Candidate 2 evidence

Advanced Higher Physics

Speed of Light

Contents

Abstract

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Aim: To calculate the permeability of free space, μ_o, using a current balance.

Conclusion: $\mu_o = 1.265 \times 10^6 \pm 0.154 \times 10^6$ m kg s^{-2} A^{-2}

Experiment 2: Capacitance

Aim: To calculate the capacitance of a capacitor using a vibrating switch.

Conclusion: $C = 2.5 \times 10^{-6} \pm 0.1 \times 10^{-6}$ F

Experiment 3: Permittivity of Free Space

Aim: To calculate the permittivity of free space, ε_o, using a parallel plate capacitor.

Conclusion: $\varepsilon_o = 1.07 \times 10^{-11} \pm 0.24 \times 10^{-11}$ m^{-3} kg^{-1} s^4 A^2.

Overall conclusion

The speed of light is $2.718 \times 10^8 \pm 0.69 \times 10^8$ m s^{-1}.

Introduction

There have been many previous account to calculate the speed of light throughout history, beginning with Galileo. He looked at timing light over a distance, and using the formula $v = \frac{d}{t}$. However this was unsuccessful as the methods used to time the light were not advanced enough and the uncertainty would have been too high to come up with a valid conclusion on the value of the speed of light.

In 1629, Isaac Beckman positioned a mirror behind a cannon and asked spectators if they observed a visual delay in the reflection when the cannon was fired, and to time this delay. This was intended to conclude if light was instantaneous or not, by looking at if the light from the explosion took longer to travel distance 1 or distance 2, as shown in diagram 2. However, due to a lack of resources, the experiment was unsuccessful. (Smallwood, K (2013))

Diagram 2

In 1676, the speed of light was successfully measured for the first time by astronomer Olaus Roemer, through his study of Jupiter's moons. He discovered that it took 7 minutes longer between each eclipse if the Earth was moving away from the planet during its orbit of the sun, than if it was moving towards Jupiter. This was because the light had further to travel and so took longer to reach the Earth. From this, he was able to conclude that light is not instantaneous. As the speed of Earth's orbit was known, it could be calculated how far the Earth had moved, and so the speed that the light had travelled at could be determined. He approximated that the speed of light is around 225 000 000 m s^{-1}, astonishingly close to the actual value of 299 792 458 m s^{-1}given the method used. (Lee, A)

Armand Fizeau was able to further improve the estimation of the speed of light in 1849, when he created an experiment using a rapidly spinning toothed wheel. A light beam was set up and positioned facing the teeth of the wheel, as shown in diagram 3. 8 km away from the light source was a mirror intended to reflect the light. The angular velocity of the light was then altered until the teeth of the wheel do not interfere with the reflected beam of light, and it returns to the observer through the gap next to the one it previously travel through. As the angular velocity, the length of each tooth on the wheel and the distance between the wheel and the mirror was known, Fizeau was able to calculate the speed of light, estimating a velocity of 315 000 000 m s^{-1}. This experiment was later repeated by Leon Foucault, although his use of rotating mirrors allowed him to get a much more accurate result of 298 000 000 m s^{-1}. (Gibbs, P (1997))

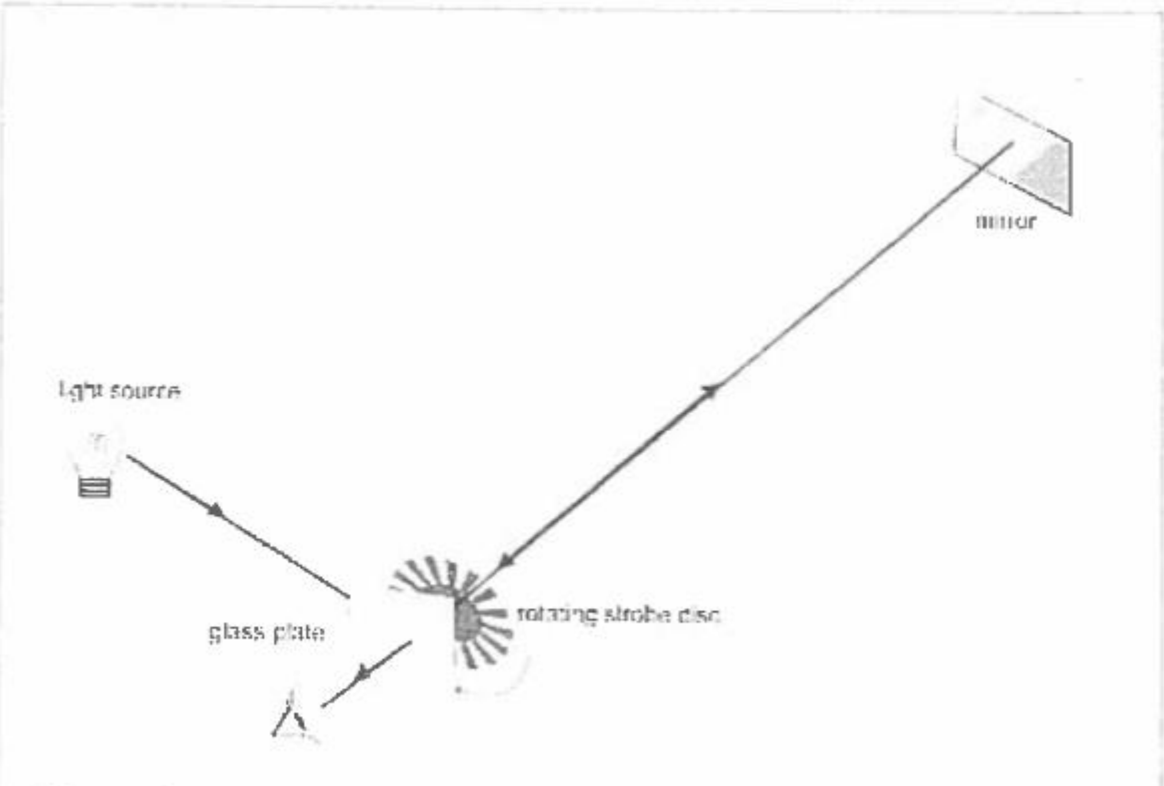


Diagram 3[1]

Calculating the speed of light was a major breakthrough in Physics and has created the foundation for many discoveries and equations since.

Perhaps the most famous use of the speed of light is in Einstein's $E = mc^2$. This formula shows that there is a relationship between the energy of an object or particle and it's mass, and allows the energy that has been converted from mass in a nuclear reaction to be calculated. The difference in mass of the particle(s) before and after the reaction can be substituted into the equation and by using the equation, including the speed of light at 3×10^8 m s^{-1}, the energy released can be calculated. This equation has since been used in the creation of atomic bombs, and featured in a report to the American government by Henry DeWolf Smyth, on the progress of the creation of an atomic bomb which was later used in Hiroshima and Nagasaki. Jha, A (2014)

The speed of light is also fundamental in Einstein's theory of relativity. This theory suggests that is an object travelling at a velocity nearing that of the speed of light, it will experience some relativistic effects such as length contraction and time dilation. Einstein predicted, through many thought experiments, that the speed of light is constant, and so suggested that as a result, everything else must not be constant, in order to fit with this theory. He proposed that mass, length and time are all able to change in relation to a stationary observer, only noticeable at velocities greater than 0.9c. Einstein came up with three equations to predict this relative alteration:

$$t' = \frac{t}{\sqrt{1-\frac{v^2}{c^2}}}$$ (Equation 1)

$$L = L'\sqrt{1-\frac{v^2}{c^2}}$$ (Equation 2)

$$m' = \frac{m}{\sqrt{1-\frac{v^2}{c^2}}}$$ (Equation 3)

[1]http://ysjournal.com/archive/ysj-issue-4/how-has-the-speed-of-light-been-measured-experimentally-historically/

Understanding relativity has been fundamental in the creation of satellites and GPS, as the orbiting objects must take the effects of high speed into consideration when being programmed, to ensure they function successfully.

The constant of the speed of light also allows the Schwarzchild radius, or event horizon, of a black hole to be calculated. This is the distance from a black hole at which light can escape its gravitational field. This distance can be calculated using the mass of the black hole and the universal gravitational constant, with the formula $r_s = \frac{2GM}{c^2}$.

Knowing the value of the speed of light has also provided crucial evidence to the big bang. Red shift is one of the many phenomena that prove the universe is continuously expanding and would not have been discovered without the speed of light. Stars in the distance appear red, due to the Doppler effect, as the light waves emitted are being expanded due to the star travelling away, as in diagram 4, and so appear red. Stars closer to Earth often appear blue, as the light waves are being compressed, indicating that they are travelling towards us. This suggests that the Universe is expanding from a single point and so proposes the idea that the universe was created in the way suggested by the big bang theory.

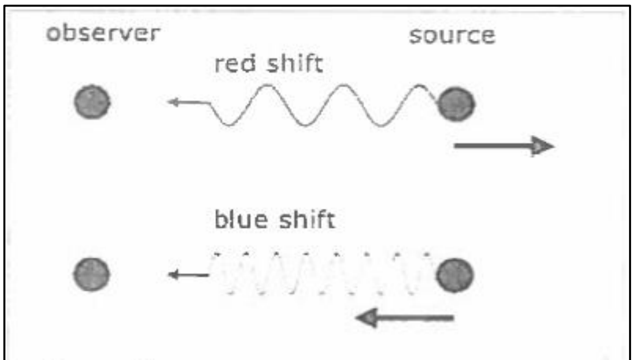


Diagram 4[2]

The speed of all electromagnetic waves in a vacuum is constant, regardless of wavelength or frequency. James Clark Maxwell proposed the idea that a "changing electric field could set up a changing magnetic field", and these are linked to electromagnetic waves. This agrees with the discovery of Faraday, that a moving or changing magnetic field can create a changing electric field. EM waves have both magnetic and electric mechanisms, which oscillate perpendicular to each other in phase. They also both oscillate perpendicular to the direction of the flow of energy, as shown in diagram 1.

[2]http://a-levelphysicstutor.com/wav-doppler.php

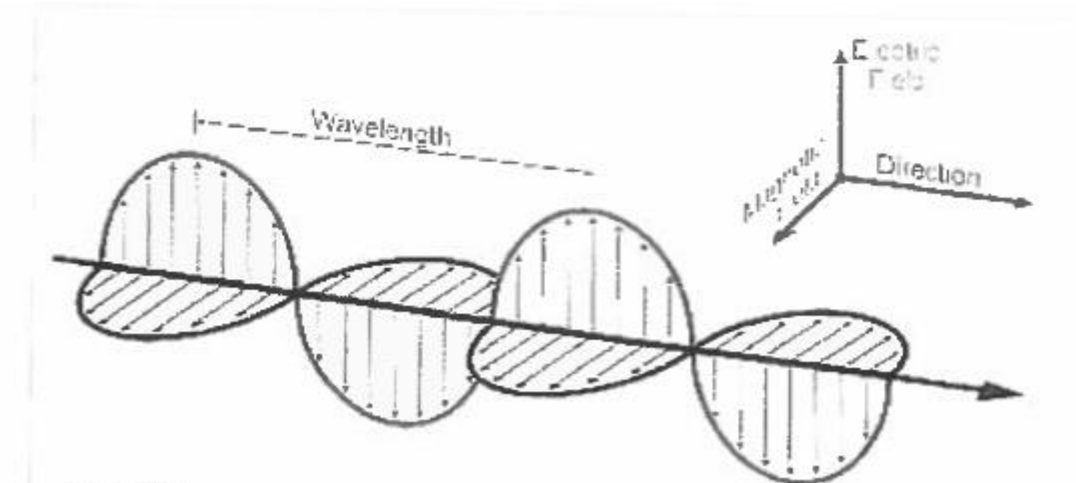


Diagram 3[1]

Through studying this, Maxwell was able to come up with an equation to calculate the speed of light in a vacuum, c:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \quad \text{(Equation 4)}$$

This is calculated, using ε_0, the permittivity of free space, and μ_0, the permeability of free space.

The permeability of a medium is a way of calculating the change in its magnetic induction due to the presence of an electric field. It can be calculated using a current balance, as shown in the first experiment. In order to calculate μ_0, a current balance must be set up, and different forces (in the form of paper masses) must be applied to the top wire. The current must then be increased until the top wire returns to its original position and this value is noted. A graph of Force and the average current squared is created and the gradient is inserted into the equation:

$$\frac{F}{I^2} = \frac{\mu_0 L}{2\pi r} \quad \text{(Equation 5)}$$

The length of the top wire, L, and the distance between the wires, r, are also substituted into the formula, which is then rearranged, to find a value for μ_0.

The permittivity of a medium defines how an electric charge would be affected by the matter, or vacuum. A higher permittivity means the medium is less likely to conduct electric charge and therefore decreases the electric field. The permittivity of free space can be calculated using a parallel plate capacitor, as the final experiment. ε_0 can be calculated using a parallel plate capacitor but first it needs to be confirmed that the capacitance can be measured, using a signal generator and a vibrating switch, with the formula

$I = fCV$ (Equation 6)

as in the second experiment. By measuring the values of current, as voltage increases, a graph of I/V can be obtained. Using the frequency supplied by the signal generator, the capacitance of the capacitor can be calculated, confirming this relationship. This formula can then be used to calculate the capacitance of a parallel plate capacitor. Once this value has been determined, it can be substituted into the formula

$C = \frac{\varepsilon_0 A}{d}$ (Equation 7)

along with the area of the parallel plated and the distance between them, the value of ε_0 can be calculated.

[1]http://www.visionlearning.com/en/library/Physics/24/Light-and-Electromagnetism/138

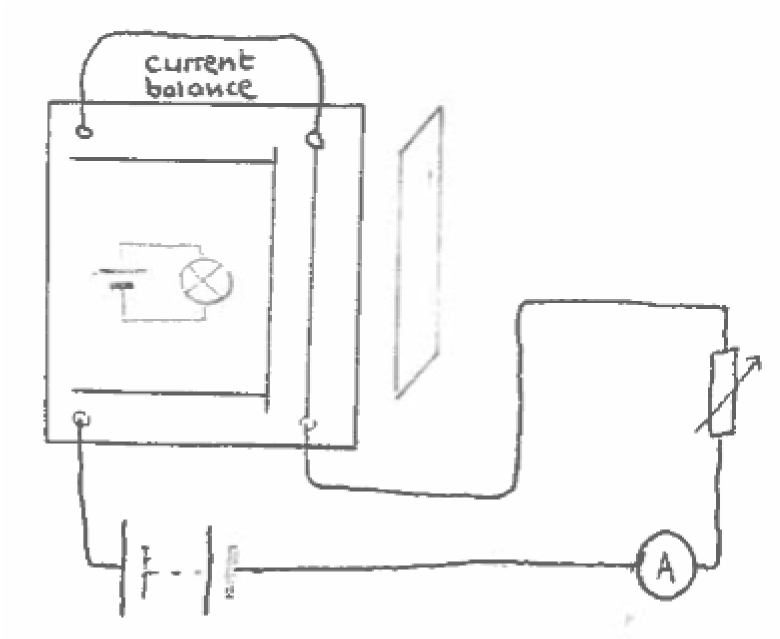
Permeability of Free Space Experiment

Aim: To calculate the permeability of free space, μ_0, using a current balance.

Hypothesis: The value of μ_0 will be 1.257×10^{-6} m kg s^{-2} A^{-2}.

Apparatus:
Current balance
Variable resistor
Paper masses
Ammeter
Power supply

Method: A current balance is attached to a power pack, an ammeter and a variable resistor. The distance between the shadows of the two wires is measured, when no current is applied, and a note is taken of where the shadows fall.
A force, in the form of a paper weight, is then applied to the wire using plastic tweezers, and the current is increased, using the variable resistor until the top wire returns to its original position, measured using the shadows. The current is noted.
The experiment is carried out with various forces and repeated four times, so the average can be calculated.



Results:

Mass (g)	Force (μN)	Current (A) 1	Current (A) 2	Current (A) 3	Current (A) 4	Current (A) Average	Average current squared (A^2)
0.011	108	4.28	4.08	4.21	4.23	4.20	17.64
0.019	186	10.17	9.94	8.33	8.47	9.23	85.15
0.026	255	9.66	11.23	8.99	10.05	9.98	99.65
0.032	314	11.92	12.97	11.05	12.46	12.10	146.41
0.039	382	12.47	14.17	13.11	13.23	13.25	175.43

$L = 107 \times 10^{-3}$ m

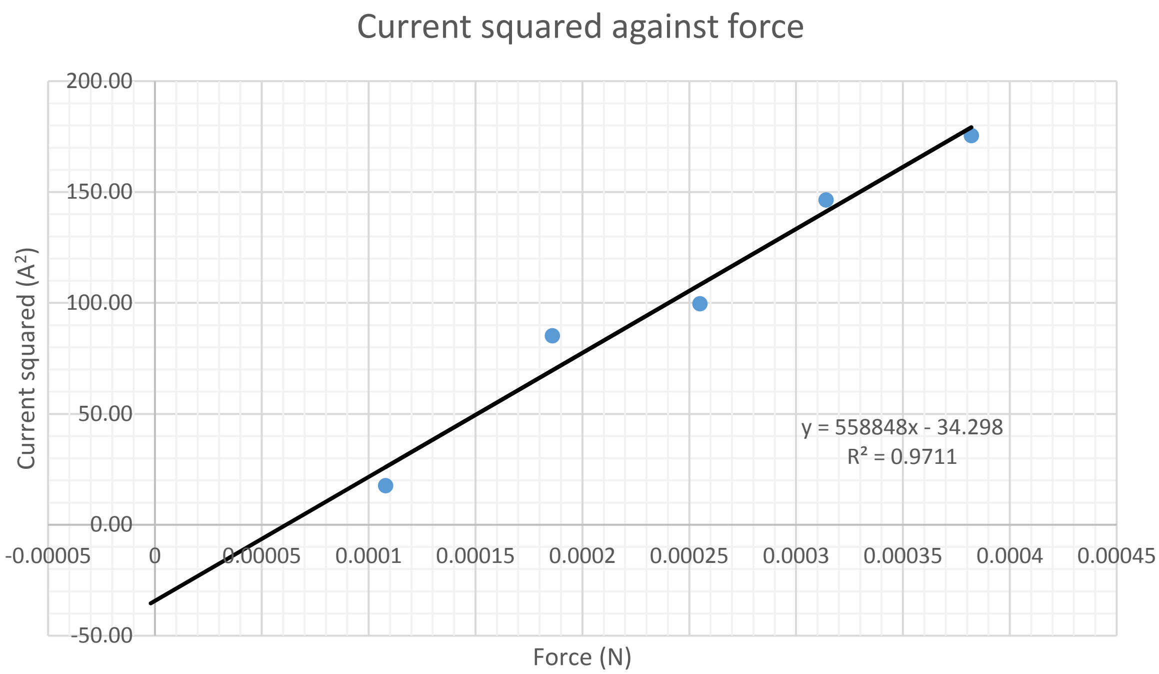
$R = 12 \times 10^{-3}$ m

Uncertainties

Current (A)	Current squared	Calibration uncertainty (A)	Random Uncertainty (A)	Scale reading uncertainty (A)	Combined Uncertainty (A)	Current squared Uncertainty (A^2)	Percentage uncertainty (squared)
4.20	17.64	±0.03	±0.05	±0.01	±0.06	±0.12	±0.68%
9.23	85.15	±0.06	±0.46	±0.01	±0.46	±0.92	±1.08%
9.98	99.65	±0.06	±0.56	±0.01	±0.56	±1.12	±1.12%
12.10	146.41	±0.07	±0.48	±0.01	±0.49	±0.98	±0.67%
13.25	175.43	±0.08	±0.43	±0.01	±0.44	±0.88	±0.50%

Length:
Value: 107×10^{-3} m
Calibration: $\pm 0.5 \times 10^{-3}$ m
Scale reading: $\pm 0.5 \times 10^{-3}$ m
Combined uncertainty: $\pm 0.7 \times 10^{-3}$ m
Percentage uncertainty: ±0.66%

Radius uncertainty:
Value: 12×10^{-3} m
Calibration: $\pm 0.5 \times 10^{-3}$ m
Scale reading: $\pm 0.5 \times 10^{-3}$ m
Combined uncertainty: $\pm 0.7 \times 10^{-3}$ m
Percentage uncertainty: ±5.89%



$$\frac{F}{I^2} = \frac{\mu_0 L}{2\pi r}$$

$$m\ (gradient) = \frac{I^2}{F}$$

$$m = 558848$$

$$\frac{F}{I^2} = \frac{1}{m}$$

$$\frac{F}{I^2} = \frac{1}{558848}$$

$$\frac{F}{I^2} = 1.7893\ldots\times 10^{-6}$$

$$\frac{F}{I^2} = \frac{\mu_0 L}{2\pi r}$$

$$L = 107\times 10^{-3}$$

$$r = 12\times 10^{-3}$$

$$\frac{F}{I^2} = 1.7893\ldots 10^{-6}$$

$$1.7893\ldots 10^{-6} = \frac{\mu_0 \times 107\times 10^{-3}}{2\pi \times 12\times 10^{-3}}$$

$$\mu_0 = 1.261\times 10^{-6}\,\mathrm{m\ kg\ s^{-2} A^{-2}}$$

From Linest

Gradient:	558848.4611	y intercept:	-34.29784932
Gradient uncertainty:	55664.61732	y intercept uncertainty:	14.849104
R^2:	0.9711		

Gradient uncertainty

Absolute: ± 55664.61732
Percentage: ± 9.96 %

Total uncertainty: $\sqrt{5.89^2 + 9.96^2}$ (rule of three, so no 0.66)

=±11.57 %

Absolute combined uncertainty: $\pm 0.146 \times 10^{-6}$ m kg s^{-2} A^{-2}

Conclusion

The permeability of free space was found to be $1.261 \times 10^{-6} \pm 0.146 \times 10^{-6}$ m kg s^{-2} A^{-2}

Evaluation

The value obtained from the experiment, 1.261×10^{-6} is very close to the expected value of 1.257×10^{-6}, and this value is within the uncertainty. The masses were able to be measured to three decimal places, which allowed them to be quite precise and give more accurate results. As well as this, the same current balance was used for each reading, meaning the length of the wire was constant throughout the experiment. In an ideal world, the experiment would be repeated more than four times in order to get more accurate current values and to reduce the uncertainty of the graph. As the masses placed on the current balance were very small, the current value fluctuated and hence was not very precise, as seen in the second current reading for the 0.026 g mass and the third current reading for the 0.032 g mass. When comparing these two results, the larger mass appeared to require less current to return the wire to its original position than the smaller mass, and so could be misleading. Another issue faced, which could ideally be eliminated in a scientific laboratory, was time constraints. As the experiment had to be conducted within the school hours and not overrun into class time, the experiment had to be left unattended in a room with other students. Inevitably this caused the experiment to be knocked various times and the positioning of the wire to change, meaning that it cannot be guaranteed that the distance between the wires, r, was constant at all times. Also, a dampener was not available and the lack of this may have impeded the results, as it would restrict the oscillation of the top wire when a mass is added to it, which would make the displacement clearer.

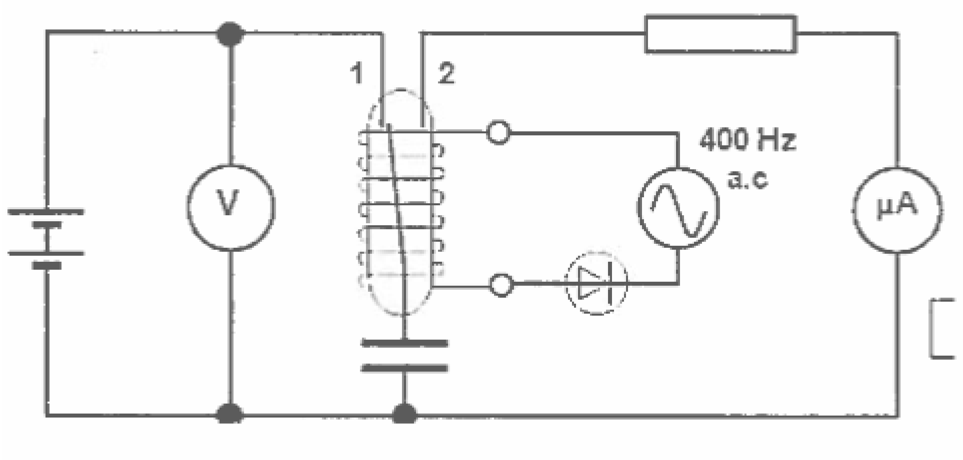
Capacitance Experiment

Aim: To calculate the capacitance of a capacitor using a vibrating switch.

Hypothesis: The capacitance will be 2.2 μF, as stated on the capacitor.

Apparatus:
Variable 100 V dc supply
Signal generator
Voltmeter
Capacitor
Ammeter
Vibrating switch
Smoothing unit
Switch

Method: The apparatus is set up as shown in the diagram below.



The voltage is increased and the current recorded at various voltages.
This is repeated five times for each voltage and the average current for each result is calculated.
A graph is then created of the average current against voltage and the gradient of the graph is calculated.
The gradient is divided by the frequency of the signal generator, to find the capacitance according to the equation I = fCV.

[4]http://www.schoolphysics.co.uk/age16-19/Electricity%20and%20magnetism/Electrostatics/text/Capacitor_types_and_measurement/index.html

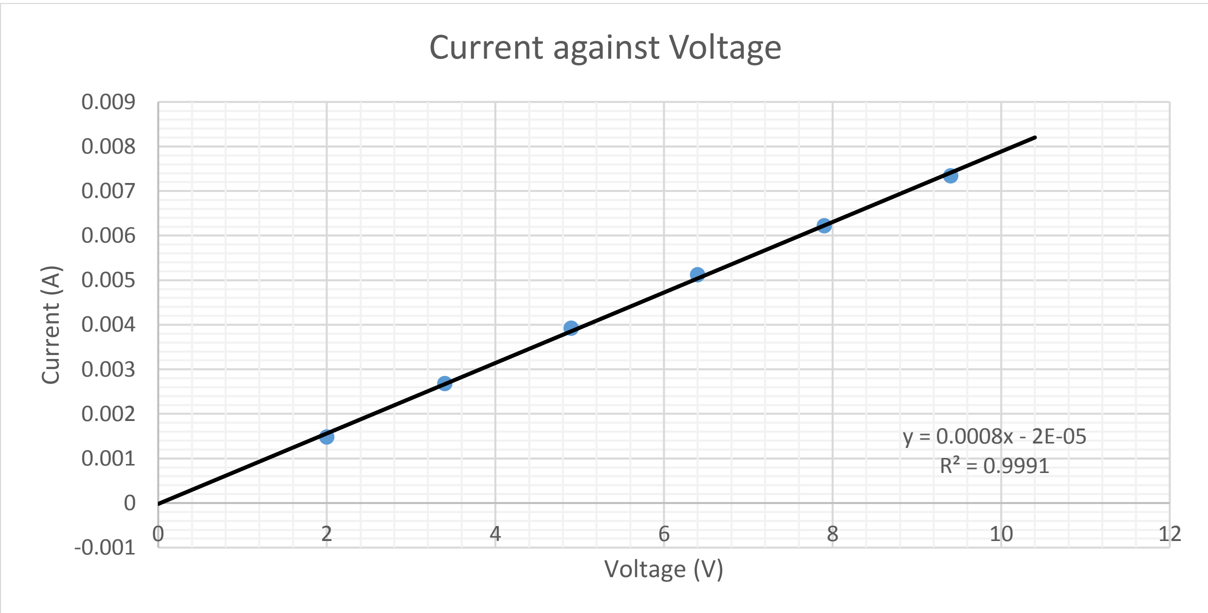
Results:

Voltage (V)	Current 1 (mA)	Current 2 (mA)	Current 3 (mA)	Current 4 (mA)	Current 5 (mA)	Average Current (mA)
2.0	1.4	1.4	1.6	1.5	1.5	1.5
3.4	2.6	2.5	2.8	2.8	2.7	2.7
4.9	3.8	3.7	4.1	4.0	4.0	3.9
6.4	5.0	4.9	5.4	5.2	5.1	5.1
7.9	6.0	5.9	6.6	6.3	6.3	6.2
9.4	6.9	7.0	7.8	7.5	7.5	7.3

Frequency = 320 Hz

Uncertainties:

Voltage (V)	Average Current (mA)	Calibration Uncertainty (mA)	Random Uncertainty (mA)	Scale Reading Uncertainty (mA)	Combined Uncertainty (mA)	Percentage Uncertainty (%)
2.0	1.5	±0.1	±0.1	±0.1	±0.1	9.9
3.4	2.7	±0.1	±0.1	±0.1	±0.2	5.7
4.9	3.9	±0.1	±0.1	±0.1	±0.2	4.1
6.4	5.1	±0.1	±0.1	±0.1	±0.2	3.4
7.9	6.2	±0.1	±0.1	±0.1	±0.2	3.2
9.4	7.3	±0.1	±0.2	±0.1	±0.2	3.1



Gradient = I/V = 8×10^{-4}

I/V = fc

$8 \times 10^{-4} = 320 \times C$

C = 2.5×10^{-6} F

Frequency

Value: 320Hz
Calibration uncertainty: ±3 Hz
Scale reading uncertainty: ±1 Hz
Combined uncertainty: ±3 Hz
Percentage uncertainty: ±0.99 %

From Linest

Gradient:	0.000790561	y intercept:	-0.00001984
Gradient uncertainty:	0.000012118	y intercept uncertainty:	0.000075237
R^2:	0.9991		

Gradient
Value: 8×10^{-4}
Absolute uncertainty: $\pm 0.121 \times 10^{-4}$
Percentage uncertainty: ±1.51%

Total Uncertainty

Percentage combined: $\sqrt{0.99^2 + 1.51^2}$
=± 1.81%

Absolute combined uncertainty: = $\pm 0.04 \times 10^{-6}$ F
= $\pm 0.1 \times 10^{-6}$ F

Conclusion

The capacitance was found to be $2.5 \times 10^{-6} \pm 0.1 \times 10^{-6}$ F

Evaluation

This experiment was relatively successful; however the small uncertainty did not cover the predicted value of 2.2 μF. This experiment could have been improved by repeating it more, in order to gain more reliable average currents. The frequency also should have been tested with a frequency meter, and this test should have been repeated, in order to ensure that the frequency reading is correct to allow a more precise result. The smoothing unit ensured that there was direct current, despite the energy source being from the mains, which allowed the experiment to run successfully. As well as this, efforts were made to ensure the frequency was kept constant, in order to increase the reliability of the experiment.

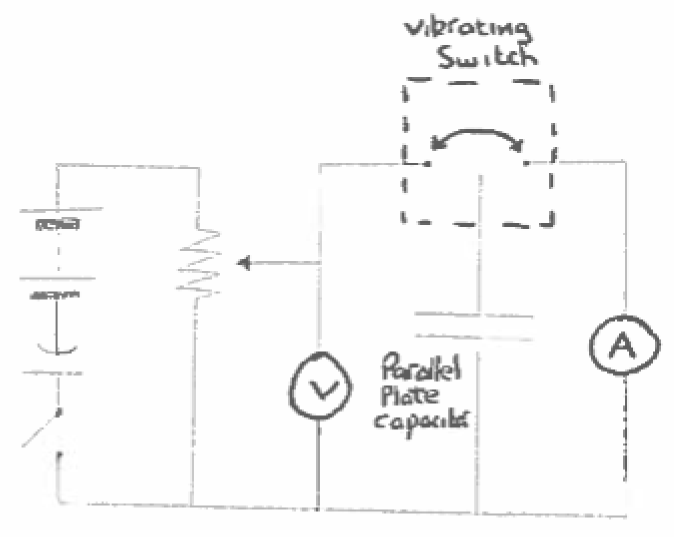
Permittivity of Free Space Experiment

Aim: To calculate the permittivity of free space, ε_0, using a parallel plate capacitor.

Hypothesis: The value of ε_0 will be 8.85×10^{-12} m^{-3} kg^{-1} s^4 A^2.

Apparatus:
Variable 100 V dc supply
Smoothing unit
Voltmeter
Parallel plate capacitor
Ammeter
Vibrating switch
Switch

Method: The apparatus is set up as shown in the diagram.
The distance between the two plates in the capacitor is measured, as is the area of the plates.
The voltage is increased using the variable supply, and the readings on the ammeter are noted at each value of voltage.
This is repeated four times so that the average current can be calculated.
The graph of I/A is plotted to calculate the capacitance.
This is then used to determine ε_0, using the formula $C = \frac{\varepsilon_0 A}{d}$, using the distance between the plates and the area of the plates.



Results:

Voltage (V)	I_1 (μA)	I_2 (μA)	I_3 (μA)	I_4 (μA)	I_5 (μA)	$I_{Average}$ (μA)
0.55	0.02	0.02	0.02	0.02	0.02	0.02
1.90	0.11	0.11	0.08	0.08	0.08	0.09
3.35	0.14	0.14	0.14	0.14	0.14	0.14
4.80	0.21	0.22	0.20	0.20	0.20	0.21
6.25	0.26	0.27	0.27	0.27	0.27	0.27
7.70	0.33	0.34	0.34	0.33	0.33	0.33

Voltage (V)	Average Current (μA)	Calibration Uncertainty (μA)	Random Uncertainty (μA)	Scale Reading Uncertainty (μA)	Combined Uncertainty (μA)	Percentage Uncertainty (%)
0.55	0.02	±0.01	±0.00	±0.01	±0.01	71%
1.9	0.09	±0.01	±0.01	±0.01	±0.02	17%
3.35	0.14	±0.01	±0.00	±0.01	±0.01	10%
4.8	0.21	±0.01	±0.00	±0.01	±0.01	7%
6.25	0.27	±0.01	±0.00	±0.01	±0.01	5%
7.7	0.33	±0.01	±0.00	±0.01	±0.01	4%

Radius = 0.07m

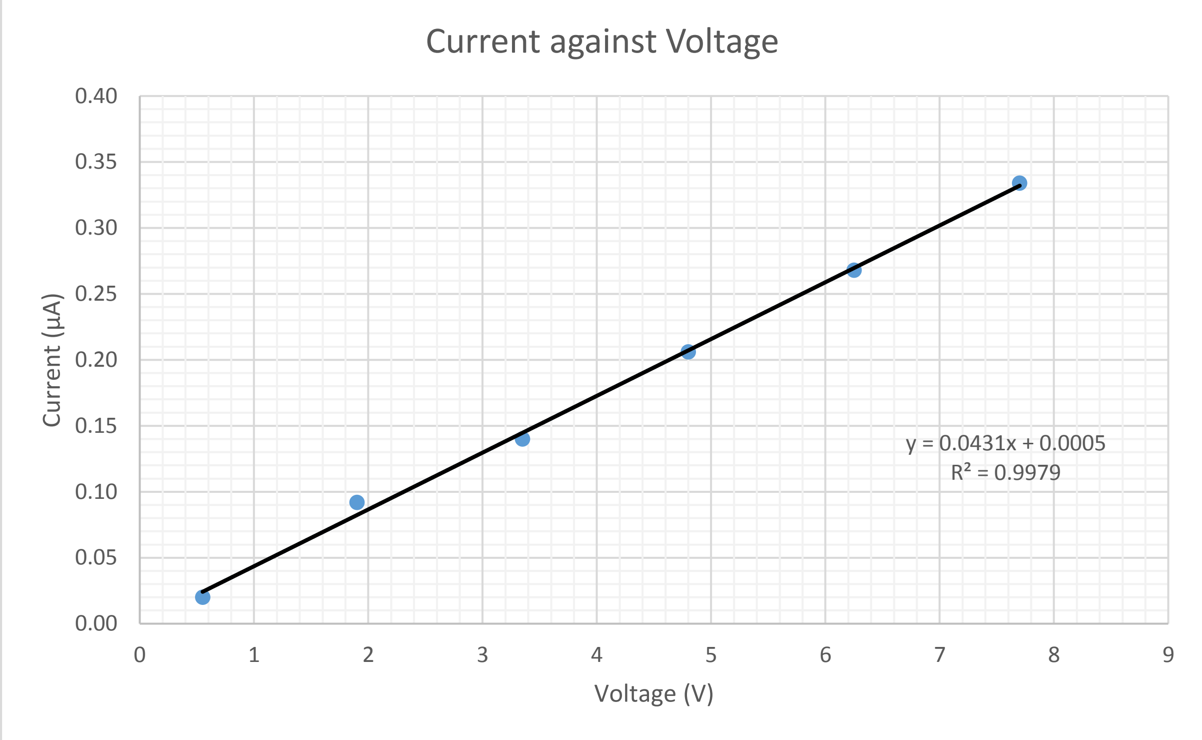
$$A = \pi r^2 \times 2$$

$$A = \pi \times 0.0049 \times 2$$

$$A = 0.0098\pi m^2$$

D = 4×10^{-3} m

f = 520 Hz



$\frac{I}{V}$ = m = 4.31 × 10^{-8}

$\frac{I}{V}$ = fC

4.31 × 10^{-8} = 520 × C

C = 8.28… × 10^{-11}

$$C = \frac{\varepsilon_0 A}{d}$$

$$8.28\ldots \times 10^{-11} = \frac{\varepsilon_0 \times 0.0098 \times \pi}{4 \times 10^{-3}}$$

$$\varepsilon_0 = \frac{8.26\ldots \times 10^{-11} \times 4 \times 10^{-3}}{0.0098 \times \pi}$$

ε_0 = 1.08 × 10^{-11} m^{-3} kg^{-1} s^4 A^2

From Linest

Gradient:	0.043053×10^{-6}	y intercept:	0.000507×10^{-6}
Gradient uncertainty:	0.000991×10^{-6}	y intercept uncertainty:	0.004727×10^{-6}
R^2:	0.9979		

Uncertainties

Radius
Value: 0.07 m
Calibration uncertainty: $\pm 0.5 \times 10^{-3}$ m
Scale reading uncertainty: $\pm 5 \times 10^{-3}$ m
Combined uncertainty: $\pm 5 \times 10^{-3}$ m
Percentage uncertainty: 7.1%
Squared Percentage uncertainty: 14.3%

Distance
Value: 4×10^{-3}m
Calibration uncertainty: $\pm 0.5 \times 10^{-3}$ m
Scale reading uncertainty: $\pm 0.5 \times 10^{-3}$ m
Combined uncertainty: $\pm 0.7 \times 10^{-3}$ m
Percentage uncertainty: 17.5%

Frequency
Value: 520 Hz
Calibration uncertainty: ±4 Hz
Scale reading uncertainty: ±1 Hz
Combined uncertainty: ±4 Hz
Percentage uncertainty: 0.8%

Gradient
Value: 4.31×10^{-8}
Absolute Uncertainty: $\pm 5.07 \times 10^{-10}$
Percentage uncertainty: 1.18%

Total combined uncertainty

Percentage:

$$\pm\sqrt{14.3^2 + 17.5^2}$$

= ±22.6%

Absolute Uncertainty:

$$\frac{1.08 \times 10^{-11}}{100} \times 22.6 = 0.24 \times 10^{-11}\ m^{-3}\ kg^{-1}\ s^4\ A^2$$

Conclusion

Permittivity of free space is $10.8 \times 10^{-12} \pm 2.4\ m^{-3} \times 10^{-12}\ m^{-3}\ kg^{-1}\ s^4\ A^2$

Evaluation

The predicted value for the permittivity of free space falls into the uncertainty of the results of this experiment, however is near the lower limit of it. To increase the accuracy of the result, the experiment should be repeated more than five times, to give a more precise average current for each value and reduce the uncertainty. As well as this, a lack of equipment in the school environment meant the current could not have been measured to more significant figures, which would have given a more reliable result. The frequency should also have been measured more than once, and tested with a frequency meter, as it cannot be assumed that the frequency displayed on the signal generator was precise. As the parallel plate capacitor took a long time to discharge, the experiment took a long time, and could not be completed in one go. This meant that the apparatus could have been moved and the distance between the parallel plates may not have remained constant throughout the duration of the experiment. The smoothing unit was used again, to guarantee that there was direct current, which allowed the experiment to be successful. The same parallel plate capacitor was used throughout the experiment, meaning that the area was constant at all times, creating a more reliable experiment.

Overall Conclusion

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

$$c = \frac{1}{\sqrt{1.261\times10^{-6}\times1.08\times10^{-11}}}$$

C = 2.71×10^8 ms^{-1}

Overall percentage uncertainty:

$$\sqrt{22.6^2 + 11.6^2}$$

= 25.4%

Overall absolute uncertainty:

$$\frac{2.71\times10^8}{100}\times25.4 = 0.69\times10^8 \text{ ms}^{-1}$$

The speed of light is $2.71 \times 10^8 \pm 0.69 \times 10^8$ ms^{-1}

Overall Evaluation

The correct value for the speed of light fell into the uncertainty of the value obtained. The experiments were repeated, increasing the reliability, and although this ideally would have been done more, it was not possible in the school environment and timescale. This meant that the experiment had a large uncertainty, which was beneficial when comparing the result to the correct value. In order to improve the experiment, it should be done in a closed environment with limited access for other people, and with a large amount of time to complete the experiment in one go. This would prevent the experiment being moved or knocked, which limited the accuracy of the results, as measurements may not have been kept constant.

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