This report describes the result of re-performing the Millikan Oil Drop Experiment. It shows under an agreeable uncertainty that electrical charge is always an integer multiple of e, the charge of a single electron. We used a flat plate capacitor to suspend oil drops charged by tribo-electric charging. We measured the capacitor voltage needed to suspend a particular oil drop and its terminal velocity to extract its charge. This was repeated for 50 oil drops and the greatest common divisors of all calculated charges was found to be $(1.5 \pm 0.2) \times 10^{-20}$ C, which is our measurement of elementary charge. This agrees with the true elementary charge $e = 1.602 \times 10^{-19}$ C under 5% error.

1 Introduction

We performed a version of the Millikan Experiment to show that charged oil drops possess a charge that is an integer multiple of the charge of an electron i.e. $e = 1.60210^{-19}C$. The experiment involves injecting oil drops into the Capacitor cavity encompassed by the two plates of a parallel plate capacitor (see figure 1) and then making measurements of the terminal velocity of the oil drop as well as the voltage it takes to suspend the oil drop to calculate its electric charge. After attaining the charge values of many such oil drops, we deduce the elementary charge.

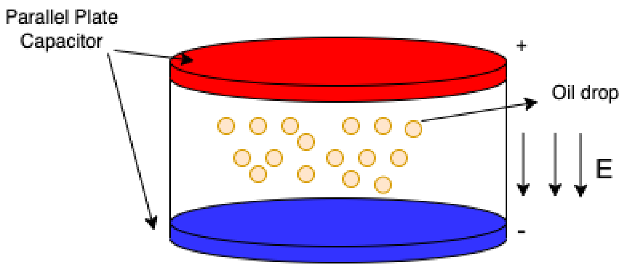

Figure 1: Capacitor cavity with the parallel plates of the capacitor. The red one is positively charged and the blue one is negatively charged. The electric field points downwards and hence negatively charged oil drops move upwards.

The oil drops are inserted into the cavity through an atomizer, which charges the oil drops via friction. This process is known as tribo-electric charging. This adds a few electrons to the oil drops adding a negative charge. The inserted oil drops are then subjected to a downward facing homogeneous electric field created by a flat plate capacitor. The electric field is directed downwards so that the oil drops which are negatively charged travel opposite to electric field direction. These upward moving oil drops were selected via a camera connected to a microscope.

To measure the charge of the oil drop, it's necessary to analyze forces acting on it because the electric force on the oil drop depends on the charge q of an oil drop via $F_e = qE$, where E is electric field strength. Now, various forces act on any particular charged oil drop in a homogeneous electric field. These are shown on the free body diagram in figure 2. The gravitational force $F_g = m_{oil}g$ on the oil drop is opposed by the upward electric force $F_e = qE$, the buoyant force $F_b = m_{air}g$ which is caused by the displacement of air by the oil drop, and the force of viscosity $F_v = 6\pi r\eta v$ shown pointing upwards because the oil drop is falling down. The viscous force is given by Stokes' Law which provides the magnitude of resistive force an object of radius r experiences when moving at a velocity v in a fluid with viscosity η.

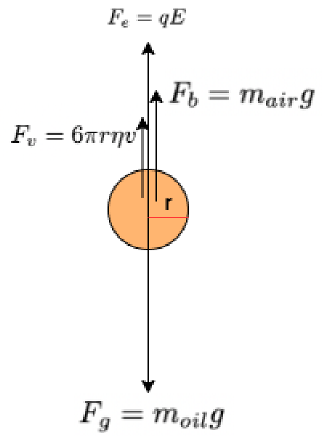

Figure 2: Free body diagram of a negatively charged oil drop of charge q and mass m_{oil} falling at an instantaneous velocity v in air. E is electric field magnitude, m_{air} is the mass of air displaced by the presence of the oil drop, and r is radius of the oil drop.

To extract the charge of the oil drop, we had two methods. We decided to use the first method which included measuring the "floating voltage" of the oil drop i.e. the potential difference V_f between the capacitor plates such that the oil drop is floating / stationary. Then, we measured the terminal velocity v_t of the oil drop with no electric field. The terminal velocity of the oil drop is the constant velocity it reaches in absence of electric force due to the resistive force of viscosity. The charge of oil drop is then given by:

$$q = 2 \cdot 10^{-10} \cdot \frac{v_t^{\frac{3}{2}}}{V_f} C \tag{1}$$

The method and procedure to calculate the floating voltage V_f and the terminal velocity v_t of negatively charged oil drops is outlined in the next section.

2 Procedure

2.1 Material Required

We used the following equipment (see figure 3) for the experiment: (1) Capacitor cavity; (2) Oil Atomizer with rubber bulb; (3) Wires providing power to the parallel plate capacitor via the power supply (4) with a knob (5) to alter potential difference; (6) light source; and (7) a microscope connected to a CCD camera, a stopwatch and a voltmeter. Note that except the power supply, voltmeter, and stopwatch, the whole experiment is called Leybold-Heraeus apparatus.

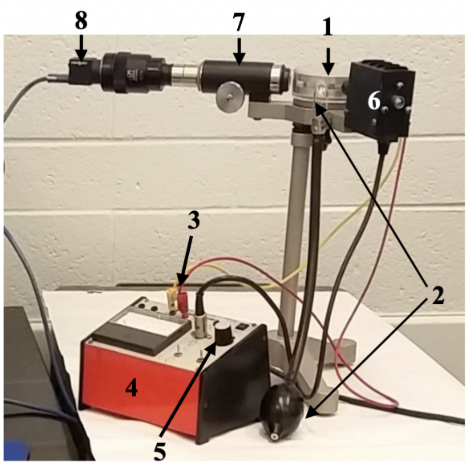

Figure 3: Picture of the Millikan Experiment Apparatus. Image courtesy of PHY 224 instructors.

2.2 Method

First, we inspected the given apparatus to make sure it was arranged properly. For example, we made sure the two holes in the capacitor cavity meant as an opening for the oil drops were clean so that oil drops can easily enter the cavity through the oil atomizer. We also made sure the spray nozzle from the oil atomizer was pointed at the two tiny holes in the capacitor cavity to get the best yield of oil drops. Then, we checked the wiring of the capacitor cavity to the voltage to make sure the electric field was pointing downwards. Finally, we turned on the voltage supply, the light source, the CCD camera, and opened the Millikan Experiment video tracking application on a desktop computer (see Figure 4). Now, to get the floating voltage and terminal velocity data for one particular oil drop, we proceeded as follows.

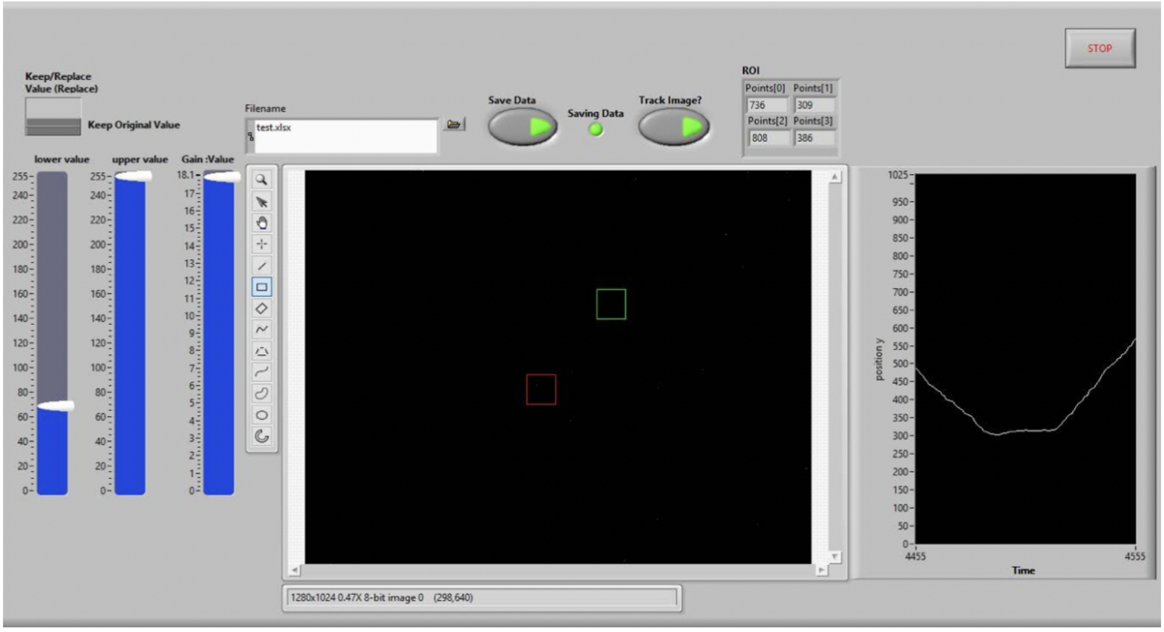

Figure 4: Image of the Millikan Experiment Software screen. The 3 blue bars on the far left are meant for adjusting the gain, upper, and lower values for the CCD camera. The middle black screen is the observation field of the camera where the oil drops are observed to be falling. The red square is the active tracking rectangle containing the oil drop. The graph on the far right is plotting the position of the centre of tracking rectangle (red) in terms of pixel position as a function of time. Image courtesy of PHY 224 instructors.

First, we set the gain value and upper gain of the CCD camera (see figure 4) at maximum via the software so that we can observe as many oil drops as possible. Next, we set the potential difference / voltage across the capacitor to be maximum by turning the knob on the voltage supply so that very heavy oil drops can just go across the screen and we can observe upward moving oil drops which are our ideal candidates for attaining a measureable floating voltage. Then, we pressed the rubber bulb of the oil atomizer to pump oil droplets into the capacitor cavity and observed the oil drops. As soon as we saw them, we slowly turned a circular knob on the microscope to get a particular oil drop moving upwards into focus on the screen. Then, to ensure that the tracking software doesn't loose the candidate oil drop, we turned the lower value (see figure 4) bar in the software to a high enough value to increase the contrast in the observation field. This eliminated the out of focus oil drops from the observation field because they appeared faint. This had the effect of being able to clearly see the oil drop under focus as a clear distinct white spot.

Since the candidate oil drops generally moved upwards very slowly, we waited for them to just reach the top of the screen. Then, we would draw a tracking rectangle encompassing the oil droplet and making it as small as possible and press "track image" button. This was because the tracking software outputted the position of the centre of the tracking rectangle and hence drawing a bigger rectangle could mean that the centre of the tracking rectangle might not move but the oil drop might be substantially moving. Then, we lowered the applied voltage with the knob provided on the power source to approximately attain the voltage at which the oil drop was almost floating i.e. the floating voltage V_f. Since the oil drop would wobble due to the Brownian motion from the collisions with the air molecules, we observed the graph of position vs time of the centre of the tracking rectangle and waited to observe a constant horizontal graph of position vs time. We noted the value of the floating voltage from the multimeter in an excel file.

Now, we put the name of the excel file in the file name field (see figure 4) where we want to record the position time data of the oil drop when we let it fall without the electric field. Once we had the oil drop stationary, we recorded the voltage and then we turned off the voltage supply. In absence of the electric force, the oil drop would fall under just the influence of gravity and the motion opposing forces in this case: the buoyant force and the viscous force. After the oil drop had reached its terminal velocity, we clicked on the save data button to start saving the pixel position of the centre of the tracking rectangle vs time to another excel file. When the oil drop neared the bottom of the screen, we clicked "Save Data" button again to stop saving the data. The difference between the last data point and the first data point combined with the total time of the data collection gives the velocity of the droplet. The total time is found in section 2.3. Then, we decreased the lower value in the program to 20 so that when we pump more oil drops, we can see them. This procedure was repeated multiple times to get floating voltage and terminal velocity for a total of 50 oil drops (see Table 1 in Appendix A). We use Equation 1 to find the charge of each oil droplet, and the Greatest Common Denominator (GCD) of each of these charges is the elementary charge we found which would be our measurement of elementary charge

To analyze the recorded data, we first had to figure out a way to convert the distance the oil drop travels in the recorded interval from pixels to actual physical distance in meters. We also had to calculate the time step i.e. the time between successive data points recorded by the software. The methods used to determine these values can be found in Appendix B.

3 Results

For the oil drop tracking software, the time step found is $\Delta t_{avg} = (2.0 \pm 0.1) \cdot 10^{-1} s$ and the distance per pixel is $(1.8 \pm 0.1) \times 10^{-6}$ m. We then calculated the terminal velocity of each oil drop by dividing the total distance travelled by the oil drop in the recorded time interval. The recorded data was converted into actual distance and time data via the conversion relations determined in Data Analysis section. After using the floating voltage V_f and the terminal velocity v_t to calculate the charge q, we plotted the 50 charge values on a histogram (see Figure 5) with a bin size of $3.7 \cdot 10^{-20}$ C [1].

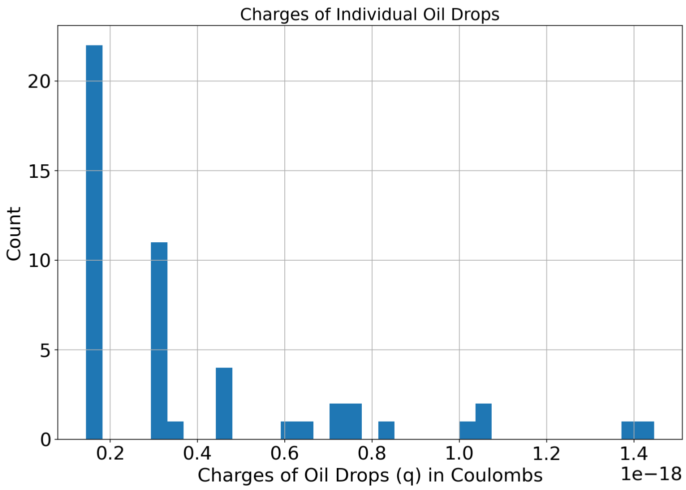

Figure 5: A histogram of the Millikan oil drop experiment. The x-axis is the charge of oil drops. The bin size is $3.7 \cdot 10^{-20} C$. Out of 50 oil drops, about 21 had their charge approximately in the range $0.145 \cdot 10^{-18}$ C to $0.182 \cdot 10^{-18}$ C, where the charge of the electron $e = 1.60 \cdot 10^{-19}$ C lies in the range.

From figure 5, we clearly saw that out of 50 oil drops, about 21 had their charge approximately in the range $0.145 \cdot 10^{-18}$ C to $0.177 \cdot 10^{-18}$ C, where the charge of the electron $e = 1.60 \cdot 10^{-19}$ C lies in the range. Thus, to get a sense of how the charge of the oil drops are distributed across in that single leftmost bar of the histogram above, we decided to plot another histogram for oil drops with charges less than $2.5 \cdot 10^{-19}$ C (see figure 6)

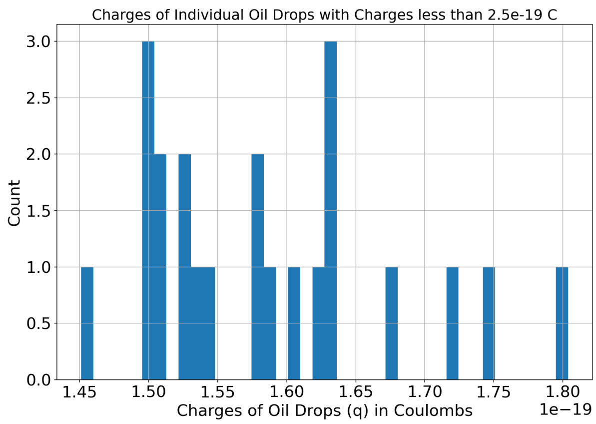

Figure 6: A histogram of the Millikan oil drop experiment of oil drops with charge less than $2.5 \cdot 10^{-19}$ C. The bin size here is $9 \cdot 10^{-22}$ C. Since the charge of the electron is $e = 1.60 \cdot 10^{-19}$ C, we see that the charge of oil drops are evenly spread around e indicating that under experimental uncertainty, all of them are charged by just one electron.

[1] see Appendix B.1 for calculation of bin size from data.

4 Data Analysis: Finding the elementary charge

To find the elementary charge, we need to find the greatest common divisor of the charges on the oil droplets. This can be difficult for decimals, especially with arbitrarily long decimal places. The method we used tests several candidate GCDs and compares them to find the most appropriate one.

First, we use the smallest 20 charges as candidate GCDs. If q_j is the j^{th} candidate GCD, or the j^{th} lowest charge, we find $\frac{q_i}{q_j}$ for each q_i, where q_i is the i-th charge (out of 50). If q_j is the real GCD, then each $\frac{q_i}{q_j}$ will be an integer. Therefore, to assess the goodness of each candidate GCD, we want to find d_j, the absolute value of the difference between $\frac{q_i}{q_j}$ and the nearest integer. Then, the total error for the j^{th} candidate to be the GCD could be calculated as

$$\sigma_j = \sum_i d_j$$

The best candidate GCD has the lowest value of σ. We find that σ_7 is the lowest error, so the 7^{th} smallest charge is the best candidate for the GCD which had the charge $q_7 = (1.5 \pm 0.2) \times 10^{-19}$ C

We then answer if some integer divided by the best GCD candidate is an even better candidate for the GCD. We find δ_k, the absolute value of the distance between $\frac{q_i}{q_7/k}$ and the nearest integer for k any integer from 1-100. The total error for each k is therefore

$$\beta_k = \sum_i \delta_k$$

The smallest β_k occurs at k=1, meaning that $\frac{q_7}{1} = q_7 = (1.5 \pm 0.2) \times 10^{-19}$ C is the best candidate for the GCD. To assess truly how good this GCD is, we found that 36 out of 50 charges have a value of d_j less than 0.1, and 45 out of 50 charges have a value of d_j less than 0.25. Since these values are quite small, we are confident that this value is an appropriate GCD. Therefore, the elementary charge calculated is $(1.5 \pm 0.2) \times 10^{-19}$ C.

5 Analysis

The results of the Millikan experiment are as expected. The value of the elementary charge we calculated is $e = (1.5 \pm 0.2) \times 10^{-19}$ C which when compared to the true elementary charge $e = 1.60 \times 10^{-19}$ C, is within 5% i.e. the standard elementary charge value is within the uncertainty of the calculated value.

The histogram in Figure 5 has specific bins with a high number of droplets in them. This shows the quantization of charge. For larger values on the histogram, the quantization is more ambiguous. If the percent error on each charge is the same, then larger charges have larger errors. These errors could be large enough that the measured charge is no longer close to an integer multiple of the elementary charge. This explains why the larger charges on the histogram seem less discrete, and why proving the quantization of charge for larger charges becomes more difficult.

We initially had two choices of methods to calculate the charge of the oil drops. Method 1, the one we decided to use, included finding the floating voltage and terminal velocity of the oil drops. Whereas, method 2 relied on getting the rise velocity, applied voltage, and the terminal velocity. We decided not to use the second method because in the time period the rising oil drop transitions from rising under the voltage V to falling at terminal velocity, the data collection software would still keep recording the data points which would have to be systematically removed, even manually. We could've made 2 sets of data points for each oil drop but we felt we can get equivalently good set of data in one go with method 1.

Furthermore, method 2 would introduce more error into the measurements than method 1. In method 1, we use Equation 1 to find the charge. This takes only two measurements. In method 2, the equation to find the charge takes an extra rise velocity measurement. Since each measurement has an uncertainty, and the combination of two different uncertainties yields a higher uncertainty, the charge from method 2 must have a higher uncertainty.

There were a few sources of error in the experiment. For example, even after we managed to narrow down the floating voltage V_f for the oil drops, sometimes due to Brownian motion i.e. the collision with air molecules, the oil drop and the tracking rectangle would move up and down randomly or even go sideways. This added error in what the actual floating voltage was. Furthermore, since we were only able to alter the voltage with a knob on the power supply, it was generally difficult to alter the applied voltage by small increments. Furthermore, due to collisions with air molecules again, when a candidate oil drop was allowed to fall without the electric field, sometimes it didn't quite follow a straight trajectory downwards. Since the terminal velocity was total downward distance travelled by the oil drop in a given time, we would have potentially under estimated the terminal velocity due to a slightly longer travel time. Both of these errors were enormous for light oil drops, which we identified as they seemed quite faint. Thus, we ignored these kind of oil drops. For these reasons, we tried to only chose oil drops that appeared sufficiently bright and were slightly heavy i.e. took generally longer to rise under a high electric field. However, a lot of times, even decently bright, and hence massive, oil drops had slanted trajectories and fluctuations at V_f. Thus, we believe these errors could have been minimized by having a more powerful and precise voltage source which would have allowed us to make choose more massive oil drops as our candidates for the experiment and get V_f just right. These oil drops would have felt less effects from brownian motion. Further, a cavity longer in height would be needed with camera kept in its lower part as it would take longer for them to reach terminal velocity due to a higher gravitational force. These sources of error meant that there was a range of 16 V that would stop the oil droplet, so we use an uncertainty of $u(V_f) = 8$ V for each oil droplet.

The smallest oil drops had unusual motions, so they were ignored. Their unusual motion could be due to an absence of charge, and a higher susceptibility to air motion. Also, drops with a smaller mass and volume have only a slightly smaller radius. This means that Stokes' resistance force becomes more important compared to the gravitational and buoyant forces.

6 Conclusion

In this experiment, we found considerable evidence of quantization of charge of oil drops. The elementary charge was measured to be $(1.5 \pm 0.2) \times 10^{-19}$ C which is within 5% error of the actual elementary charge $e = 1.6 \cdot 10^{-19}$ C. Overall, it was a successful experiment where some sources of error could have been minimized by using a larger cavity and a more powerful and precise voltage source.

A Data

Table 1: The charge (q), uncertainty in charge ($u(q)$), terminal velocity (v_t), uncertainty in terminal velocity ($u(v_t)$), and floating voltage (V_f) of the 50 candidate oil drops used in the experiment.

Serial No	q in C	$u(q)$ in C	v_t in ms^{-1}	$u(v_t)$ in ms^{-1}	V_f in V
1	1.57527E-19	2.33177E-20	5.49386E-05	5.39177E-06	517
2	1.51055E-19	2.23366E-20	5.7281E-05	5.62166E-06	574
3	3.29512E-19	4.96233E-20	5.56537E-05	5.46195E-06	252
4	1.50411E-19	2.22964E-20	4.92801E-05	4.83644E-06	460
5	1.80373E-19	2.67256E-20	5.69069E-05	5.58494E-06	476
6	3.19585E-19	4.77375E-20	6.34106E-05	6.22323E-06	316
7	3.02269E-19	4.50161E-20	6.60279E-05	6.48009E-06	355
8	1.37903E-18	2.04164E-19	0.000230944	2.26652E-05	509
9	3.02555E-19	4.49294E-20	7.27286E-05	7.13771E-06	410
10	7.63243E-19	1.13545E-19	0.00012654	1.24188E-05	373
11	4.57923E-19	6.88468E-20	7.11283E-05	6.98065E-06	262
12	1.71579E-19	2.5493E-20	4.88516E-05	4.79438E-06	398
13	4.49386E-19	6.64216E-20	0.000122715	1.20434E-05	605
14	1.06194E-18	1.59207E-19	0.000130882	1.28449E-05	282
15	1.49987E-19	2.22006E-20	5.33082E-05	5.23175E-06	519
16	1.45123E-19	2.14687E-20	5.40743E-05	5.30694E-06	548
17	3.53076E-19	5.21837E-20	0.000104947	1.02997E-05	609
18	1.0485E-18	1.5883E-19	0.000111307	1.09239E-05	224
19	1.50066E-19	2.25097E-20	3.51721E-05	3.45185E-06	278
20	1.5782E-19	2.33257E-20	6.12853E-05	6.01465E-06	608
21	1.62866E-19	2.40568E-20	6.61711E-05	6.49414E-06	661
22	1.63475E-19	2.41781E-20	5.94642E-05	5.83591E-06	561
23	3.08744E-19	4.58603E-20	7.29961E-05	7.16396E-06	404
24	1.52995E-19	2.26285E-20	5.68272E-05	5.57711E-06	560
25	4.44737E-19	6.63853E-20	8.03671E-05	7.88737E-06	324
26	1.52593E-19	2.31701E-20	2.99661E-05	2.94092E-06	215
27	3.10069E-19	4.6141E-20	6.87887E-05	6.75104E-06	368
28	8.36242E-19	1.24076E-19	0.000148317	1.45561E-05	432
29	2.98593E-19	4.41478E-20	9.10574E-05	8.93652E-06	582
30	7.35181E-19	1.11157E-19	8.99293E-05	8.82582E-06	232
31	4.54292E-19	6.73856E-20	9.99628E-05	9.81052E-06	440
32	1.62547E-19	2.41175E-20	4.97686E-05	4.88437E-06	432
33	3.22422E-19	4.8212E-20	6.22964E-05	6.11387E-06	305
34	1.67653E-19	2.49527E-20	4.54064E-05	4.45626E-06	365
35	1.54607E-19	2.38443E-20	2.62522E-05	2.57644E-06	174
36	1.60614E-19	2.38067E-20	5.17079E-05	5.0747E-06	463
37	7.23465E-19	1.07404E-19	0.000131527	1.29083E-05	417
38	3.10121E-19	4.60529E-20	7.39361E-05	7.25621E-06	410
39	6.10979E-19	9.20113E-20	8.39971E-05	8.24362E-06	252
40	1.58392E-19	2.34557E-20	5.37801E-05	5.27807E-06	498
41	6.29988E-19	9.65389E-20	7.05191E-05	6.92086E-06	188
42	1.44613E-18	2.17005E-19	0.000158127	1.55189E-05	275
43	1.5329E-19	2.26611E-20	5.90478E-05	5.79505E-06	592
44	3.04133E-19	4.50151E-20	8.56211E-05	8.403E-06	521
45	1.63286E-19	2.41403E-20	6.13101E-05	6.01707E-06	588
46	1.49854E-19	2.3199E-20	2.50171E-05	2.45522E-06	167
47	7.56997E-19	1.1178E-19	0.00019056	1.87019E-05	695
48	3.2662E-19	4.88349E-20	6.29732E-05	6.1803E-06	306
49	1.74312E-19	2.59549E-20	4.60031E-05	4.51482E-06	358
50	1.01449E-18	1.5032E-19	0.000179725	1.76385E-05	475

For each of the 50 oil drops, its position in pixels was calculated every 0.2 ± 0.1 seconds. Below we have provided the data for the 18^{th} oil drop. This drop was chosen because it has a relatively short data table. The entirety of the data can be found at https://drive.google.com/drive/folders/1ojFmcDcrxFDmljtSbyrpKv7MlWfiHzvk?usp=sharing. The time step and length per pixel are found in Table 3.

Table 2: Sample raw data of the positions of the 18^{th} oil drop while falling at terminal velocity with no electric field present.

t (s)	d (pixels)	t (s)	d (pixels)	t (s)	d (pixels)	t (s)	d (pixels)
0.2	331	2	448	3.8	562	5.6	676
0.4	337	2.2	461	4	575	5.8	689
0.6	351	2.4	474	4.2	589	6	703
0.8	366	2.6	487	4.4	600	6.2	717
1	379	2.8	501	4.6	611	6.4	731
1.2	392	3	513	4.8	622	6.6	744
1.4	405	3.2	526	5	635	6.8	758
1.6	419	3.4	537	5.2	648	7	772
1.8	434	3.6	550	5.4	662		

Table 3: Raw data used to determine the timestep between data points and the distance between each pixel in Table 2. The measurements of each trial along with the mean and standard deviation are shown.

	t (s)	Pixels per mm
Trial #1	0.1974647887	516
Trial #2	0.2158666667	582
Trial #3	0.1967391304	601
Mean	0.2033568619	566.3333333
Std Dev	0.01083988264	44.61315202

The timestep found is 0.20 ± 0.01 s and the distance per pixel is $(1.8 \pm 0.1) \times 10^{-6}$ m. The distance per pixel is found by taking the reciprocal of the mean pixels per millimeter, and the uncertainty is found through propagation of uncertainties.

B Calculations

B.1 Bin size of histogram

The program calculated the appropriate bin size for the histograms based on the smallest and highest charge values. In our data set, the minimum charge measured was $q_{min} = 1.45 \cdot 10^{-19}$ C and the maximum charge as $q_{max} = 1.45 \cdot 10^{-18}$ C. To properly see the quantization of charge, we decided to use 35 bins. This meant the bin size was:

$$= \frac{1.45 \cdot 10^{-18} - 1.45 \cdot 10^{-19}}{35} \text{ C}$$

$$= 3.7 \cdot 10^{-20} \text{ C}$$

B.2 Charge of an oil droplet

Using the first oil droplet in Table 1, we use Equation 1 to find the charge.

$$\begin{aligned} q &= 2 \cdot 10^{-10} \cdot \frac{v_t^{\frac{3}{2}}}{V_f} C \\ &= 2 \cdot 10^{-10} \cdot \frac{(5.49 \times 10^{-5})^{\frac{3}{2}}}{517} C \\ &= 1.58 \times 10^{-19} C \end{aligned}$$

We use error propagation to determine the uncertainty in the charge.
First, we find $u(v^{3/2})$.

$$\begin{aligned} u(v^{3/2}) &= 1.5 \cdot v^{3/2} \cdot u(v)/v \\ &= 1.5 \cdot (5.49 \times 10^{-5})^{3/2} \cdot \frac{5.39 \times 10^{-6}}{5.49 \times 10^{-5}} \\ &= 5.99 \times 10^{-8} ms^{-1} \end{aligned}$$

Finally, we find $u(q)$.

$$\begin{aligned} u(q) &= 2 \cdot 10^{-10} \cdot \frac{v_t^{\frac{3}{2}}}{V_f} \sqrt{\left(\frac{u(v^{3/2})}{v^{3/2}}\right)^2 + \left(\frac{u(V_f)}{V_f}\right)^2} \\ &= 2 \cdot 10^{-10} \cdot \frac{(5.49 \times 10^{-5})^{\frac{3}{2}}}{517} \sqrt{\left(\frac{5.39 \times 10^{-6}}{5.49 \times 10^{-5}}\right)^2 + \left(\frac{8}{517}\right)^2} \\ &= 2.33 \times 10^{-20} C \end{aligned}$$

C Time step and distance conversion

To determine the time step between data points, we repeated the above procedure 3 more oil drops, meaning three data sets to measure time step, with one exception. This time we used a stop watch to mark the time between the the moments we pressed the "Save Data" button presses which started and stopped recording position-time data for the oil drop to the excel file. We timed all the three data sets and then divided the number of data points by the total time of the data collection measured by the stopwatch. Then, we took the average of the three time step values we found: $\Delta t_{avg} = (2.0 \pm 0.1) \cdot 10^{-1} s$. The total time of each fall is the time step multiplied by the number of data points.

To determine the distance between each pixel, we removed the capacitor cavity and put a ruler in front of the camera. We then drew a tracking rectangle with its height equal to one millimeter mark on the ruler. The software provided us with the dimensions i.e. height in pixels of the box and we used it to find the number of pixels between the millimeter marks. Since small movements of the ruler move the image by large amounts, it is difficult to get an accurate reading and to obtain an accurate uncertainty in this measurement. Three measurements were made and we got the conversion formula as: 1 pxl $= (1.8 \pm 0.1) \times 10^{-6}$ m. For the timestep and the pixels to meter ratio, the value used in this report is the mean of the measurements, and the uncertainty is the standard deviation.

D Indication of who did what?

Both Meet and Sam collaborated on all aspects of the lab. Sam lead the work on the coding and the Appendix, and Meet lead the work on the rest of the report.