NL-110
Physics Laboratory for Engineers
Lab Manual

DEPARTMENT OF ELECTRICAL ENGINEERING,

FAST-NU, LAHORE

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64	DC Power Supply	SE-9720
65	Digital Multimeter	SE-9786
66	Basic Optics System (Track and 4-in-1 Light Source)	OS-8515
67	Aperture Bracket	OS-8534
68	20 g hooked mass (Hooked Mass Set)	SE-8759

EXPERIMENT # 1:

Centripetal Force

EQUIPMENT

	INCLUDED:	ScienceWorkshop	PASPORT
1	Centripetal Force Apparatus	ME-8088	ME-8088
1	Force Sensor	CI-6746	PS-2104
1	Photogate Head	ME-9498A	ME-9498A
1	Photogate Port	(Not Required)	PS-2123
1	Large Rod Base	ME-8735	ME-8735
1	90 cm Steel Rod	ME-8738	ME-8738
1	Multi-Clamp	SE-9442	SE-9442
1	45 cm Steel Rod	ME-8736	ME-8736
1	Banana Plug Cord-Red (5 pack)	SE-9750	SE-9750
1	Triple Output Power Supply	SE-8587	SE-8587

1	Interface	CI-6400	PS-2001
1	DataStudio Software	CI-6870	CI-6870

INTRODUCTION

In this activity, students will use a Force Sensor and Photogate to discover the relationship of centripetal force, mass, velocity and radius for an object in uniform circular motion. Students will determine what happens to centripetal force as the result of changes in mass, velocity, and radius.

THEORY

According to Newton's First Law, an object in motion tends to stay in motion in a straight line at a constant speed if there is no external net force applied to the object. Does an object in circular motion tend to stay in circular motion if there is no external net force applied to it?

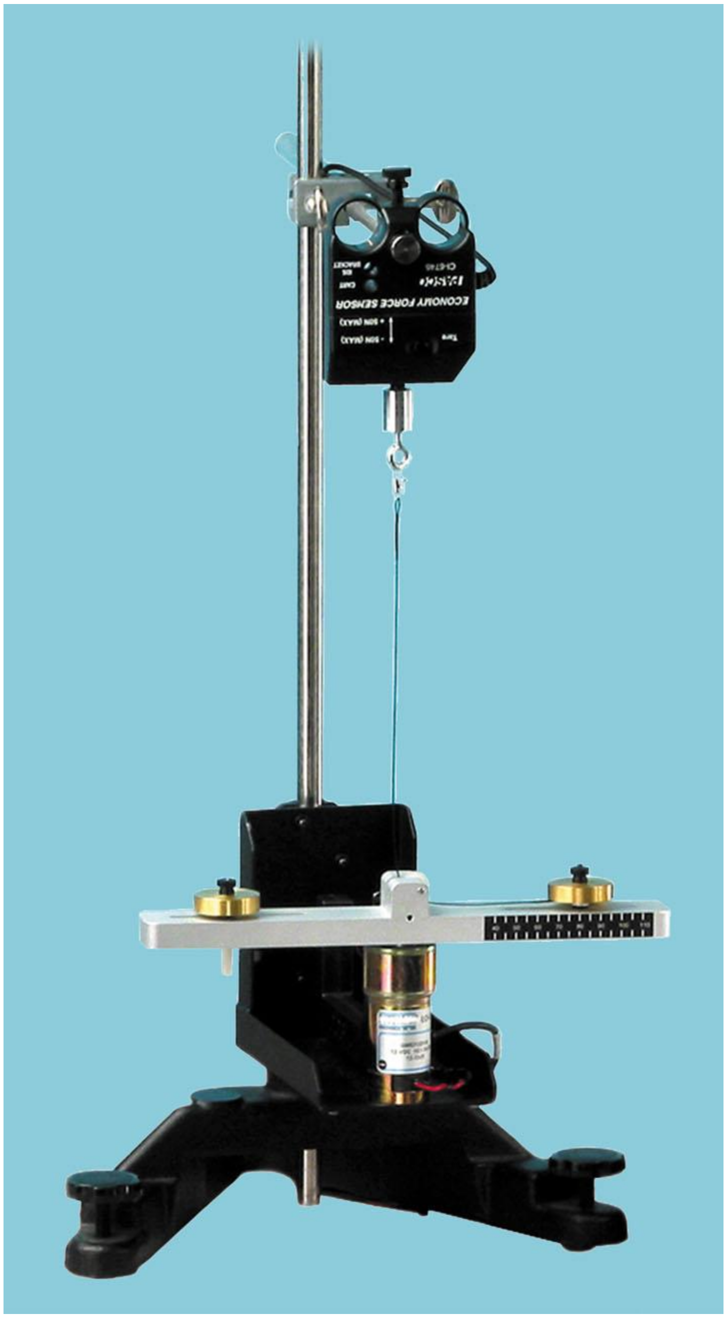
A constant force is required to keep an object in circular motion. Centripetal force is the force that maintains an object’s circular motion.

Examples of centripetal force include the tension in a string attached to a can twirled in a circular path, the friction between the road and the tires of a car on a curve, or the force of gravity pulling a satellite toward the center of Earth as the satellite moves in a circular orbit.

The magnitude of centripetal force F_c depends on the mass m of the object, its circular speed v, and the radius r of the circular motion.

$$F_c = m\frac{v^2}{r}$$

SET UP for Science Workshop Sensors



1. Screw the Photogate to the frame of the Centripetal Force Apparatus. (Figure 1)
2. Attach the entire Centripetal Force Apparatus as low as possible to the 90cm rod and base.
3. Attach the 45cm rod horizontally to the 90 cm rod with the multi-clamp.
4. Hang the Force Sensor from the horizontal rod.
5. Screw the Ball Bearing Swivel to the Force Sensor.
6. Thread the cable through the plastic pulley and attach the other end to the sliding post.
7. Plug the Photogate into Digital Channel 1. Plug the Force Sensor into Analog Channel A.
8. Making sure it is off, connect the power supply to the Centripetal Force Apparatus with banana plugs.
9. Level the base.

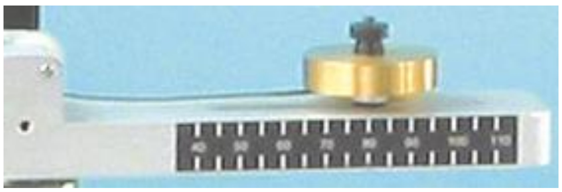
Figure 1: Centripetal Force Apparatus

Software Setup

1. Open any of the files CentripetalForce_A.ds, CentripetalForce_B.ds, and CentripetalForce_C.ds.
2. Select the “Setup” button in DataStudio. Double click the Smart Pulley Icon. In the Sensor Properties Dialog Box select the "Constant" tab. Highlight "Spoke Arc Length." Enter the value of 0.3142 for the arc length (in meters). This corresponds to a 0.050 m radius.

EXPERIMENT 1A – FORCE VS. MASS (Radius and Velocity Must be Constant)

1. Science Workshop Interface users, open the file "CentripetalForce_A.ds." PASPORT Interface users, open the file "CentripetalForce_A (PP).ds."
2. Make sure the power supply is off when you begin.
3. Find the total mass of the 5 g mass, screw, washers, bolt, and nut that comprise the rotating mass. Enter that value in kilograms into the Force v Mass data table in DataStudio.



4. Attach this mass to the cable and the rotating platform as in figure 2. Make certain that the cable is attached below the mass. At this point it should be able to slide freely back and forth in the slot. If it does not, adjust the nuts and washers accordingly.

Figure 2: Attaching the "free" mass

5. Now, adjust the height of the force sensor so that this mass maintains a 0.050 m radius. Pull the mass to tighten the cable to determine the actual radius.
6. To avoid wobbling, tighten an identical mass directly to the rotating platform as a counterbalance so that it is also 0.050 m away from the center of the rotating platform.
7. Turn on the power supply and adjust the voltage from 0 to 5 V. Observe the vertical section of cable. If it is not completely vertical, adjust the horizontal rod. Turn the power supply down to 0 V.
8. From the Experiment Menu, select "Monitor Data."
9. Slowly increase the voltage until the velocity maintains a constant value; for example, 2.0 m/s.
10. Press the Stop Stop button.
11. Without changing the voltage, turn off the power supply.
12. Press the "TARE" or "ZERO" button.
13. Turn on the power supply.
14. Press the Start Start button. Observe the velocity data. If it does not maintain a constant value return to step 9.
15. Allow data collection to occur for approximately 5 seconds. Press the Stop Stop button.
16. Decrease the voltage to 0 V. Turn off the power supply.
17. Enter the value of the Mean Force into the Force v. Mass data table.
18. From the Experiment Menu, select "Delete All Data Runs."
19. Return to step 3 and increase the mass by 5.0 g (0.005kg).
20. Repeat data collection until at least 6 data pairs are recorded.

ANALYSIS - FORCE VS. MASS

1. Observe the Force v Mass Graph. Select the "fit" button Fit and choose the appropriate fit.

Calculate % error $= \left|\frac{Exp.Slop - Cal.Slop}{Cal.Slop}\right| \times 100$

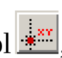
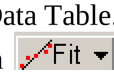
EXPERIMENT 1B – FORCE VS. VELOCITY (Radius and Mass Must be Constant)

1. Science Workshop Interface users, open the file "CentripetalForce_B.ds." PASPORT Interface users, open the file "CentripetalForce_B (PP).ds."
2. Make sure the power supply is off when you begin.
3. Keep the **30g** mass attached to the cable and the rotating platform as it was in Experiment 1. It should be able to slide freely back and forth in the slot. If it does not, adjust the nuts and washers accordingly.
4. If necessary, adjust the height of the force sensor so that this mass <u>maintains</u> a 0.050 m radius. Pull the mass to tighten the cable to determine the actual radius.
5. Turn on the power supply and adjust the voltage from 0 to 5 V. Observe the vertical section of cable. If it is not completely vertical, adjust the horizontal rod. Turn the power supply down to 0 V.
6. Press the "TARE" or “ZERO” button on the Force Sensor.
7. Select “Start” 

in DataStudio.
8. Turn on the power supply and adjust the voltage from 0 to 10 V. Do not exceed 10 V on the power supply. Collect data only as the velocity increases.
9. Press "Stop" 

in DataStudio when the voltage reaches 10 V.

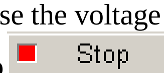
ANALYSIS – FORCE VS. VELOCITY

1. Observe your Force v Velocity Graph and Data Table. Using the Smart Tool , select about 20 representative data points.
2. Enter the Force values from the Force v Velocity Data Table into the "Force v V^2" Data Table.
3. Square the Velocity values and enter them into the "Force v V^2" Data Table.
4. Observe the Force v Velocity Squared Graph. Select the "fit" button 

and choose the appropriate fit.

Calculate % error $= \left| \frac{Exp.Slop - Cal.Slop}{\mathbf{Cal.Slop}} \right| \times \mathbf{100}$

EXPERIMENT 1C – FORCE VS. RADIUS (Mass and Velocity Must be Constant)

1. Science Workshop Interface users, open the file "CentripetalForce_C.ds." PASPORT Interface users, open the file "CentripetalForce_C (PP).ds."
2. Make sure the power supply is off when you begin.
3. Keep the **30g** mass attached to the string and the rotating platform as it was in Experiment 1. It should be able to slide freely back and forth in the slot. If it does not, adjust the nuts and washers accordingly.
4. Now, adjust the height of the force sensor so that the sliding mass maintains an approximately 0.050 m radius. Turn on the power supply and adjust the voltage from 0 to 5 V. Observe the vertical section of cable. Turn the power supply down to 0 V. If the vertical section of cable is not completely vertical, adjust the horizontal rod. Pull the mass to tighten the cable to determine the actual radius. Record the value of the radius in the Force v. Radius data table. Remember to adjust the fixed mass to match the radius of the free mass.
5. Select the “Setup” button in DataStudio. **For ScienceWorkshop Users:** Double click the Smart Pulley Icon. In the Sensor Properties Dialog Box select the "Constant" tab. Highlight "Spoke Arc Length." **For PASPORT Users:** If necessary, scroll until the Smart Pulley (Linear) Icon is visible. Click the “Change Value” button.
6. Enter the value of the spoke arc length using the following equation: spoke arc length = 2 x □ x radius.
7. **For ScienceWorkshop Users:** Select "OK" and minimize the Sensor Properties Dialog Box to return to the previous graphs in DataStudio. **For PASPORT Users:** Select “OK” and minimize the “Experiment Setup” window to return to the previous graphs in DataStudio.
8. From the Experiment Menu, select “Monitor Data.”
9. Slowly increase the voltage until the velocity maintains a constant value; for example, 2.0 m/s.
10. Press the Stop 

button.
11. Without changing the voltage, turn off the power supply.
12. Press the “TARE” or “ZERO” button.
13. Turn on the power supply.
14. Press the Start 

button. Observe the velocity data. If it does not maintain a constant value return to step 9.
15. Allow data collection to occur for approximately 5 seconds. Press the Stop 

button.
16. Decrease the voltage to 0 V. Turn off the power supply.
17. Enter the value of the Mean Force into the Force v. Radius data table.
18. From the Experiment Menu, select “Delete All Data Runs.”
19. Return to step 4 and increase the radius by approximately 0.010 m (1.0cm). **Important: The spoke arc length must be recalculated each time the radius is adjusted.**
20. Repeat data collection until at least 6 data pairs are recorded.

ANALYSIS – FORCE VS. RADIUS

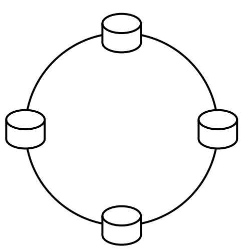
1. Observe your Force v Radius Graph and Data Table.
2. Enter your Force values from the Force v Radius Data Table into the "Force v 1/Radius" Data Table.
3. Inverse the Radius values and enter them into the "Force v 1/Radius " Data Table.
4. Observe the Force v 1/Radius Graph. Select the "fit" button 

and choose the appropriate fit.

Calculate % error $= \left|\frac{Exp.Slop - Cal.Slop}{\mathbf{Cal.Slop}}\right| \times \mathbf{100}$

FINAL ANALYSIS

1. Using words and a mathematical expression, describe the relationship between force and mass in uniform circular motion.
2. Using words and a mathematical expression, describe the relationship between force and velocity in uniform circular motion.
3. Using words and a mathematical expression, describe the relationship between force and radius in uniform circular motion.
4. Combine the three relationships above to create one relationship for force, mass, velocity, and radius.
5. How would you convert this expression into an equation?
6. What is the constant of proportionality for this equation? Explain.
7. How could such an equation be used?



8. The figure above is an overhead view of the rotating mass. For each of the 4 points, draw the direction and relative magnitude of the force.

EXPERIMENT # 2:

To find the coefficient of static friction and the coefficient of kinetic friction for different surfaces

EQUIPMENT

	INCLUDED:	ScienceWorkshop	PASPORT
1	Discover Friction Accessory	ME-8574	ME-8574
1	Force Sensor	CI-6746	PS-2104
4	500g Cart Masses	648-04636	648-04636
1	Physics String	SE-8050	SE-8050

1	Computer Interface	CI-6400	PS-2100
1	DataStudio Software	CI-6870	CI-6870

INTRODUCTION

The purpose of this experiment is to find the coefficient of static friction and the coefficient of kinetic friction for different surfaces. As it pulls a Friction Tray from rest to a constant velocity, the Force Sensor can measure both the static friction and the kinetic friction. A plot of each of these forces versus their respective normal forces yields both coefficients.

THEORY

When a force is applied to an object resting on a surface, it will not move until the force applied to it is greater than the maximum force due to static friction. The coefficient of static friction (μ_s) is simply the ratio between the maximum static frictional force (F_s) and the normal force (F_N):

$$\mu_s = \frac{F_s}{F_N}$$

To keep the object moving at a constant velocity, a force must be applied to the object equal to the kinetic frictional force. Hence, the coefficient of kinetic friction (μ_k) is the ratio between the kinetic frictional force (F_k) and the normal force (F_N):

$$\mu_k = \frac{F_k}{F_N}$$

SET-UP for ScienceWorkshop Sensors (see Figure 1 below)

Figure 1: **SET-UP**

1. Cut about 15 cm of Physics String
2. Make a loop on each side of the string.
3. Connect the Force Sensor to Channel A of the ScienceWorkshop Interface.
4. Connect the ScienceWorkshop Interface to the computer.
5. Open the DataStudio file "Sliding Friction.ds."

PROCEDURE

1. Measure the mass of the Friction Tray and each bar mass. Record these values.
2. With no tension on the string, press the "tare" or "zero" button on the force sensor.
3. Place one mass in the Friction Tray. Attach one end of the string to the tray. Attach the other end to the hook of the Force Sensor.
4. Press the START button.
5. Place the Friction Tray on a rough surface (carpet works well). With the force sensor tied to the tray, slowly pull the Friction Tray horizontally, from rest, across the lab station until it reaches a constant velocity. Continue pulling at a constant velocity for 5 seconds.
6. DataStudio will automatically stop collecting data after 5.0 seconds.

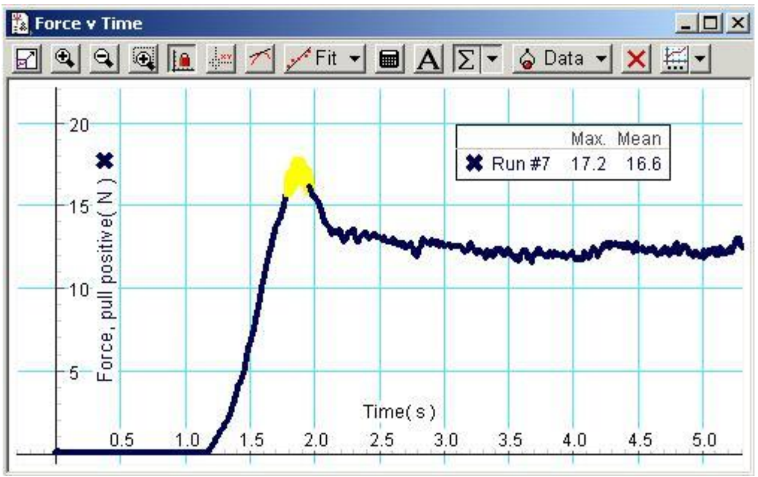


Figure 2: Force vs Time graphs in Datastudio

7. Use the cursor to highlight the region that corresponds to the maximum static friction. The legend box gives the value of the maximum Static Friction. Enter this value into the corresponding STATIC data table. Also, enter the value of the Friction Tray's normal force. (Figure 2)

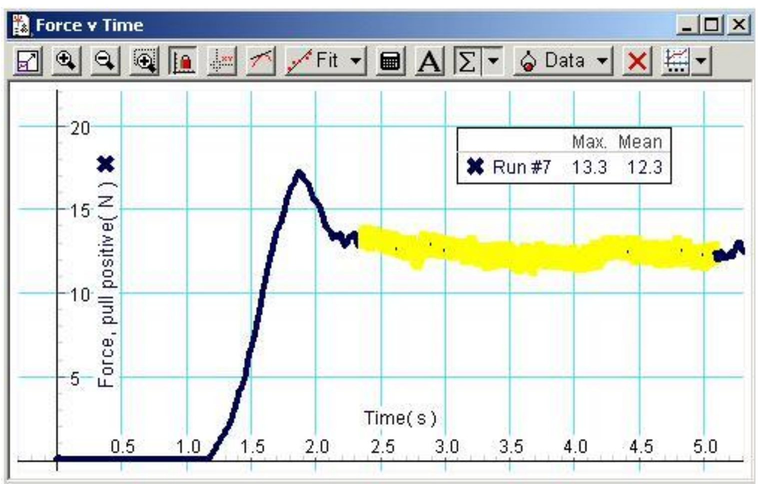
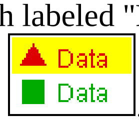


Figure 3: Force vs Time graphs in Datastudio

8. Use the cursor to highlight the region where the velocity is constant. The legend box gives the MEAN or average Kinetic Friction. Enter this value into the corresponding KINETIC data table. Also, enter the value of the Friction Tray's normal force. (Figure 3)
9. Repeat steps 4-8 with two masses on the Friction Tray.
10. Repeat steps 4-8 with three masses on the Friction Tray.
11. Repeat steps 4-8 with four masses on the Friction Tray.
12. Click on the graph labeled "Friction v Normal."
13. In the legend box 

, highlight the Data that corresponds to the static frictional force. From the "Fit" menu 

at the top of the graph, select "Linear." Record the slope and vertical intercept.
14. From the legend box, highlight the Data that corresponds to the kinetic frictional force. From the "Fit" menu at the top of the graph, select "Linear." Record the slope and vertical intercept.
15. Repeat the previous steps using the other Friction Trays.

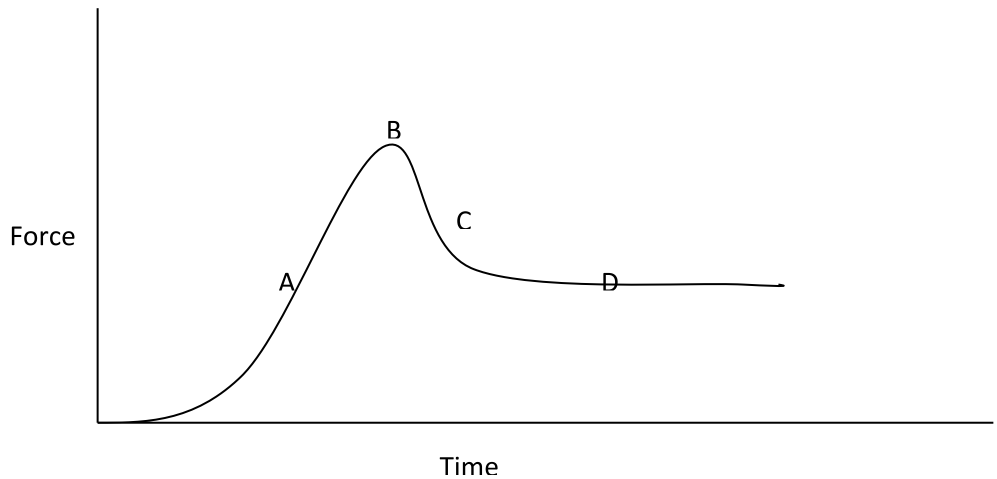


Figure 4

Questions

1. The graph above (figure 4) is representative of the force applied to an object as it is pulled across a horizontal surface. Draw a force diagram for each of the positions labeled in the graph above. Describe the motion of the object for the positions labeled in the graph.

2. What relationship exists between the static frictional force and the normal force on an object?

3. What specific equation describes this relationship? (Include numbers and units for both the slope and vertical intercept)

4. What is the physical meaning of the slope for the static frictional force vs. normal force graph?

5. What is the physical meaning of the vertical intercept for the static frictional force vs. normal force graph?

6. What relationship exists between the kinetic frictional force and the normal force on an object?

7. What specific equation describes this relationship? (Include numbers and units for both the slope and vertical intercept)

8. What is the physical meaning of the slope for the kinetic frictional force vs. normal force graph?

9. What is the physical meaning of the vertical intercept for the kinetic frictional force vs. normal force graph?

10. Did the normal force on the friction tray affect either the coefficient of static friction or the coefficient of kinetic friction? Explain.

11. Rank the friction trays from highest coefficients of friction to lowest. What is physically different with the surfaces with high coefficients versus the surfaces with low coefficients? Explain.

EXPERIMENT # 3:
To find out rotational inertia of a ring and a disk

EQUIPMENT

	INCLUDED:	ScienceWorkshop	PASPORT
1	Large Rod Stand	ME-8735	ME-8735
1	90 cm Long Steel Rod	ME-8738	ME-8738
1	Mini-Rotational Accessory	CI-6691	CI-6691
1	Mass Set (5 g resolution)	ME-9348	ME-9348
1	Rotary Motion Sensor	CI-6538	PS-2120
1	Mass Balance (not supplied)	SE-8723	SE-8723
1	Calipers (not supplied)	SE-8711	SE-8711

1	Computer Interface	CI-6400	PS-2100
1	DataStudio Software	CI-6870	CI-6870

INTRODUCTION

The purpose of this experiment is to find the rotational inertia of a ring and a disk experimentally and to verify that these values correspond to the calculated theoretical values. A known torque is applied to the pulley on the Rotary Motion Sensor, causing a disk and ring to rotate. The resulting angular acceleration is measured using the slope of a graph of angular velocity versus time. The rotational inertia of the disk and ring combination is calculated from the torque and the angular acceleration. The procedure is repeated for the disk alone to find the rotational inertias of the ring and disk separately.

THEORY

Theoretically, the rotational inertia, I, of a ring is given by

$$I = \frac{1}{2}M\left(R_1^2 + R_2^2\right) \qquad (1)$$

where M is the mass of the ring, R_1 is the inner radius of the ring, and R_2 is the outer radius of the ring. The rotational inertia of a disk is given by

$$I = \frac{1}{2} MR^2 \quad (2)$$

where M is the mass of the disk and R is the radius of the disk.

To find the rotational inertia of the ring and disk experimentally, a known torque is applied to the ring and disk, and the resulting angular acceleration, α, is measured. Since τ = Iα,

$$I = \frac{\tau}{\alpha} \quad (3)$$

where τ is the torque caused by the weight hanging from the string which is wrapped around the 3-step pulley of the apparatus.

$$\tau = rT \quad (4)$$

where r is the radius of the pulley about which the string is wound and F is the tension in the string when the apparatus is rotating. Also, a=rα, where "a" is the linear acceleration of the string.

Applying Newton's Second Law for the hanging mass, m, gives (See Figure 2)

$$\Sigma F = mg - F = ma \quad (5)$$

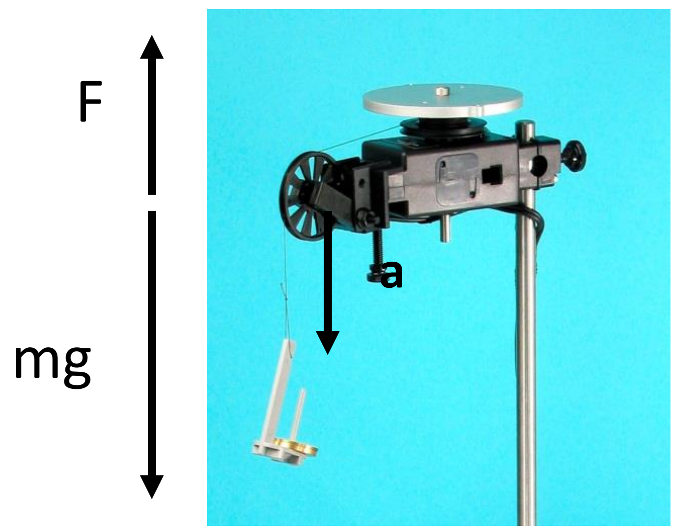


Figure 2: Rotational Apparatus and Free-Body Diagram

Solving for the tension in the string gives

$$F = m(g - a). \quad (6)$$

Once the linear acceleration of the mass (m) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

SET-UP for ScienceWorkshop Sensors

1. Set up the rotational apparatus as shown in

   Figure 3. The thread should be tied around the smallest step on the Rotary Motion Sensor pulley, then threaded down through the edge hole, and wrapped around the middle step of the pulley.

2. Plug the Rotary Motion Sensor plugs into digital Channel 1 and 2 on the interface. Switching the yellow and black plugs reverses the direction of positive rotation.

3. Run DataStudio on the computer and open the file called "Rotational Inertia".

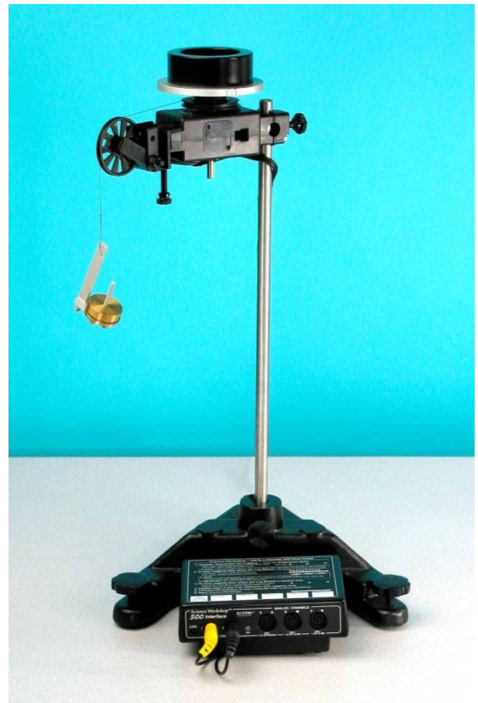


Figure 3: Setup

PROCEDURE

A. MEASUREMENTS FOR THE THEORETICAL ROTATIONAL INERTIA

1. Find the masses of the ring and the disk using the mass balance.

2. Measure the inside and outside diameters and calculate the radii R_1 and R_2 and R.

B. MEASUREMENTS FOR THE EXPERIMENTAL METHOD

1. FINDING THE ACCELERATION OF THE RING AND DISK

   (a) Put the ring and disk on the Rotary Motion Sensor. To find the acceleration of this combination, put about 20 g over the pulley and record the angular velocity versus time on a graph as the mass falls to the table.

   (b) Use the curve fit button on the graph to find the straight line that best fits the data. Use the mouse to select the part of the graph where the mass was falling, so the line will be fitted only to this part of the data.

   (c) The slope of the best-fit line is the angular acceleration of the apparatus. Record this acceleration.

   (d) Remove the ring and repeat this procedure with only the disk on the Rotary Motion Sensor.

2. FINDING THE ACCELERATION OF THE ROTARY MOTION SENSOR

In Step 1 the Rotary Motion Sensor is rotating as well as the ring and disk. It is necessary to determine the acceleration, and the rotational inertia, of the Rotary Motion Sensor by itself so this rotational inertia can be subtracted from the total, leaving only the rotational inertia of the ring and disk. To do this, take the ring and disk off the rotational apparatus and repeat Step 1 for the Rotary Motion Sensor alone. Note that it is only necessary to put about 5 g over the pulley in Step 1.

3. Use the calipers to measure the diameter of the middle pulley and calculate the radius of the pulley.

i.e) r_p=____________m

CALCULATIONS

1. Calculate the experimental value of the rotational inertia of the ring, disk, and Rotary Motion Sensor together using Equations (3), (4), and (5).

2. Calculate the experimental value of the rotational inertia of the disk and Rotary Motion Sensor together using Equations (3), (4), and (5).

3. Calculate the experimental value of the rotational inertia of the Rotary Motion Sensor alone using Equations (3), (4), and (5).

$(\text{Mass})_{disc}$ = ___________ g

$(\text{Diameter})_{disc}$ =_______________mm

$(\text{Radius})_{disc}$ =_____________m

$(\text{Mss})_{ring}$ = ____________ g

$(\text{Internal diameter})_{ring}$= _______________ m

$(\text{External diameter})_{ring}$= ______________ m

$(\text{Internal radius})_{ring}$ = _________________m

$(\text{External radius})_{ring}$ = _________________m

Using eq#(1)and eq#(2)to find the rotational inertia of Ring and disc,

$(I)_{ring}$ = __________________

$(I)_{disc}$ = __________________

Calculate the experimental value of the rotational inertia of the rotary motion sensors & disc

$\alpha_{1(D+R+P)}$ =________________________

$\alpha_{2(D+P)}$ = ________________________

$\alpha_{3(P)}$ = ________________________

m = 50gm=

10g

4. Subtract the rotational inertia of the Rotary Motion Sensor from the rotational inertia of combination of the disk and Rotary Motion Sensor. This will be the rotational inertia of the disk alone.
5. Subtract the rotational inertia of the combination of the disk and Rotary Motion Sensor from the rotational inertia of combination of the ring, disk, and Rotary Motion Sensor. This will be the rotational inertia of the ring alone.

$I_1=(r_p mg)/\alpha_1 - m r_p^2$=________________________

$I_2=(r_p mg)/\alpha_2 - m r_p^2$=________________________

$I_3=(r_p mg)/\alpha_3 - m r_p^2$=__________________________

6. Calculatetheexperimentalvaluesoftherotationalinertiaoftheringanddisk.

Rotational Inertia of ring=$I_1 - I_2$=____________________

Rotational Inertia of Disc=I_2-I_3=___________________

7. Use percent differences to compare the experimental values to the theoretical values.

$$\%difference = \left| \frac{Experimental - Theoretical}{Theoretical} \right| x100$$

%age error for ring=______________________

%age error for disc=_______________________

FINAL ANALYSIS: (Post-Lab Questions)

1)Write conclusion of the experiment.

2)Name the sensors used in the experiment. And also write the function and characteristics of these sensors.

Experiment # 4:
To find the spring constant for several springs

EQUIPMENT

	Included:	ScienceWorkshop	PASPORT
1	Demonstration Spring Set	ME-9866	ME-9866
1	Force Sensor	CI-6746	PS-2104
1	Universal Table Clamp	ME-9376B	ME-9376B
1	Heavy Spring Bumper	003-05809	003-05809
1	Light Spring Bumper	003-05808	003-05808
1	Four-Scale Meter Stick	SE-8695	SE-8695

1	Computer Interface	CI-6400	PS-2100
1	DataStudio Software	CI-6870	CI-6870

INTRODUCTION
The purpose of this experiment is to find the spring constant for several springs. The force applied to the spring is measured using a force sensor. The subsequent extension or compression is measured with a meter stick. A close analysis of the data produces the spring constant.

THEORY
When force is applied to a spring, the resulting extension or compression of the spring maintains a linear relationship with the applied force. This relationship manifests itself in the following equation: $F = k\Delta x$
Where F is the applied force, Δx is the extension or compression of the spring and k is the spring constant. The following sample graph (figure 1) of force and extension (or compression) yields a linear slope defined as the spring constant:

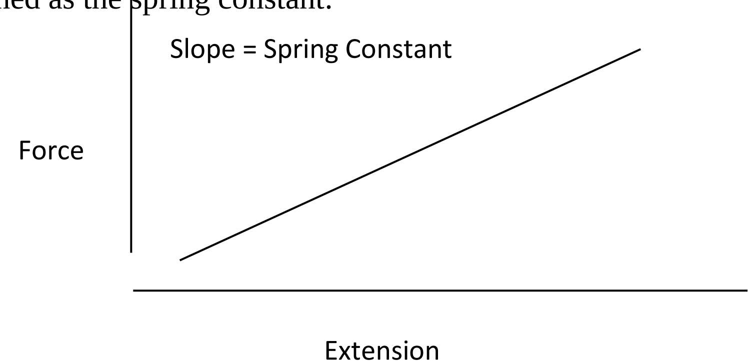


Figure 1: Graph F vs. Extension

SETUP PART A: EXTENSION

1. Slip the post of the Universal Table Clamp through one of the end-loops of the SHINY (10 cm long) spring.
2. Screw down the clamp to the edge of a table. (See photo below Figure 2)

Figure 2: ScienceWorkshop Sensors

Line up the 0 cm mark of the Meter stick to the end of the spring. (See the photo above.) Note: The student may choose to define the "end of the spring" as either the end of the end-hoop or the end of the coils. However, the student must make all measurements from this position once it has been determined.

3. Connect the Force Sensor to the interface. Connect the interface to the computer.
4. "Zero" the Force Sensor by holding it horizontally on the table and pressing the "Zero" or "Tare" button.
5. Attach the hook of the Force Sensor to the other end-loop of the spring.
6. Open the file "HookesLawExtension.ds." For PASPORT users, open the file "HookesLawExtension(PP).ds."

PROCEDURE PART A: EXTENSION

1. Press  in DataStudio.

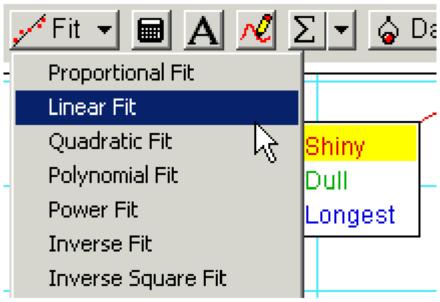
2. Pull the Force Sensor until the spring is stretched 10 cm.
3. Press  to save the current measurement.

4. When prompted, enter the amount the spring has been stretched then click OK.
5. Repeat Steps 2-4 for 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm.
6. Press  in DataStudio.
7. Change the name of "Run 1" in the data window to "Shiny."
8. Repeat Steps 1-7 for the "DULL" and "LONGEST" springs.

ANALYSIS

1. Choose a particular data set by clicking in the legend box.

2. From the "Fit" menu button select "Linear Fit."



3. Record the slope and vertical intercept.
4. Repeat Steps 1-3 for the other data sets.

SETUP PART B: COMPRESSION

1. Remove the previous spring from the Universal Table Clamp. Screw down the clamp to the edge of a table.
2. Unscrew the hook of the Force Sensor. Replace the hook with the Light Spring Bumper.
3. Hold the Force Sensor so that the exposed end of the spring just touches the section of the clamp that forms a "T." (See photo below, Figure 3)

Figure 3: ScienceWorkshop Sensors

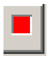
4. Line up the 0 cm mark of the Meter Stick to the end of the spring. (See the photo above.)
5. Open the file "HookesLawCompression.ds." For PASPORT users, open the file "HookesLawCompression (PP).ds."

PROCEDURE PART B: COMPRESSION

1. Press 

in DataStudio.

2. Carefully push the Force Sensor until the spring is compressed by 0.5 cm.
3. Press 

to save the current measurement.
4. When prompted click the OK button.
5. Repeat Steps 2-4 for 1.0 cm, 1.5cm, and 2.0 cm.
6. Press  in DataStudio.
7. Change the name of “Run 1” in the data window to “Light.”
8. Repeat Steps 1-7 for the Heavy Spring Bumper.

ANALYSIS

Repeat the steps from the “Analysis” section of Part A.

CALCULATIONS/QUESTIONS

1. In general, what pattern do you notice between the force and the displacement/extension of the spring?

2. Starting with y = mx + b, write an equation that represents the relationship between force and displacement. Don't forget to include units on all numbers!

3. What is the physical meaning of the slope for the force-displacement graph? (Hint: Look at the units!)

4. What is the physical meaning of the vertical intercept for the force-displacement graph?

5. Using this equation, what would be the force required to stretch the "SHINY" spring 90 cm?

6. If you hung the "LONGEST" spring from the ceiling and placed a 50 g mass on it, how far would it extend?

7. If you placed a 100 g mass on the Heavy Spring Bumper, how much would it compress?

8. Some springs are considered non-Hookian. Explain what this term means.

EXPERIMENT # 5:

To calculate the period of oscillation is measured from a plot of the angular displacement versus time from a torsional pendulum

EQUIPMENT

	INCLUDED:	ScienceWorkshop	PASPORT
1	Torsion Pendulum Accessory	ME-6694	ME-6694
1	Large Rod Stand	ME-8735	ME-8735
1	45 cm Long Steel Rod	ME-8736	ME-8736
1	Mini-Rotational Accessory	CI-6691	CI-6691
1	Rotary Motion Sensor	CI-6538	PS-2120
1	Force Sensor	CI-6746	PS-2104
	NOT INCLUDED, BUT REQUIRED:		
1	Pliers for bending wire		
1	Mass Balance	SE-8757	SE-8757
1	Computer Interface	CI-6400	PS-2001
1	DataStudio	CI-6870	CI-6870

INTRODUCTION

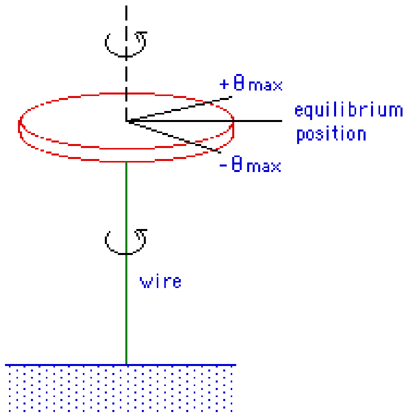
The torsional pendulum consists of a torsion wire attached to a Rotary Motion Sensor with an object (a disk, a ring, or a rod with point masses) mounted on top of it. The period of oscillation is measured from a plot of the angular displacement versus time. To calculate the theoretical period, the rotational inertia is determined by measuring the dimensions of the object and the torsional spring constant is determined from the slope of a plot of force versus angular displacement.

The dependence of the period on the torsional constant and the rotational inertia is explored by using different diameter wires and different shaped objects.

THEORY

Consider a wire securely fixed on both ends (Figure 1). If the wire is twisted, it will exert a restoring torque when trying to return to its original untwisted position. For small twists, the restoring torque is proportional to the angular displacement of the wire.

$$\tau = \kappa\theta \qquad (1)$$



The proportionality constant, κ, depends on the properties of the wire and is called the torsional spring constant.

When the object attached to the wire is twisted and released, the objects executes simple harmonic motion with a period, T, given by

$$T = 2\pi\sqrt{\frac{I}{\kappa}} \qquad (2)$$

Figure 1: Mechanical diagram (torsional Pendulum)

Where, I is the rotational inertia of the object about the axis of rotation. Theoretically, the rotational inertia, I, of a ring is given by

$$I = \frac{1}{2}M(R_1^2 + R_2^2) \qquad (3)$$

where M is the mass of the ring, R_1 is the inner radius of the ring, and R_2 is the outer radius of the ring. The rotational inertia of a disk is given by

$$I = \frac{1}{2}MR^2 \qquad (4)$$

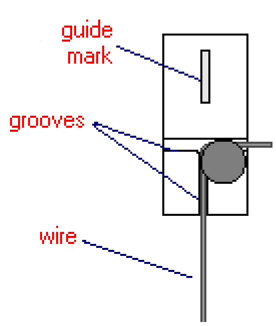
The rotational inertia of a point mass rotating in a circle of radius r is given by

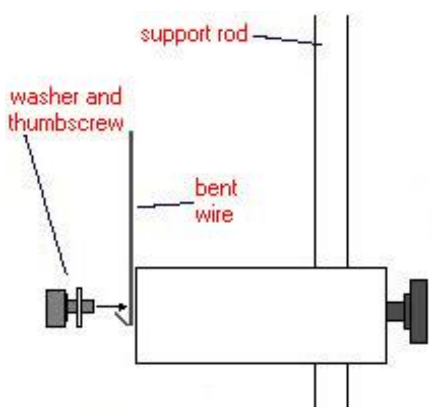
$$I = MR^2 \qquad (5)$$

SET UP for ScienceWorkshop Sensors

1. Start with the 0.032" diameter wire. Use pliers to bend each end of the wire into an "L" shape.

2. Fit the bent ends of the wire under the screws and washers of the upper and lower clamps, as illustrated in Figures 2-4. Make sure the screws are firmly tightened.





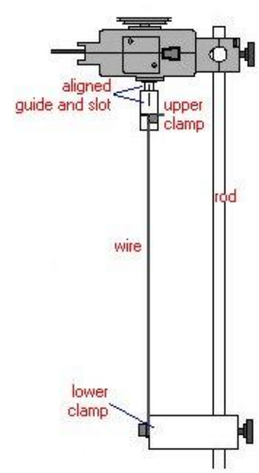


Figure 2: Upper Clamp

Figure 3: Lower Clamp

Figure 4: Setup

3. Adjust the Rotary Motion Sensor on the support rod such that the guide on the upper clamp is aligned with the slot on the shaft of the Rotary Motion Sensor. See Figure 5.

4. Adjust the height of the set up so that the upper clamp is approximately half way up the shaft of the Rotary Motion Sensor (see Figure 3). NOTE: When switching to a new diameter wire, try to keep the length of the wires, from clamp to clamp, relatively constant.

5. Plug the Rotary Motion Sensor into Channels 1 and 2 on the ScienceWorkshop interface. Reversing the yellow and black plugs will just change the direction of positive rotation. Plug the Force Sensor into Channel A.

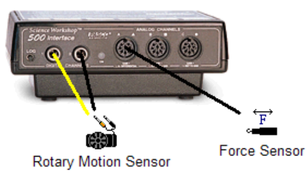


Figure 6: Rotary Motion Sensor.

6. Open the DataStudio file called "Torsional Pendulum".

PROCEDURE

A. Determining the Torsional Spring Constant

1. Measure the radius of the medium pulley of the Rotary Motion Sensor in meters. Enter this radius (not diameter!) into the DataStudio calculator window where it asks for the experimental constants. The torque is calculated using τ=rF, where F is the force measured using the Force Sensor.

2. Attach about 20 cm of string to the Rotary Motion Sensor by tying it around the small pulley. Then thread the string through the notch in the medium pulley and wrap the string around the medium pulley 3 times. Attach the Force Sensor to the end of the string.

3. Hold the force sensor parallel to the table at the height of the large pulley and prepare to pull it straight out as shown in Figure 7.

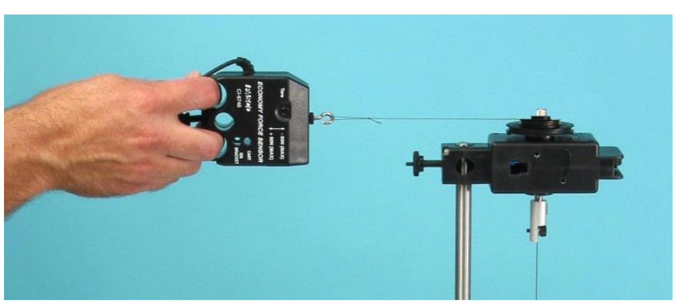


Figure 7: Measuring the Torque

4. Let the string go slack and press the tare button on the Force Sensor. Click the START button in

DataStudio and pull the Force Sensor horizontally until the pulley turns about one revolution. Click on STOP.

5. Use the Fit Tool to determine the slope of the graph of Torque vs. Angle. This slope is equal to the torsional spring constant for the wire (see Equation 1).

B. Determining the Rotational Inertia

1. Measure the mass and radius of the disk.

2. Calculate the rotational inertia of the disk using Equation (4).

C. Calculating the Theoretical Period of Oscillation

Using the rotational inertia of the disk and the torsional spring constant for the wire, calculate the theoretical period using Equation (2).

D. Measuring the Period of Oscillation

1. Remove the Force Sensor. The string can still be attached in this part of the experiment as long as it does not impede the oscillation. Twist the disk 1/4 of a turn.

2. Click on the Angle vs. Time graph to bring it forward. Then click on the START button and release the disk.

3. After several oscillations have been completed, click on STOP.

4. Use the Smart Tool to find the period of oscillation.

5. Compare the measured and calculated values of the period using a percent difference.

$$\%difference = \left| \frac{measured - calculated}{calculated} \right| x100$$

E. Repeating the Experiment

1. Repeat Steps B through D with the ring added to the top of the disk.
2. Remove the disk and the ring. Repeat Steps B through D using the rod with a point mass on each end of the rod. Invert the 3-step pulley on the Rotary Motion Sensor before attaching the rod (see Figure 8). For this part of the lab, the rotational inertia of the rod is ignored because it is small compared to the point masses. However, you can take the rotational inertia of the rod into account. For a thin rod of length L and mass m, the rotational inertia is $I = \frac{1}{12} mL^2$.

Figure 8: Point Masses

3. Replace the wire with a wire of different diameter but same length. Return to using the disk. Repeat Steps A, C, and D.

QUESTIONS

1. Which of the wires was harder to twist? What does κ tell you about how much a wire resists bending and twisting?

2. Which of the wires oscillated faster (smaller Period)?

3. How does the period relate to which wire is harder to twist? Explain.

4. Using the same wire, which object had the least rotational inertia?

5. Using the same wire, which object oscillated faster?

6. How does the period depend on the rotational inertia of the object?

7. How much error is caused by ignoring the rod in the point mass part of the experiment?

8. Was there any other source of rotational inertia that was ignored in this experiment?

9. How could you use a torsional pendulum to determine the rotational inertia of any object that could be mounted on the Rotary Motion Sensor?

EXPERIMENT# 6:
To explore the dependence of the period of a simple pendulum on the acceleration due to gravity

EQUIPMENT

INCLUDED:

1	Large Rod Stand	ME-8735
1	45 cm Long Steel Rod	ME-8736
1	Variable-g Pendulum Accessory	ME-8745
1	Mini-Rotational Accessory (Need rod and masses only)	CI-6691
1	Rotary Motion Sensor	CI-6538
1	ScienceWorkshop 500 Interface	CI-6400
1	DataStudio Software	CI-6870

INTRODUCTION

This experiment explores the dependence of the period of a simple pendulum on the acceleration due to gravity.

A simple rigid pendulum consists of a 35-cm long lightweight (28 g) aluminum tube with a 150-g mass at the end, mounted on a Rotary Motion Sensor. The pendulum is constrained to oscillate in a plane tilted at an angle from the vertical. This effectively reduces the acceleration due to gravity because the restoring force is decreased.

THEORY

A simple pendulum consists of a point mass at a distance L away from a pivot point. In this experiment, a mass is attached to a lightweight rod and the mass is concentrated enough to assume it is a point mass and the rod's mass can be neglected.

The period of a simple pendulum is given by

$$T \cong 2\pi\sqrt{\frac{L}{g_{effective}}} \qquad (1)$$

for small amplitude (less than 20º).

In this experiment, the acceleration due to gravity (g) will be varied. To accomplish the variation in g, the plane of oscillation of the pendulum will be varied. See Figure 1. The component of g that pulls straight down on the pendulum when it is in equilibrium is the effective g:

$$g_{effective} = g\cos\Theta \qquad (2)$$

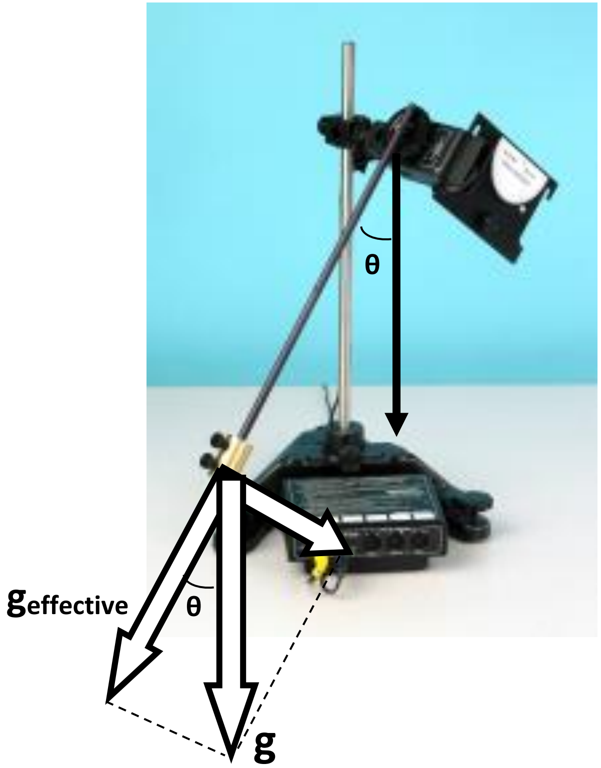


Figure 1: Plane of oscillation rotated to vary g

SET UP

1. Remove the thumb screw from the clamp on the Rotary Motion Sensor. See Figure 2.

2. Remove one of the rod clamps from the Adjustable Angle Clamp.

3. Screw the Adjustable Angle Clamp onto the Rotary Motion Sensor.

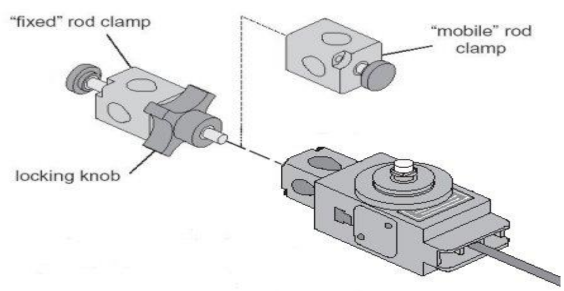


Figure 2: Attaching the Rod Clamp

4. Mount the Rotary Motion Sensor on the rod stand (see Figure 3).

5. Put the pulley on the Rotary Motion Sensor with the largest step outward. Attach the rod to the Rotary Motion Sensor pulley and put the two 75 g masses on the end of the rod.

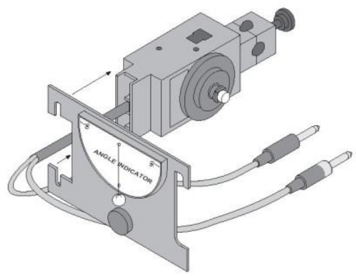


Figure 3: Setup

Figure 4: Attaching Angle Indicator

6. Slide the angle indicator onto the end of the Rotary Motion Sensor (see Figure 4).

7. Plug the Rotary Motion Sensor into Channels 1 and 2 on the ScienceWorkshop interface.

8. Open the DataStudio file called "Variable-g".

PROCEDURE

1. Clamp the pendulum clamp at zero degrees. Click on START and displace the pendulum from equilibrium (no more than 20 degrees amplitude) and let go. Read the period on the digits display and type the value into the table on the line next to zero degrees. Do NOT click on STOP.

2. Clamp the pendulum at 5 degrees. Displace the pendulum from equilibrium (no more than 20 degrees amplitude) and let go. Record the new period in the table.

3. Repeat Step 2 for 10 degrees to 85 degrees, in increments of 5 degrees. Then click on STOP.

4. Examine the graph of the period vs. $g_{effective}$. To determine how the period depends on g, use the Curve Fit by clicking on the Fit button at the top of the graph. Select various functions to try to find which function fits the data.

QUESTIONS

1. How does the period depend on the acceleration due to gravity?

2. What do the constants in the curve fit for the Period vs. g data represent? Calculate what they should be theoretically and compare the theoretical value to the curve fit constants.

3. Would the pendulum be longer or shorter on the Moon?

4. What would the period be if the pendulum had been inclined to 90 degrees? What value of g does this correspond to?

EXPERIMENT # 7

Ratio of Specific Heats of a Gas

EQUIPMENT

INCLUDED:

1	Heat Engine/Gas Law Apparatus	TD-8572
1	Large Rod Stand	ME-8735
1	45 cm Long Steel Rod	ME-8736
1	Low Pressure Sensor	CI-6534A
1	ScienceWorkshop 500 or 750 Interface	CI-6400
1	DataStudio Software	CI-6870

INTRODUCTION

A cylinder is filled with air and a Pressure Sensor is attached. The piston is plucked by hand and allowed to oscillate. The oscillating pressure is recorded as a function of time and the period is determined. The ratio of specific heat capacities is calculated using the period of oscillation, according to Ruchhardt's method.

Figure 1: The piston is plucked by hand.

THEORY: In Ruchhardt's Method, a cylinder of gas is compressed adiabatically by plucking the piston. The piston will then oscillate about the equilibrium position (Figure 1 left). Gamma, the ratio of specific heat, can be determined by measuring the period of oscillation.

If the piston is displaced downwards a distance x, there will be a restoring force which forces the piston back toward the equilibrium position.

Just like a mass on a spring, the piston will oscillate. The piston acts as the mass and the air acts as the spring. The period of oscillation of a mass on a spring (or for the piston and air) is

$$T = 2\pi\sqrt{\frac{m}{k}} \qquad (1)$$

To determine the spring constant, **k,** for air, calculate the force when the piston is displaced a distance x. When the piston is displaced downward a distance x, the volume decreases by a very small amount compared to the total volume: dV = xA where A is the cross-sectional area of the piston.

The resulting force on the piston is given by F = (dP)A where dP is the small change in pressure. To find a relationship between dP and dV, we assume that if the oscillations are small and rapid, no heat is gained or lost by the gas. Thus the process is adiabatic and

PV=constant (2)

where

$$\gamma = \frac{C_P}{C_V} = \text{Ratio of Molar Specific Heats} \qquad (3)$$

For a diatomic gas, C_V = 5/2 R and C_P = 7/2 R, so γ = 7/5.

Taking a derivative of Equation (2) gives

$$P\gamma V^{\gamma-1}dV + V^{\gamma}dP = 0 \qquad (4)$$

Solving for dP, $dP = -\frac{P\gamma V^{\gamma-1}}{V^{\gamma}}dV$ (5)

Since dV = xA, $dP = -\frac{\gamma PxA}{V}$ (6)

Plugging into F = (dP)A gives

$$F = -\left(\frac{\gamma PA^2}{V}\right)x \qquad (7)$$

Comparing this to F = -kx shows that

$$k = \left(\frac{\gamma PA^2}{V}\right) \qquad (8)$$

Substituting into the period equation for k gives

$$T = 2\pi\sqrt{\frac{mV}{\gamma PA^2}} \qquad (9)$$

Solving for the volume gives $V = \frac{\gamma A^2 P T^2}{4\pi^2 m}$. The total volume is $A(h+h_o)$, where h is the height measured on the labeled scale and h_o is the unknown height below zero on the label. Substituting in for the volume and solving for the height of the piston, h, gives

$$h = \left(\frac{\gamma AP}{4\pi^2 m}\right)T^2 - h_o \tag{10}$$

Thus, if the piston height is plotted versus the square of the period, the resulting graph will be a straight line with $slope = \left(\frac{\gamma AP}{4\pi^2 m}\right)$ and y-intercept h_o.

Therefore the ratio of specific heats is given by

$$\gamma = \frac{4\pi^2 m(slope)}{AP} \tag{11}$$

where m = mass of piston, A = cross-sectional area of piston, P = atmospheric pressure, and the slope is from the graph of h vs. T^2.

SETUP

1. Slide the Heat Engine/Gas Laws Apparatus onto the rod stand as shown in Figure 1.

2. Attach a Low Pressure Sensor to one of the ports on the Heat Engine Apparatus. Unclamp both of the tube clamps at the bottom of the apparatus.

3. Raise the piston to the 9-cm mark and clamp it at this position with the side thumb screw at the top of the cylinder. Close the tube clamp on the open port. Loosen the side thumb screw and now the piston will stay at 9 cm.

4. Plug the Low Pressure Sensor into Channel A on theScienceWorkshop 500 interface.

5. Run the DataStudio program called "Ratio of Specific Heats".

PROCEDURE

1. Find the mass (m) of the piston (given on the apparatus label) and the cross-sectional area (A) of the piston (the piston diameter is given on the apparatus label).

2. Click on Start in the DataStudio program.

3. Using the tip of your finger, pluck the top of the piston. Click Stop on the computer.

4. Using the Smart Cursor, determine the period of the oscillation from the pressure versus time graph. Expand the area of the graph that shows the oscillation. Measure the period by measuring the time for several peaks and dividing by the number of peaks. Type this period and the corresponding piston height into the table in DataStudio.

5. Lower the piston to 8 cm and repeat the procedure. Then continue to lower the piston in steps of 1 cm, repeating the procedure at each piston position down to 1 cm.

6. Unless a barometer is available, assume the atmospheric pressure is 1.01 x 10^5 Pa.

8. If another gas is available, determine (for that gas. NOTE: Another gas, such as Helium, can be introduced into the cylinder by moving the piston to its lowest position, attaching a rubber balloon filled with Helium to the unused port and opening the hose clamp and letting the Helium from the balloon flow into the cylinder, pushing the piston up to the top. Then the hose clamp is closed with the piston at 9 cm. Never attach a high pressure hose directly to the apparatus.

QUESTIONS

1. What is the ratio of specific heats of a diatomic gas in theory? Why?

2. What is the ratio of specific heats of a monatomic gas in theory? Why?

3. Would the slope of the graph for Helium be greater or less than the slope for air?

4. Why can we assume air is diatomic? What are the main components of air?

EXPERIMENT # 8

To verify the inverse-square relationship of Coulomb's law and find the value of Coulomb's constant from Coulomb torsional balance

EQUIPMENT

1	Coulomb's Law Apparatus	ES-9070A
1	Kilovolt Power Supply	SF-9586
1	Basic Electrometer	ES-9078
1	Faraday Ice Pail	ES-9042A
1	Charge Producers and Proof Plane	ES-9057B
1	Experiment Resources CD	EX-9922
1	DataStudio Software	CI-6870

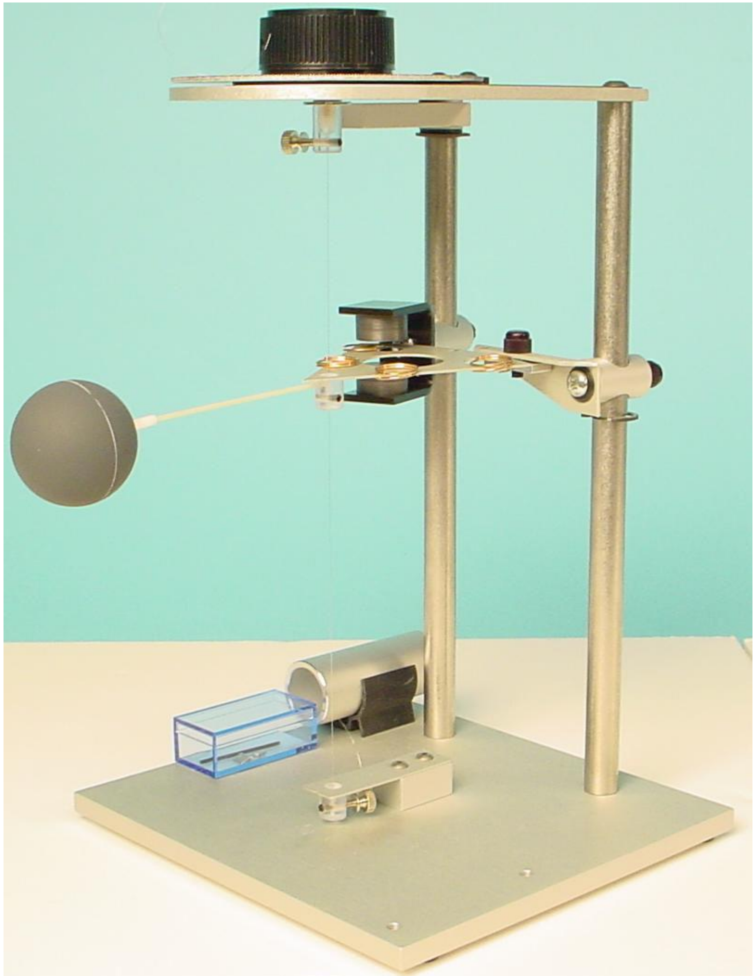
INTRODUCTION

The Coulomb Balance (Figure 1) is a delicate torsion balance that can be used to investigate the force between charged objects. A conductive sphere is mounted on a rod, counterbalanced, and

Figure 1: Equipment Separated to Show Components

suspended from a thin torsion wire. An identical sphere is mounted on a slide assembly so it can be positioned at various distances from the suspended sphere. To perform the experiment, both spheres are charged, and the sphere on the slide assembly is placed at fixed distances from the equilibrium position of the suspended sphere. The electrostatic force between the spheres causes the torsion wire to twist. The experimenter then twists the torsion wire to bring the balance back to its equilibrium position. The angle through which the torsion wire must be twisted to reestablish equilibrium is directly proportional to the electrostatic force between the spheres. All the variables of the Coulomb relationship $(F = \frac{kq_1q_2}{R^2})$ can be varied and measured using the Coulomb Balance. The experimenter can verify the inverse square relationship and the charge dependence using the balance and any electrostatic charging source.

THEORY



Take one gram of protons and place them one meter away from one gram of electrons. The resulting force is equal to 1.5 x 10^{23}Newtons; roughly the force it would take to "lift" an object from the surface of the Earth that had a mass about 1/5 that of the moon. So, if such small amounts of charge produce such enormous forces, why does it take a very delicate torsion balance to measure the force between charged objects in the laboratory? In a way, the very magnitude of the forces is half the problem. The other half is that the carriers of the electrical force-the tiny proton and the even tinier electron-are so small, and the electrons are so mobile. Once you separate them, how do you keep them separated? The negatively charged electrons are not only drawn toward the positively charged protons; they also repel each other. Moreover, if there are any free electrons or ions between the separated charges, these free charges will move very quickly to reduce the field caused by the charge separation. So, since electrons and protons stick together with such tenacity, only relatively small charge differentials can be sustained in the laboratory. This is so much the case that, even though the electrostatic force is more than a billion-billion-billion-billion times as strong as the gravitational force, it takes a very delicate torsion balance to measure the electrical force; whereas, the gravitational force can be measured by weighing an object with a spring balance. (see Figure 2): Setting Up the Coulomb Balance)

SET UP

1. Slide the copper rings onto the counterweight vane, as shown in Figure 2. Adjust the position of the copper rings so the pendulum assembly is level.
2. Reposition the index arm so it is parallel with the base of the torsion balance and at the same height as the vane.
3. Adjust the height of the magnetic damping arm so the counterweight vane is midway between the magnets.

4. Turn the torsion knob until the index line for the degree scale is aligned with the zero degree mark.
5. Rotate the bottom torsion wire retainer (do not loosen or tighten the thumbscrew) until the index line on the counterweight vane aligns with the index line on the index arm.

Figure 3: Zeroing the Torsion Balance

6. Carefully turn the torsion balance on its side, supporting it with the lateral support bar, as shown in Figure 3. Place the support tube under the sphere, as shown.
7. Adjust the positions of the copper rings on the counterweight vane to realign the index line on the counterweight with the index line on the index arm.
8. Place the torsion balance upright.

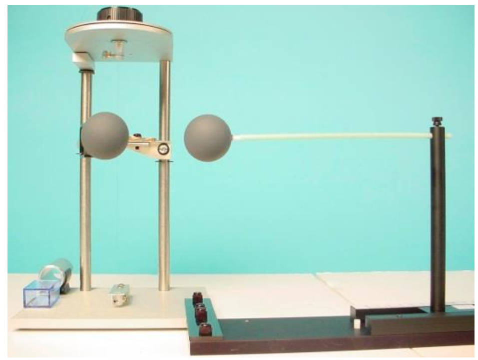


Figure 4: Slide Assembly Setup

9. *Connect the slide assembly* to the torsion balance as shown in Figure 4, using the coupling plate and thumbscrews to secure it in position.
10. *Align the spheres vertically* by adjusting the height of the pendulum assembly so the spheres are aligned: Use the supplied allen wrench to loosen the screw that anchors the pendulum assembly to the torsion wire. Adjust the height of the pendulum assembly as needed.
11. Readjust the height of the index arm and the magnetic damping arm as needed to reestablish a horizontal relationship.
12. *Align the spheres laterally* by loosening the screw in the bottom of the slide assembly that anchors the vertical support rod for the sphere, using the supplied allen wrench (the vertical support rod must be moved to the end of the slide assembly, touching the white plastic knob to access the screw). Move the sphere on the vertical rod until it is laterally aligned with the suspended sphere and tighten the anchoring screw.

13. *Position the slide arm* so that the centimeter scale reads 3.8 cm (this distance is equal to the diameter of the spheres).
14. *Position the spheres* by loosening the thumbscrew on top of the rod that supports the sliding sphere and sliding the horizontal support rod through the hole in the vertical support rod until the two spheres just touch. Tighten the thumbscrew.

At this point the experiment is ready. The degree scale should read zero, the torsion balance should be zeroed (the index lines should be aligned), the spheres should be just touching, and the centimeter scale on the slide assembly should read 3.8 cm. (This means that the reading of the centimeter scale accurately reflects the distance between the centers of the two spheres.)

SOFTWARE SET UP

Start DataStudio and open the file called "ColoumbsLaw_A.ds".

PROCEDURE - FORCE VS. DISTANCE (PART A)

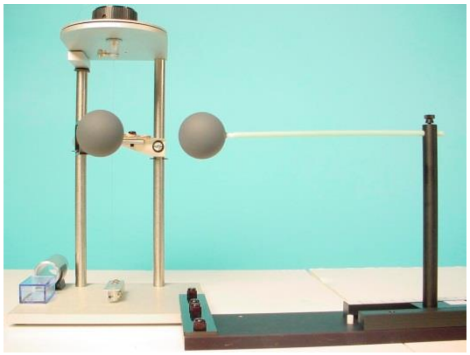


Figure 5: Experimental Setup

1. Be sure the spheres are fully discharged (touch them with a grounded probe) and move the sliding sphere as far as possible from the suspended sphere. Set the torsion dial to 0 degrees. Zero the torsion balance by appropriately rotating the bottom torsion wire retainer until the pendulum assembly is at its zero displacement position as indicated by the index marks.
2. With the spheres still at maximum separation, charge both the spheres to a potential of 6 kV, using the charging probe. (One terminal of the power supply should be grounded.) Immediately after charging the spheres, turn the power supply off to avoid high voltage leakage effects.
3. Position the sliding sphere at a position of 20 cm. Adjust the torsion knob as necessary to balance the forces and bring the pendulum back to the zero position.
4. Separate the spheres to their maximum separation, recharge them to the same voltage, then reposition the sliding sphere at a separation of 20 cm. Measure the torsion angle and record your results again. Repeat this measurement several times, until your result is repeatable to within ± 1 degree.
5. Record the distance (R) and the angle (θ) in the Data Table "Twist Angle v Distance" in DataStudio.
6. Repeat steps 1-5 for 14, 10, 9, 8, 7, 6 and 5 cm.

ANALYSIS

1. Calculate the inverse square of the distance values and enter them into the Data Table "Twist Angle vs 1/(R^2)." Observe the resulting graph. Note: DataStudio automatically corrects the data to resemble two point charges instead of two spheres.
2. Determine the functional relationship between force (which is proportional to the torsion angle (θ) and the distance (R).

PROCEDURE – FORCE VS. DISTANCE (PART B)

1. Be sure the spheres are fully discharged (touch them with a grounded probe) and move the sliding sphere as far as possible from the suspended sphere. Set the torsion dial to 0 degrees. Zero the torsion balance by appropriately rotating the bottom torsion wire retainer until the pendulum assembly is at its zero displacement position as indicated by the index marks.
2. With the spheres still at maximum separation, charge both the spheres to a potential of 3 kV, using the charging probe. (One terminal of the power supply should be grounded.) Immediately after charging the spheres, turn the power supply off to avoid high voltage leakage effects.
3. Position the sliding sphere at a position of 10 cm. Adjust the torsion knob as necessary to balance the forces and bring the pendulum back to the zero position.
4. Open the DataStudio file "CoulombsLaw_B.ds." Record the Voltage (kV) and the angle (θ) in the Data Table "Twist Angle v Voltage" in DataStudio.

ANALYSIS

1. Determine the functional relationship between force (which is proportional to the torsion angle (θ) and the charge (q) (which is proportional to the Voltage).

PROCEDURE – THE COULOMB CONSTANT (PART C)

In parts A and B of this lab, you determined (if all went well) that the electrostatic force between two point charges is inversely proportional to the square of the distance between the charges and directly proportional to the charge on each sphere. This relationship is stated mathematically in Coulomb's Law:

$$F = \frac{kq_1q_2}{R^2}$$

where F is the electrostatic force, q_1 and q_2 are the charges, and R is the distance between the charges. In order to complete the equation, you need to determine the value of the Coulomb constant, k. To accomplish this, you must measure three additional variables: the torsion constant of the torsion wire (K_{tor}), so you can convert your torsion angles into measurements of force, and the charges, q_1 and q_2. Then, knowing F, q_1, q_2, and R, you can plug these values into the Coulomb equation to determine k.

Measuring the Torsion constant, K_{tor}

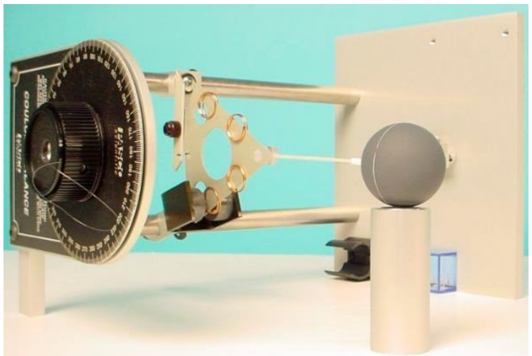


Figure 6. Calibrating the Torsion Balance

1. Carefully turn the Torsion Balance on its side, supporting it with the lateral support bar, as shown in Figure 6. Place the support tube under the sphere, as shown.

2. Zero the torsion balance by rotating the torsion dial until the index lines are aligned.

3. Open the DataStudio file "CoulombsLaw_C.ds" Record the angle of the degree plate in the Data Table "Mass(mg) v Twist Angle" in DataStudio.

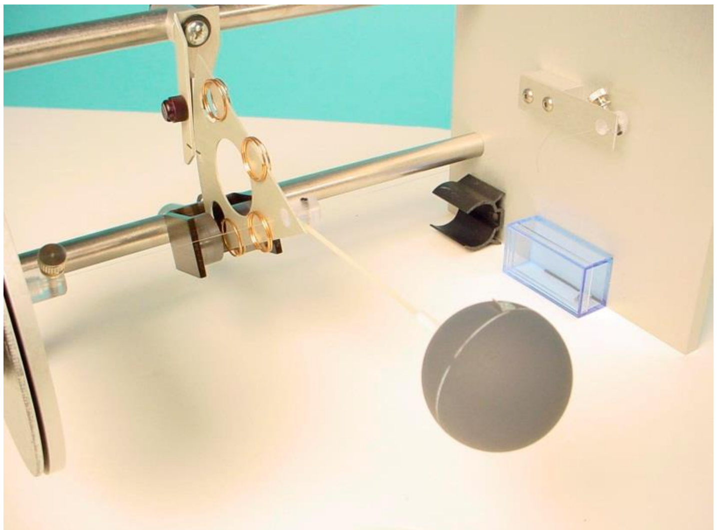


Figure 7. Placing the Mass on the Sphere

4. Carefully place the 20 mg mass on the center line of the conductive sphere.
5. Turn the degree knob as required to bring the index lines back into alignment. Read the torsion angle on the degree scale.
6. Record the angle in the Data Table "Mass (mg) v Twist Angle."
7. Repeat the previous steps, using the two 20 mg masses and the 50 mg mass to apply each of the masses shown in the table. Each time record the mass and the torsion angle.
8. Convert the values of mass in mg to Newtons. Enter these values along with the corresponding angles in the Data Table "Weight v Twist Angle."
9. **Determine** the value of the Torsion constant, K_{tor} from the graph of "Weight v Twist Angle."

Finding the Charge

Figure 8. Measuring the Charge with an Electrometer and a Faraday Ice Pail

The charge on the spheres can be measured more accurately using an electrometer with a Faraday ice pail. The setup for the measurement is shown in Figure 8. The electrometer and ice pail can be modeled as an infinite impedance voltmeter in parallel with a capacitor. A sphere with a charge q is touched against the ice pail. Since the capacitance of the ice pail and electrometer is much greater than that of the sphere, virtually all of the charge q is transferred onto the ice pail. The relationship between the voltage reading of the electrometer and the charge deposited into the system is given by the equation q = CV, where C is the combined capacitance of the electrometer, the ice pail, and the connecting leads. Therefore, in order to determine the charge, you must know the capacitance of the system.

Finding the Capacitance of the System

1. First find the capacitance of the ice pail and the connecting leads. Attach the alligator clips to the ice pail. Use a capacitor meter to measure the capacitance by placing one lead of the capacitor meter to the inside of the coaxial cable and the other to the outside.
2. Add this value to the capacitance of the electrometer. The PASCO Basic Electrometer maintains a capacitance of 30 pF. Record this value.

Measuring the Charges q_1 and q_2

1. Hang the third sphere from a horizontally mounted rod. At this point make certain that the sphere is not in contact with anything.
2. Carefully charge the “sliding” sphere with the same voltage as in Part A (6.0 kV). Since only one sphere is used, this charge is half the charge of the spheres from that section of this experiment.
3. Transfer the charge to the hanging sphere by touching the “sliding” sphere to the hanging sphere.
4. Place the hanging sphere in the middle of the ice pail in contact with the inside section.

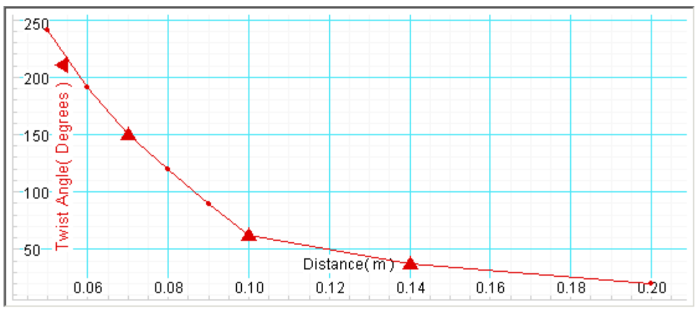
5. Making sure it is grounded, connect the electrometer leads to the ice pail. Record the value of the voltage.
6. Calculate the charge on one sphere using the equation:

$$q = CV$$

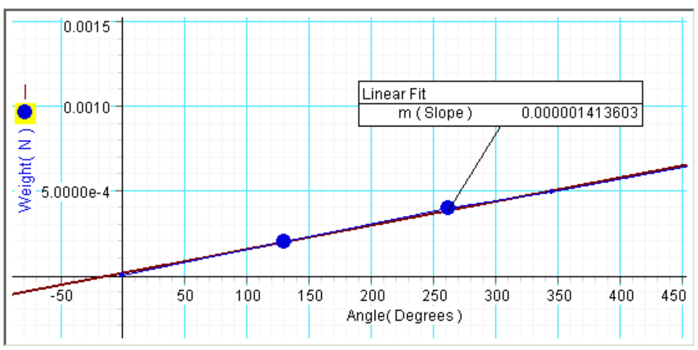
Remember that since this is half the charge, it must be multiplied by two. Remember, as well, that this charge value represents just one of the spheres.

Calculating Coulomb's Constant (k)

1. Choose a data point from the "Twist Angle v Distance" graph of Part A. (Figure 9 below)



2. Use the torsion constant to convert the twist angle to Newton force units. (Figure 10 below)



3. Use this force value (F), the accompanying distance value (R), and the charge value to calculate the Coulomb Constant (k):

$$k = \frac{FR^2}{q_1 q_2}$$

4. Calculate the Coulomb Constant with several other data points. Find the average.

EXPERIMENT # 9

To calculate the charge on an electron with Millikan's oil drop experiment.

EQUIPMENT

1	Millikan Oil Drop Apparatus	AP-8210
1	Basic Digital Multimeter	SE-9786
1	High Voltage Power Supply	SF-9585A
1	Large Rod Base	ME-8735
1	45 cm Steel Rod	ME-8736
1	Banana Plug Cord - Red (5 Pack)	SE-9750
1	Banana Plug Cord - Black (5 Pack)	SE-9751
1	DataStudio Software	CI-6870

INTRODUCTION

The electric charge carried by a particle may be calculated by measuring the force experienced by the particle in an electric field of known strength. Although it is relatively easy to produce a known electric field, the force exerted by such a field on a particle carrying only one or several excess electrons is very small. For example, a field of 1000 volts per cm would exert a force of only 1.6×10^{-14}Newtons on a particle bearing one excess electron. This is a force comparable to the gravitational force on a particle with a mass of 10^{-12} (one million millionth) gram.

The success of the Millikan Oil Drop experiment depends on the ability to measure forces this small. The behavior of small charged droplets of oil, having masses of only 10^{-12} gram or less, is observed in a gravitational and an electric field. Measuring the velocity of fall of the drop in air enables, with the use of Stokes' Law, the calculation of the mass of the drop. The observation of the velocity of the drop rising in an electric field then permits a calculation of the force on, and hence, the charge carried by the oil drop.

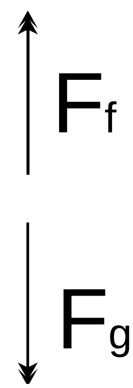
Although this experiment will allow one to measure the total charge on a drop, it is only through an analysis of the data obtained and a certain degree of experimental skill that the charge of a single electron can be determined. By selecting droplets which rise and fall slowly, one can be certain that the drop has a small number of excess electrons. A number of such drops should be observed and their respective charges calculated. If the charges on these drops are integral multiples of a certain smallest charge, then this is a good indication of the atomic nature of electricity. However, since a different droplet has been used for measuring each charge, there remains the question as to the effect of the drop itself on the charge. This uncertainty can be eliminated by changing the charge on a single drop while the drop is under observation. An ionization source placed near the drop will accomplish this. In fact, it is possible to change the charge on the same drop several times. If the results of measurements on the same drop then yield charges which are integral multiples of some smallest charge, then this is proof of the atomic nature of electricity.

THEORY

An analysis of the forces acting on an oil droplet will yield the equation for the determination of the charge carried by the droplet.

Finding the Relationship between Velocity of Oil Drop and the Electric Field

Figure 1 shows the forces acting on the drop when it is falling in air and has reached its terminal velocity. (Terminal velocity is reached in a few milliseconds for the droplets used in this experiment.) In Figure 1, F_f represents the force of friction and F_g represents the force due to gravity. Where,



$F_f = -kv_o$ $\qquad$ $F_g = -mg$

$v_o$is the terminal velocity of fall (its value is negative and constant), *k* is the coefficient of friction between the air and the drop, *m* is the mass

of the drop, and *g* is the acceleration of gravity.

Figure 1

$F_f + F_g = 0$

$-kv_o + -mg = 0$

$-kv_o = mg$

$$k = \frac{-mg}{\upsilon_o} \qquad \text{(Equation 1)}$$

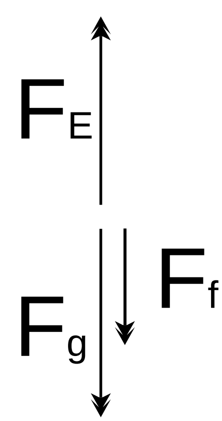


Figure 2 shows the forces acting on the drop when it is rising under the influence of an electric field.

$F_f = -kv_o$ $\qquad$ $F_g = -mg$ $\qquad$ $F_E = qE$

E is the electric field, *q* is the charge carried by the drop, and □ is the velocity.

Figure 2

$F_f + F_g + F_E = 0$

$-kv_o + -mg + qE = 0$

$qE = kv + mg$ $\qquad$ combining with Equation 1 above yields

$$qE = \frac{-mg}{v_o} v + mg$$ re-arranging gives

$$\frac{-mg}{v_o}v = qE - mg$$ solving for □o produces

$$v = \frac{-qv_o}{mg}E + v_o \qquad \text{(Equation 2)}$$

Finding the Mass

To find *m* from equation 2, one uses the expression for the volume of a sphere:

$$m = \frac{4}{3}\pi a^3 \rho \qquad \text{(Equation 3)}$$

where a is the radius of the droplet, and ρ is the density of the oil.

To calculate *a*, one employs Stokes' Law, relating the radius of a spherical body to its velocity of fall in a viscous medium (with the coefficient of viscosity, η).

$$a = \sqrt{\frac{-9\eta v_o}{2g\rho}} \qquad \text{(Equation 4)}$$

Stokes' Law, however, becomes incorrect when the velocity of fall of the droplets is less than 0.1 cm/s. (Droplets having this and smaller velocities have radii, on the order of 2 microns, comparable to the mean free path of air molecules, a condition which violates one of the assumptions made in deriving Stokes' Law.) Since the velocities of the droplets used in this experiment will be in the range of 0.01 to 0.001 cm/s, the viscosity must be multiplied by a correction factor. The resulting effective viscosity is:

$$n_{eff} = \eta \frac{1}{1 + \frac{b}{pa}} \qquad \text{(Equation 5)}$$

where*b* is a constant, *p* is the atmospheric pressure, and *a* is the radius of the drop as calculated by the uncorrectedform of Stokes' Law, equation (4).

Substituting η_{eff}in equation (5) into equation (4), andthen solving for the radius *a* gives:

$$a = \sqrt{\left(\frac{b}{2p}\right)^2 - \frac{9\eta v_o}{2g\rho}} - \frac{b}{2p} \qquad \text{(Equation 6)}$$

Finding the Charge

Observe equation 2:

$$v = \frac{-qv_o}{mg}E + v_o \qquad \text{(Equation 2)}$$

A plot of v versus E yields a slope (s) of:

$$s = \frac{-qv_o}{mg} \qquad \text{(Equation 7)}$$

Rearranging for the value of the charge (q) gives:

$$q = \frac{-smg}{v_o} \qquad \text{(Equation 8)}$$

Combining equation 8 with equations 3 and 6 produces:

$$q = \frac{-\frac{4}{3}\pi g s\rho\left[\sqrt{\left(\frac{b}{2p}\right)^2 - \frac{9\eta v_o}{2g\rho}} - \frac{b}{2p}\right]^3}{v_o} \qquad \text{(Equation 9)}$$

q = charge carried by the droplet

g = acceleration due to gravity = 9.80 m/s^2

s = slope of v versus E graph as measured in the lab by equation 2

ρ = density of oil = 886 kg/m^3

b = constant = 8.22 X 10^{-3} Pa*m

p = barometric pressure = 101.3 X 10^3 Pa

η= viscosity of dry air (see graph in appendix I)

v_o = terminal velocity of fall (its value is negative and constant) as calculated as the vertical intercept of equation 2 or as measured directly through the Millikan Oil Drop Apparatus.

SETUP

Adjusting the height of the platform and leveling it

1. Place the apparatus on a level, solid table with the viewing scope at a height which permits the experimenter to sit erect while observing the drops. If necessary to achieve the proper height, mount the apparatus on two support rods (ME-8736) on the large rod stand (ME-8735) (Figure 1).
2. Using attached bubble level as a reference, level the apparatus with the leveling screws on the rod stand or the leveling feet of the platform, as is appropriate for your setup.

Figure 1a: Equipment Set-Up

Adjusting the environment of the experiment room

1. Make the room as dark as possible, while allowing for adequate light to read the multi-meter and stopwatch, and to record data.
2. Insure that the background behind the apparatus is dark.
3. Select a location that is free of drafts and vibrations.

Equipment Set-Up

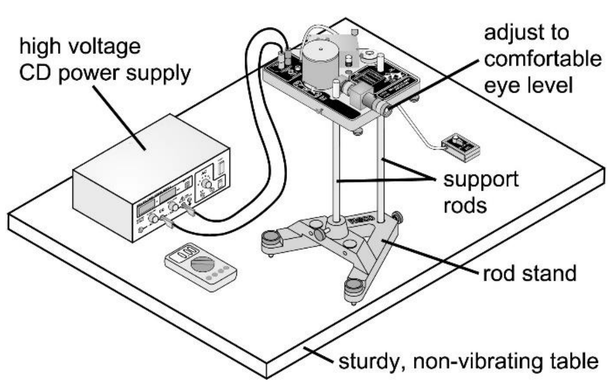


Figure 1b: Experimental Set up

Measuring Plate Separation

Disassemble the droplet viewing chamber by lifting the housing straight up and then removing the upper capacitor plate and spacer plate. (See Figure 2.)

Note: The thorium source and the electrical connection on the lower capacitor plate fit into appropriately sized holes on the plastic spacer.

Measure the thickness of the plastic spacer (which is equal to the plate separation distance) with a micrometer. Be sure that you are not including the raised rim of the spacer in your measurement. The accuracy of this measurement is important to the degree of accuracy of your experimental results. Record the measurement.

Figure 2: Disassembly of Viewing Chamber

Aligning the Optical System

Focusing the viewing scope

1. Reassemble the plastic spacer and the top capacitor plate onto the lower capacitor plate. Replace the housing, aligning the holes in its base with the housing pins. (See Figure 2)

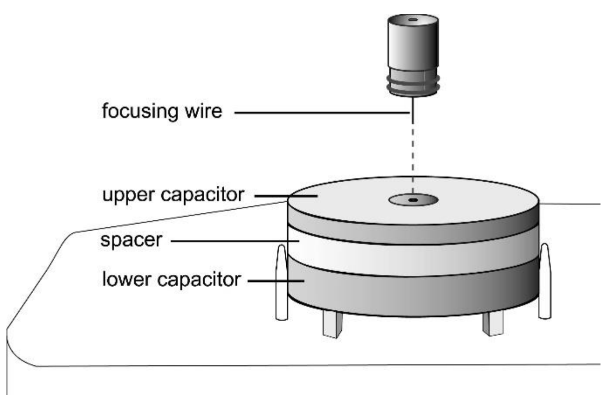


Figure 3: Insertion of the focusing wire into the top capacitor plate

2. Unscrew the focusing wire from its storage place on the platform and carefully insert it into the hole in the center of the top capacitor plate (Figure 3).
3. Connect the 12 V DC transformer to the lamp power jack in the halogen lamp housing and plug it into a wall socket. Check to be sure that the transformer is the correct voltage: 100, 117, 220, or 240 V).
4. Bring the reticle into focus by turning the reticle focusing ring.
5. View the focusing wire through the viewing scope, and bring the wire into sharp focus by turning the droplet focusing ring.

Note: Viewing will be easier for experimenters who wear glasses if the viewing scope is focused without using the glasses.

Focusing the halogen filament

1. Adjust the horizontal filament adjustment knob. The light is best focused when the right edge of the wire is brightest (in highest contrast compared to the center of the wire).
2. While viewing the focusing wire through the viewing scope, turn the vertical filament adjustment knob until the light is brightest on the wire in the area of the reticle.
3. Return the focusing wire to its storage location on the platform.

PROCEDURE

Adjusting and Measuring the Voltage

1. Connect the high voltage DC power supply to the plate voltage connectors using banana plug patch cords and adjust to deliver about 500 V.
2. Use the digital multimeter to measure the voltage delivered to the capacitor plates. Measure the voltage at the plate voltage connectors, not across the capacitor plates. There is a 10 mega-ohm resistor in series with each plate to prevent electric shock.

Determining the Temperature of the Droplet Viewing Chamber

1. Connect the multimeter to the thermistor connectors and measure the resistance of the thermistor. Refer to the Thermistor Resistance Table located on the platform to find the temperature of the lower brass plate. The measured temperature should correspond to the temperature within the droplet viewing chamber.

Although the dichroic window reflects much of the heat generated by the halogen bulb, the temperature inside the droplet viewing chamber may rise after prolonged exposure to the light. Therefore, the temperature inside the droplet viewing chamber should be determined periodically (about every 15 minutes).

Experimental Procedure

1. Complete the reassembly of the droplet viewing chamber by placing the droplet hole cover on the top capacitor plate and then placing the lid on the housing. (See Figure 2.)

   Note: The droplet hole cover prevents additional droplets from entering the chamber once the experiment has started.

2. Measure and record the plate voltage and the thermistor resistance (temperature).

Introducing the droplets into the chamber

1. Put non-volatile oil of known density into the atomizer (for example, Squibb #5597 Mineral Oil, density: 886 kg/m3).
2. Prepare the atomizer by rapidly squeezing the bulb until oil is spraying out. Insure that the tip of the atomizer is pointed down (90° to the shaft; see Figure 4).

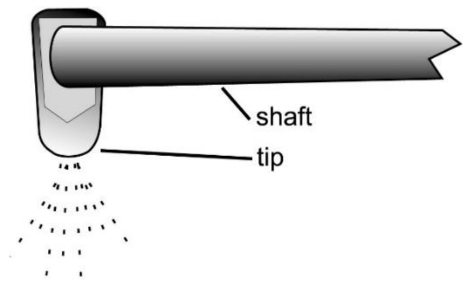


Figure 4: Correct Position of the Atomizer Tip

3. Move the ionization source lever to the Spray Droplet Position to allow air to escape from the chamber during the introduction of droplets into the chamber.

4. Place the nozzle of the atomizer into the hole on the lid of the droplet viewing chamber.

5. While observing through viewing scope, squeeze the atomizer bulb with one quick squeeze. Then squeeze it slowly to force the droplets through the hole in the droplet hole cover, through the droplet entry hole in the top capacitor plate, and into the space between the two capacitor plates.

6. When you see a shower of drops through the viewing scope, move the ionization source lever to the OFF position.

Note: If the entire viewing area becomes filled with drops, so that no one drop can be selected, either wait three or four minutes until the drops settle out of view, or disassemble the droplet viewing chamber (after turning off the DC power supply), thus removing the drops. When the amount of oil on the parts in the droplet viewing chamber becomes excessive, clean them, as detailed in the Maintenance section. Remember: the less oil that is sprayed into the chamber, the fewer times the chamber must be cleaned.

Note: The exact technique of introducing drops will need to be developed by the experimenter. The object is to get a small number of drops, not a large, bright cloud from which a single drop can be chosen. It is important to remember that the drops are being forced into the viewing area by the pressure of the atomizer. Therefore, excessive use of the atomizer can cause too many drops to be forced into the viewing area and, more important, into the area between the chamber wall and the focal point of the viewing scope. Drops in this area prevent observation of drops at the focal point of the scope.

Selection of the Drop

1. From the drops in view, select a droplet that both falls slowly (about 0.02–0.05 mm/s) when the plate charging switch is in the “Plates Grounded” position and can be driven up and down by turning on the voltage. Choose a droplet that is not too bright. Choose a droplet that does not react too suddenly to the change in polarity.

Note: If too many droplets are in view, you can clear out many of them by connecting power to the capacitor plates for several seconds.

Note: If you find that too few droplets have net charges to permit the selection of an appropriately sized and charged drop, move the ionization lever to the ON position for about five seconds.

2. When you find an appropriately sized and charged oil droplet, fine tune the focus of the viewing scope.

Note: The oil droplet is in best focus for accurate data collection when it appears as a pinpoint of bright light.

Collecting Data

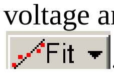
It is suggested that two individuals collect data. One person observes the droplet while changing the plate voltage in one hand and manipulating a stop watch with the other hand. The other person reads the stop watch, changes the voltage, and records the data.

1. Change the plate voltage so that the droplet is "driven" to the top of the viewing area.
2. Set the plate voltage to neutral and time the droplet as it falls a distance of 1.0 mm or 2 major divisions. Do this several times to find an average for the terminal velocity, v_o.
3. Adjust the voltage to 500 V. Drive the same droplet to the top of the viewing area. Set the plate voltage so that the droplet is driven downward. Record the voltage with the polarity required to drive the droplet downward. (Either -500V or +500 V)
4. Find the time it takes the droplet to move downward a distance of 1.0 mm or 2 major divisions. Record this value in the data table (include a negative sign for the downward motion).
5. Change the plate voltage so that the droplet is driven upward. Record the voltage and polarity required to drive the droplet upward.
6. Find the time it takes the droplet to move upward a distance of 1.0 mm or 2 major divisions. Record this value in the data table.
7. Repeat steps 3-6 with voltage values of 400 V, 300 V, 200 V, and 100V. (Table 1)

Table 1: Data Table

Voltage (V)	ΔT (s)

ANALYSIS

1. Calculate the value of the terminal velocity, v_o.
2. Open the DataStudio file "Charge of an Electron.ds."
3. Enter your values of voltage and change in time from the Data Table above into DataStudio.
4. Select the Fit Button 

. Choose the Linear Fit.
5. Record the values for the Slope and the Vertical Intercept.
6. Calculate the value of the radius using Equation 6.

$$a = \sqrt{\left(\frac{b}{2p}\right)^2 - \frac{9\eta v_o}{2g\rho}} - \frac{b}{2p}$$

where a = radius

b = constant = 8.22 X 10^{-3} Pa*m

p = barometric pressure = 101.3 X 10^{3} Pa

v= viscosity of dry air (see graph in appendix I)

v_o= terminal velocity of fall (its value is negative and constant) as calculated as the vertical intercept of the graph or as measured directly through the Millikan Oil Drop Apparatus.

g = acceleration due to gravity = 9.80 m/s^2

ρ= density of oil = 886 kg/m^3

7. Calculate the value of the mass of the droplet using Equation 3:

$$m = \frac{4}{3}\pi a^3 \rho$$

where m = mass of the droplet

a = radius of the droplet

ρ= density of oil = 886 kg/m^3

8. Calculate the value of the charge of an electron using Equation 8:

$$q = \frac{-smg}{v_o}$$

where q = charge of an electron

s = slope of v versus E graph as measured in the lab by equation 2

m = mass of the droplet

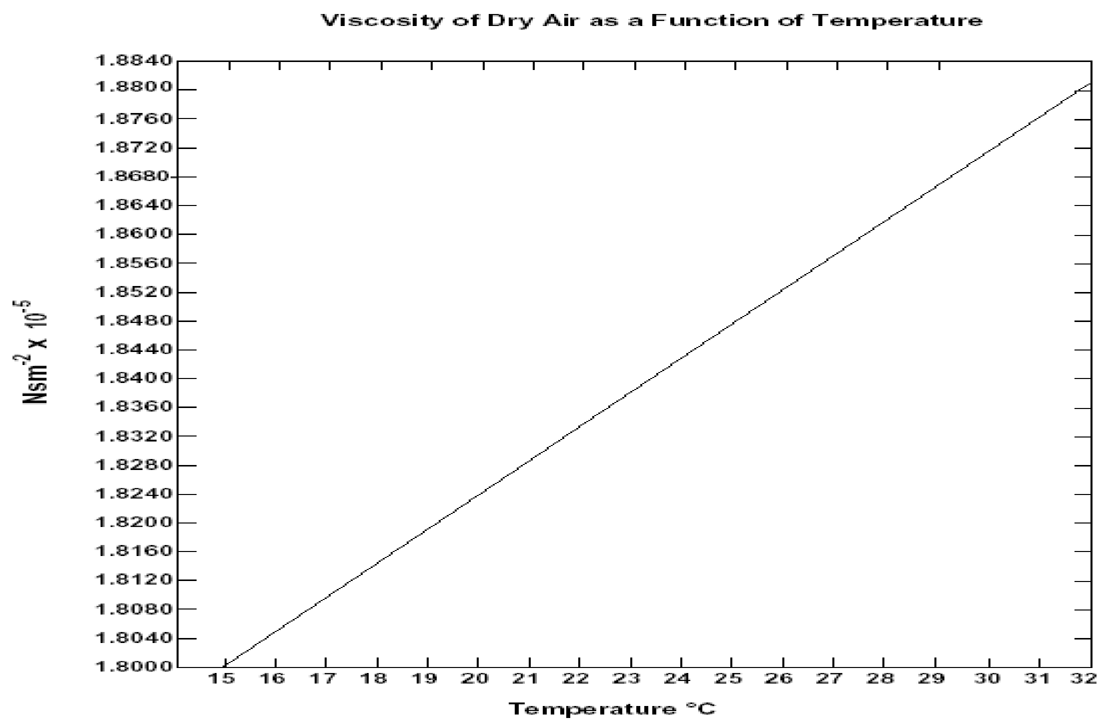
g = acceleration due to gravity = 9.80 m/s^2

v_o = terminal velocity of fall (its value is negative and constant) as calculated as the vertical intercept of equation 2 or as measured directly through the Millikan Oil Drop Apparatus.

QUESTION

1. Compare your value to the accepted value of the charge of an electron:
1.60×10^{-19} C

Appendix 1



Appendix 2

Millikan Oil Drop Apparatus Thermistor Resistance at Various Temperatures

THERMISTOR RESISTANCE TABLE

°C	X 10^6 Ω	°C	X 10^6 Ω	°C	X 10^6 Ω
10	3.239	20	2.300	30	1.774
11	3.118	21	2.233	31	1.736
12	3.004	22	2.169	32	1.700
13	2.897	23	2.110	33	1.666
14	2.795	24	2.053	34	1.634
15	2.700	25	2.000	35	1.603
16	2.610	26	1.950	36	1.574
17	2.526	27	1.902	37	1.547
18	2.446	28	1.857	38	1.521
19	2.371	29	1.815	39	1.496

Appendix 3 Sample Data and Analysis

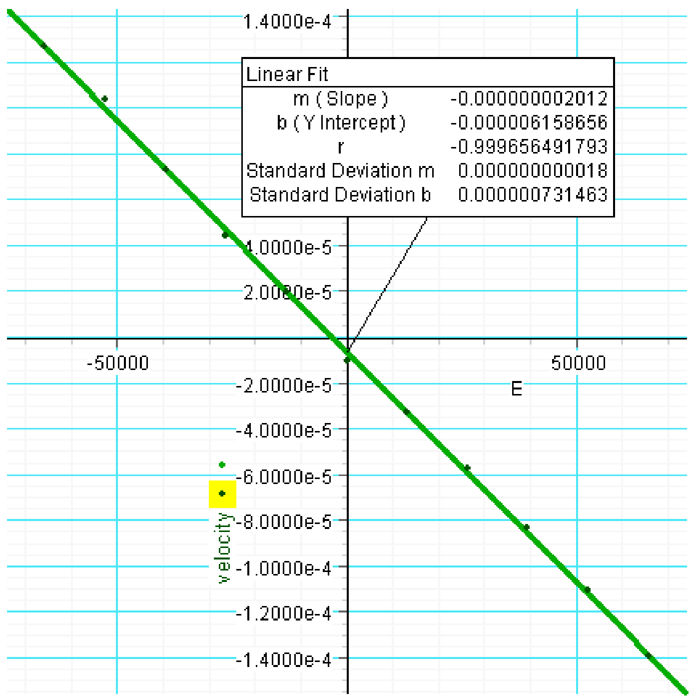
Finding the value of the Viscosity using the Thermistor Resistance and Temperature of the Air

Resistance of the Thermistor = 2.07 MΩ (measured directly using a multimeter)

Temperature of the Air = 23. 5°C (using the Thermistor Resistance Table in Appendix II)

η= 1.841 X 10^{-5} N*s/m^2 = viscosity of dry air (see graph in appendix I)

Voltage Data Voltage (+ or -) (V)	Delta T Data Delta T (+ or -) (s)
500.000	-7.190
-500.000	7.910
400.000	-9.030
-400.000	9.630
300.000	-11.960
-300.000	13.690
200.000	-17.410
-200.000	22.750
100.000	-30.060
-100.000	51.090



Data and Graph

Terminal velocity, v_o (measured directly, NOT using the vertical intercept)

$$vo = \frac{-0.001m}{95.75s} = -1.04x10^{-5}\, m/s$$

Calculation of the Radius of the Droplet

$$a = \sqrt{\left(\frac{b}{2p}\right)^2 - \frac{9\eta v_o}{2g\rho}} - \frac{b}{2p}$$

$$a = \sqrt{\left(\frac{8.22x10^{-3}\ Pa \cdot m}{2(101.3x10^{3}\ Pa)}\right)^2 - \frac{9(1.841x10^{-5}\ \frac{N \cdot s}{m^2})(-1.04x10^{-5}\ \frac{m}{s})}{2(9.81\frac{m}{s^2})(886\frac{kg}{m})}} - \frac{8.22x10^{-3}\ Pa \cdot m}{2(101.3x10^{3}\ Pa)}$$

a = 2.76 x 10^{-7} m

Calculating the Mass

$$m = \frac{4}{3}\pi a^3 \rho$$

$$m = \frac{4}{3}\pi(2.76x10^{-7}\ m)^3(886 kg/m)$$

m = 7.80 x 10^{-17} kg

Calculating the Charge of an Electron

$$q = \frac{-smg}{v_o}$$

$$q = \frac{-\left(-2.012x10^{-19}\ \frac{m/s}{V/m}\right)\left(7.80x10^{-17}\ kg\right)\left(9.81\frac{m}{s^2}\right)}{-1.04x10^{-5}\ m/s}$$

q = -1.48 x 10^{-19} C

EXPERIMENT # 10

Determine the role of resistors and capacitors in electronic circuits, verify Ohm's law and calculate time-constant of a capacitor

EQUIPMENT

	Included:	ScienceWorkshop	PASPORT
1	Charge/Discharge Circuit	EM-8678	EM-8678
1	Voltage/Current Sensor	(Not Required)	PS-2115
1	AA Batteries	PI-6601	PI-6601
1	Voltage Sensor	CI-6503	(Not Required)
1	Current Sensor	CI-6556	(Not Required)
1	Short Patch Cords	SE-7123	SE-7123
1	Computer Interface	CI-6400	PS-2100
1	DataStudio Software	CI-6870	CI-6870

INTRODUCTION

The purpose of this experiment is to determine the role of resistors and capacitors in electronic circuits. The Charge/Discharge Circuit contains several resistors, a 1.0 Farad capacitor, and battery holders. By using voltage and current sensors with this circuit, Ohm's Law can be verified or discovered.

THEORY

The Resistor

A resistor consists of a material that resists the flow of electric current. The resistance, *R*, of an electronic device is defined as the ratio of the voltage, *V*, across the device versus the current, *I*, that flows through the device:

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

Solving the equation for voltage produces Ohm's Law:

$$V = IR$$

The resistance of the device depends upon the material it is made of and the geometry of the component it resides within - according to the following equation:

$$R = \frac{\rho L}{A}$$

Where ρ is the resistivity of the material, L is the length, and A is the cross-sectional area.

The Capacitor

A capacitor is made of a dielectric material within two parallel plates. When a battery is connected to a capacitor, positive charge collects on one plate and negative charge collects on the other plate until the potential difference between the two is equal to the voltage of the battery.

The capacitance, *C*, is defined as the ratio between Q and V. Where Q is the charge imbalance needed to produce a given voltage, V, across the capacitor.

$$C = \frac{Q}{V}$$

Time Constant

Some electrical circuits contain both resistors and capacitors. These are called RC circuits. If the initial voltage applied to an RC circuit is V_0, the capacitance of the capacitor is *C*, and the resistance of the resistor is *R*, then the amount of time, *t*, it takes for the capacitor to reach the charge, *Q*, is given by:

$$Q = CV_0\left(1 - e^{\frac{-t}{RC}}\right)$$

If both sides of the equation are divided by *V*, the following equation results:

$$V = V_0\left(1 - e^{\frac{-t}{RC}}\right)$$

Where, *V* is the voltage of the capacitor at time *t*.

Similarly, the discharging of a capacitor is given by the equation:

$$V = V_0 e^{\frac{-t}{RC}}$$

Where, *Vo* is the voltage across the capacitor at *t* = 0.

The term RC in the exponent is referred to as the time constant, τ.

$$\tau = RC$$

The time constant is the amount of time it takes for the charge of the capacitor to equal 63.2% of its final value when charging or 36.8% of its initial value when discharging. Similarly, the time constant applies for both the voltage and the current in the capacitor of an RC circuit.

SETUP PART 11A: CHARGING AND DISCHARGING THE CAPACITOR

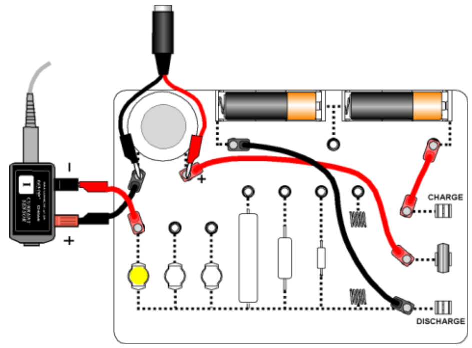


Figure 1

1. For PASPORT, arrange the Voltage-Current Sensor, the battery, and the patch cords as in Figure 1 above.
2. For ScienceWorkshop, use Figure 2. Attach the Voltage Sensor to analog channel A. Attach the Current Sensor to analog channel B.
3. Draw and label a representative circuit diagram of the above circuit.
4. Attach the sensor(s) to the interface. Connect the interface to the computer.
5. Move the switch of the Charge/Discharge Circuit to the "Discharge" position for several seconds. Then, move it to the open position where it does not contact either the "Charge" or "Discharge" slots.
6. For PASPORT, open the file "Capacitor (PP).ds." For ScienceWorkshop, open the file "Capacitor.ds."

PROCEDURE PART 11A: CHARGING AND DISCHARGING THE CAPACITOR

1. Press the 

button in DataStudio.
2. Move the switch to the "Charge" position until the values of the current and voltage remain constant.
3. Record your observations of the light bulb.
4. Move the switch to the open position where it does not contact either the "Charge" or "Discharge" slots. Remove the batteries.
5. Move the switch to the "Discharge" position until the values of the current and voltage remain constant.
6. Record your observations of the light bulb.
7. Press the 

button in DataStudio.

POST LAB QUESTIONS PART 11A: CHARGING AND DISCHARGING THE CAPACITOR

1. Describe the changes in voltage from the moment the switch is closed until the capacitor is “charged.”

2. Describe the changes in current from the moment the switch is closed until the capacitor is “charged.”

3. Describe how your observations of the light bulb correspond to your explanations in questions 1 and 2.

4. Make a diagram of the circuit as it is charging. Include the direction of charge flow. Represent positive charges with a “+.” Represent negative charges with a “-.”

5. Describe the changes in voltage from the moment after the capacitor is discharged until the voltage is constant.

6. Describe the changes in current from the moment after the capacitor is discharged until the current is constant.

7. Describe how your observations of the light bulb correspond to your explanations in questions 5 and 6.

8. Make a diagram of the circuit as it is discharging. Include the direction of charge flow. Represent positive charges with a "+." Represent negative charges with a "-."

9. Based on the conclusions from the previous questions, what is/are the role(s) of a capacitor in an electronic circuit?

SETUP PART 11B: OHM'S LAW

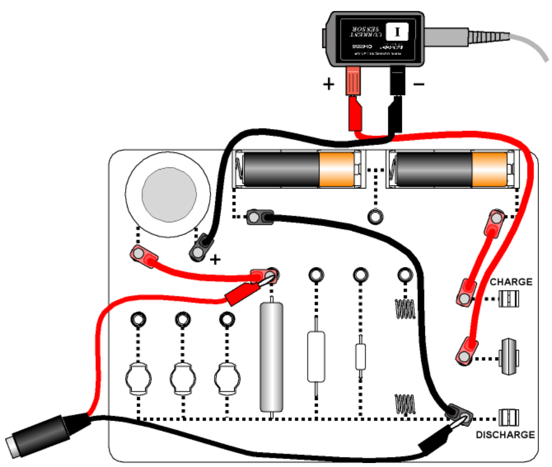


Figure 2

1. For PASPORT, arrange the Voltage-Current Sensor, the <u>two</u> batteries, and the patch cords as in Figure 3 above.
2. For ScienceWorkshop, use Figure 4. Attach the Voltage Sensor to analog channel A. Attach the Current Sensor to analog channel B.

3. Draw and label a representative circuit diagram for the circuit above.
4. Attach the sensor(s) to the interface. Connect the interface to the computer.
5. For PASPORT, open the file "OhmsLaw (PP).ds." For Science Workshop, open the file "OhmsLaw.ds."

PROCEDURE PART 11B: OHM'S LAW

1. Move the switch to the "Discharge" position. Maintain this position for approximately 15 seconds.
2. Move the switch to the "Charge" position.
3. Press the  button in DataStudio.
4. Collect data for approximately 30 seconds.
5. Press the  button in DataStudio.
6. Move the switch to the "Open" position.
7. Detach the patch cords above the 10 Ω resistor and connect them to the 33 Ω resistor. Repeat steps 1-6.
8. Detach the patch cords above the 33 Ω resistor and connect them to the bulb.Repeat steps 1-6.
9. At this point, 3 data runs should have been collected.

ANALYSIS PART 11B: OHM'S LAW

1. Using the  Button, find the appropriate fit from the data for the 10 Ω and 33 Ω resistors.
2. Determine the slope of your graph for the 10 Ω and 33 Ω resistors.

POST LAB QUESTIONS PART 11B: OHM'S LAW

1. What is the function of the capacitor in this part of the experiment?

2. How could this experiment be performed with batteries instead of a capacitor?

3. Make a diagram of the circuit . Include the direction of charge flow. Represent positive charges with a “+.” Represent negative charges with a “-.”

4. What is the physical meaning of the slope for the Voltage vs. Current graphs?

5. What is the physical meaning of the vertical intercept for the Voltage vs. Current graphs?

6. Starting with y = mx + b, write an equation that represents the relationship between Voltage vs. Current for the resistors. Don't forget to include units on all numbers.

7. Why is the voltage-current relationship different for a light bulb vs. a resistor?

SETUP PART 11C: TIME CONSTANT

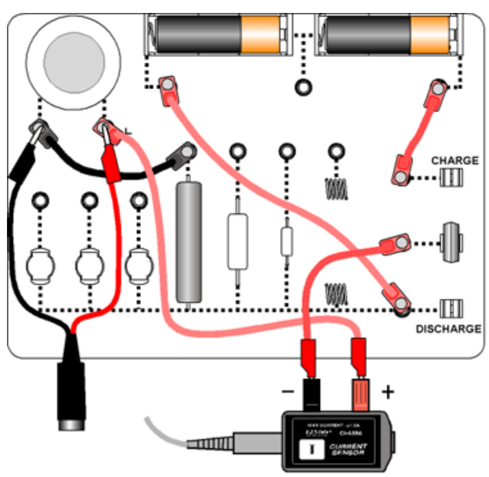


Figure 3

1. For PASPORT, arrange the Voltage-Current Sensor, the two batteries, and the patch cords as in Figure 5 above.
2. For ScienceWorkshop, use Figure 6. Attach the Voltage Sensor to analog channel A. Attach the Current Sensor to analog channel B.
3. Draw and label a representative circuit diagram.

4. Attach the sensor(s) to the interface. Connect the interface to the computer.

5. For PASPORT, open the file "TimeConstant (PP).ds." For Science Workshop, open the file "TimeConstant.ds."
6. Move the switch to the "Discharge" position. Maintain this position for approximately 30 seconds.

PROCEDURE PART 11C: TIME CONSTANT

1. Move the switch to the vertical or "open" position.
2. Press the 

button in DataStudio.
3. Move the switch to the "Charge" position.
4. When the data becomes relatively constant, move the switch to the "Discharge" position.
5. Collect data until the values once again remain relatively constant.
6. Press the 

button in DataStudio.
7. Move the switch to the "Open" position.
8. Detach the patch cord above the 10 □ resistor and attach it to the 33 □ resistor. Repeat steps 1-7.
9. Detach the patch cord above the 33□□ resistor and attach it to the 100 □ resistor. Repeat steps 1-7.
10. At this point, 3 data runs should have been collected.

ANALYSIS PART 11C: TIME CONSTANT

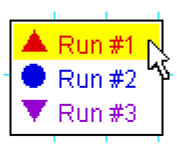


Figure 7

1. Use the cursor to highlight the first run in the legend box. (See the figure 7 above.)
2. Use the cursor to select the portion of the first run that corresponds to the **discharging** of the capacitor.
3. Using the Fit 

Button, select "Natural Exponent Fit."
4. Record the exponent values.
5. Repeat steps 1-4 for the other two data runs.

CONCLUSIONS/QUESTIONS PART 11C: TIME CONSTANT

1. What is the physical meaning of the "Scale Factor" (A) from the Natural Exponent Fit?

2. What is the physical meaning of the "Exponent" (C) from the Natural Exponent Fit?

3. Refer to the diagram of the circuit. Describe the role of the capacitor. Specifically, discuss the voltage across the capacitor while the capacitor is charging.

4. Further, discuss the current through the circuit while the capacitor is charging.

EXPERIMENT # 11

To calculate the equivalent capacitance in Series Combination Circuits and Parallel Combination Circuits

Objective:

To calculate the equivalent capacitance in the given series and parallel combinations of capacitors

Apparatus:

Digital Logic Trainer, Bread board (Figure 1), capacitors, DMMs (Digital Multimeters)SE-9786, Power supply SE-9720, connecting wires

Figure 1: Breadboard set up

Theory:

a) **Series combination circuit**

When capacitors are connected in series, the total capacitance is less than any one of the series capacitors' individual capacitances. If two or more capacitors are connected in series, the overall effect is that of a single (equivalent) capacitor having the sum total of the plate spacing of the individual capacitors. As we've just seen, an increase in plate spacing, with all other factors unchanged, results in decreased capacitance. Thus, the total capacitance is less than any one of the individual capacitors' capacitances. The formula for calculating the series total capacitance is the same form as for calculating parallel resistances:

Series Capacitances

$$C_{total} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots \frac{1}{C_n}}$$

Procedure:

1. Connect three capacitors on the bread board in the series combination as shown in figure 2.
2. Connect the power supply of voltage (5V or 12V) through wires.
3. Use DMM to measure the capacitance, charge and voltage across each capacitor.
4. Also calculate the total capacitance through the series capacitance formula.
5. Now replace all the three capacitors with its equivalent capacitor.
6. Calculate the voltage and charge across this equivalent capacitor.

Circuit Diagram:

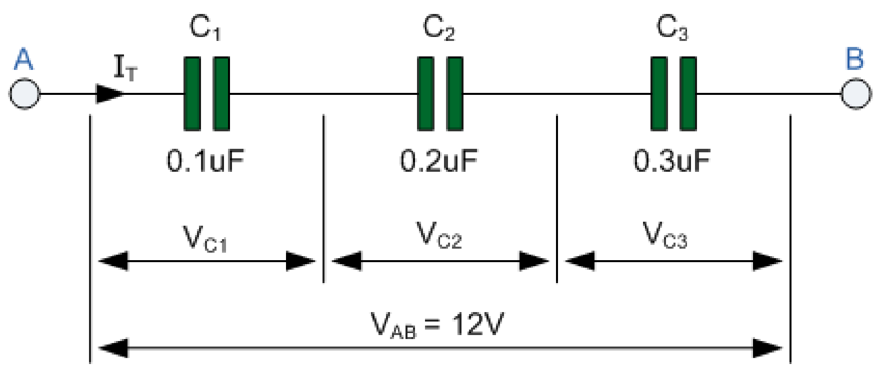


Figure 2: Capacitors in Series

Calculation:

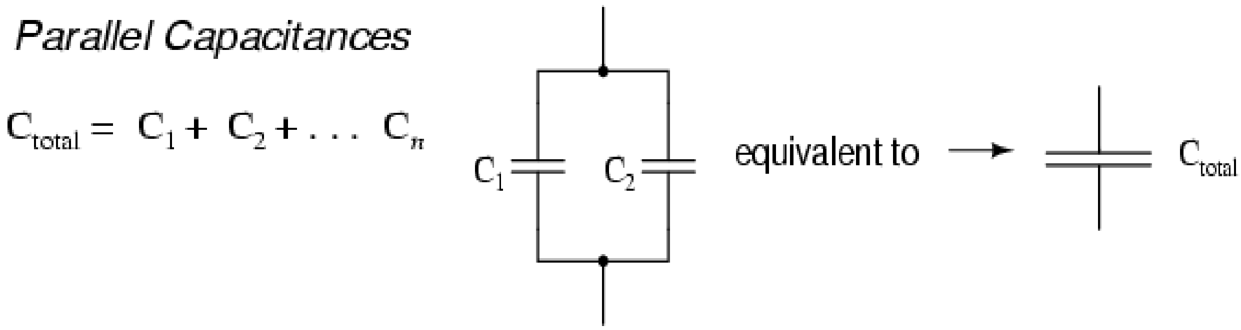
$$V_{AB} = V_{C1} + V_{C2} + V_{C3} = 12V$$

$$V_{C1} = \frac{Q_T}{C_1}, \quad V_{C2} = \frac{Q_T}{C_2}, \quad V_{C3} = \frac{Q_T}{C_3}$$

b) Parallel combination circuit

When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors' capacitances. If two or more capacitors are connected in parallel, the overall effect is that of a single equivalent capacitor having the sum total of the plate areas of the individual capacitors. As we've just seen, an increase in plate area, with all other factors unchanged, results in increased capacitance.

Thus, the total capacitance is more than any one of the individual capacitors' capacitances. The formula for calculating the parallel total capacitance is the same form as for calculating series resistances:



As you will no doubt notice, this is exactly opposite of the phenomenon exhibited by resistors. With resistors, series connections result in additive values while parallel connections result in diminished values. With capacitors, it's the reverse: parallel connections result in additive values while series connections result in diminished values.

Procedure:

1. Connect three capacitors on the bread board in the parallel combination as shown in Figure 3.
2. Connect the power supply of voltage (5V or 12V) through wires.
3. Use DMM to measure the capacitance, charge and voltage across each capacitor.
4. Also calculate the total capacitance through the parallel capacitance formula.
5. Now replace all the three capacitors with its equivalent capacitor.
6. Calculate the voltage and charge across this equivalent capacitor.

Circuit Diagram:

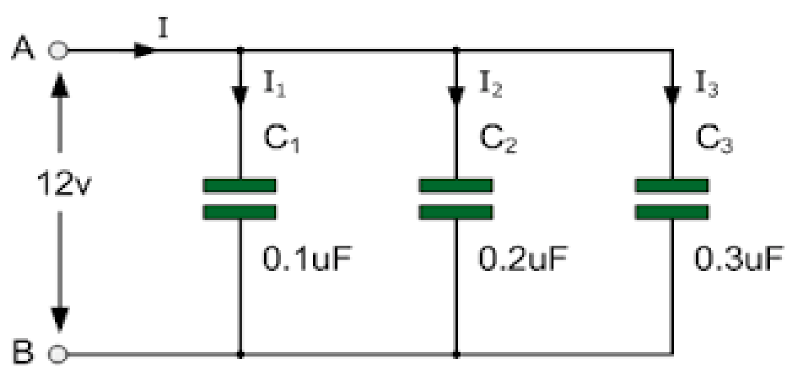


Figure 3: Capacitors in Parallel

Calculation:

$$i_1 = C_1\frac{dv}{dt}, \quad i_2 = C_2\frac{dv}{dt}, \quad i_3 = C_3\frac{dv}{dt}$$

$$i_T = i_1 + i_2 + i_3$$

$$\therefore\ i_T = C_1\frac{dv}{dt} + C_2\frac{dv}{dt} + C_3\frac{dv}{dt}$$

Post Lab Questions:

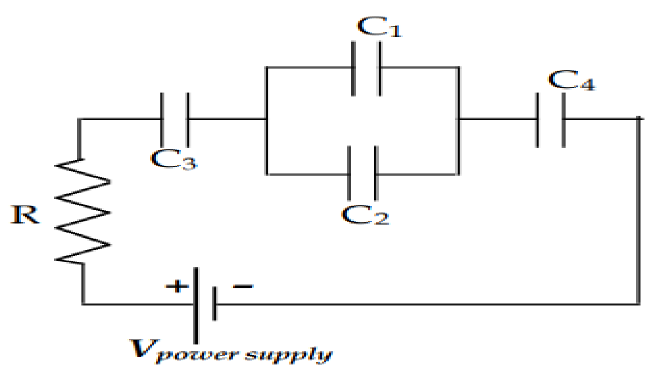
Q1) Calculate the combined capacitance in micro-Farads (uF) of the following capacitors when they are connected together in a parallel combination:

a) two capacitors each with a capacitance of 47nF
b) one capacitor of 470nF connected in parallel to a capacitor of 1µF

Q2) You have two 42µF and one 39µF all wired in parallel. Draw the schematic and calculate the total capacitance of the system.

Q3) Calculate the total capacitance of the following circuit:

a) when C1= 5µF, C2= 15µF, C3= 2.1uF, C4= 0.1µF



EXPERIMENT # 12

To investigate the magnetic force of a current carrying wire by the effect of current, length of conductor and magnetic field on the magnetic force

EQUIPMENT

	INCLUDED:	
1	Basic Current Balance	SF-8607
1	Current Balance Accessory	SF-8608
1	Ohaus Cent-o-Gram Balance	SE-8725
1	Low Voltage AC/DC Power Supply	SF-9584A
1	Large Base and Support Rod	ME-9355
1	Banana Plug Cord Set-Red (5 pack)	SE-9750
1	Banana Plug Cord Set-Black (5 pack)	SE-9751
1	Experiment Resources CD	EX-9922
1	DataStudio Software	CI-6870

INTRODUCTION

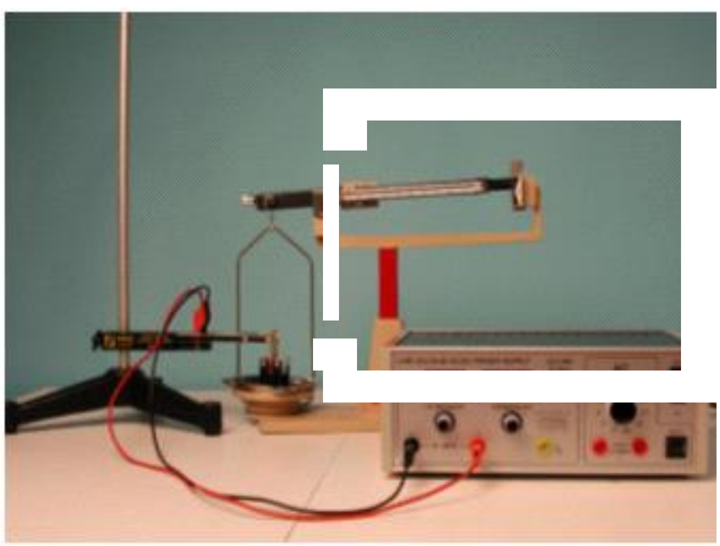


Figure 1: Experimental Set up

Magnets are mounted on an iron yoke and placed on a balance (resolution of at least 0.01g). One of the conducting paths is suspended between the magnets. The balance is used to measure the mass of the magnets and yoke prior to any current passing through the conducting path. Current is then passed through the conducting path, producing a force. The change in reading on the balance can be converted to find the magnetic force between the conductor and magnetic field. (See figure 1).

Conductors of different length are included to measure the effect of length on magnetic force. Magnetic field can be varied by changing the number of magnets in the yoke. The power source is used to change the current supplied to the conductor. The Current Balance Accessory includes all the components needed to test the effect of angle on magnetic force.

THEORY

A current carrying wire in a magnetic field experiences a force that is usually referred to as a magnetic force. The magnitude and direction of this force depend on four variables: The magnitude and direction of the current (**I**); the strength of the magnetic field (**B**); the length of the wire (**L**); and the angle between the field and the wire (**θ**).

This magnetic force can be described mathematically by the vector cross product:

$$\mathbf{F_m = IL \times B}$$

Or in scalar form,

$$\mathbf{F_m = ILB\sin\theta}$$

Using the equipment included in the Magnetic Forces on Wires Experiment, all four variables (I, B, L, and □) can be varied while measuring the resulting magnetic force.

SET UP

To set up the Current Balance:

1. Mount the Main Unit on a lab stand having with a rod 3/8 inch (1.1 cm) in diameter or smaller.
2. Select a Current Loop, and plug it into the ends of the arms of the Main Unit, with the foil extending down.
3. Place the Magnet Assembly on a balance with at least 0.01 gram sensitivity. Position the lab stand so the horizontal portion of the conductive foil on the Current Loop passes through the pole region of the magnets. The Current Loop shouldn't touch the magnets.
4. Connect the power supply and ammeter as shown above.

EXPERIMENT 12 A - FORCE VS. CURRENT

7. Insert between 4 – 6 magnets into the magnet holder to provide a constant magnetic field. Enter the number of magnets used above Table 1.
8. Choose one of the current loops to use throughout the experiment and record the length of the current loop above Table 1.
9. Setup the current balance as shown above.
10. Determine the mass of the magnet holder and magnets with no current flowing. Record this value in the column under "Mass" in Table 1 below.
11. Turn on the power supply and set the current to 0.5 A. Determine the new "Mass" of the magnet assembly. Record this value under "Mass" in Table 1 below.
12. Increase the current in 0.5 A increments to a maximum of 5.0 A, each time measuring the new "mass" of the magnet assembly and recording this value in Table 1 below.

ANALYSIS

# of Magnets Used: __________
Current Loop Used: __________

TABLE 1: Calculation of Force

Current (A)	"Mass" (grams)	"Force" (grams)

1. Subtract the "Mass" value for each of the currents from the "Mass" value for zero current to get the "Force" for each current.
2. Open the DataStudio file, Force_Current.ds
3. Enter the Current values used into the Force vs. Current table.
4. Enter the "Force" values into the Force vs. Current table.
5. Observe the shape of the Force vs. Current graph.

QUESTIONS

1. What relationship exists between the magnetic force and current through the conductor?

2. What is the physical meaning of the slope of the Force vs. Current graph?

3. What is the physical meaning of the vertical intercept of the Force vs. Current graph?

4. Can the vertical intercept be attributed to measurement error? Explain.

5. Write a proportionality expression that represents the relationship between Magnetic Force and Current.

EXPERIMENT 12B - FORCE VS. LENGTH OF WIRE

1. Insert between 4 – 6 magnets into the magnet holder to provide a constant magnetic field. Be sure to center the magnets in the holder. (See Figure 2)

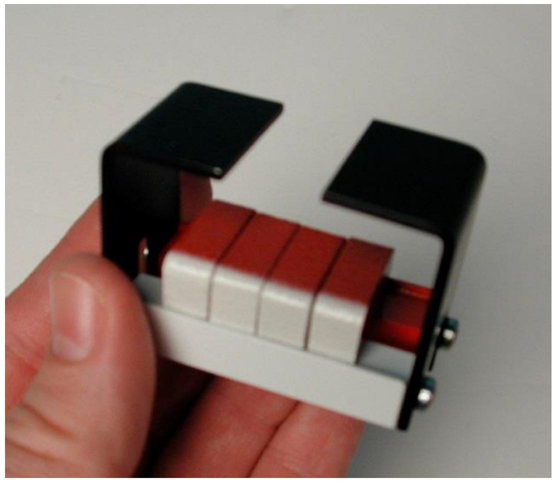


Figure 2: Magnets of the set up

2. Enter the number of magnets used above Table 2.
3. Choose the shortest current loop to begin the experiment.
4. Setup the current balance as shown above.
5. Determine the mass of the magnet holder and magnets with no current flowing. Record this value above Table 2 below.
6. Turn on the power supply and set the current between 2.0 and 3.0 Amps. Record this value above Table 2.
7. Determine the new "Mass" of the magnet assembly. Record this value under "Mass" in Table 2 below.
8. Swing the arm of the main unit up, to raise the present current loop out of the magnetic field gap.

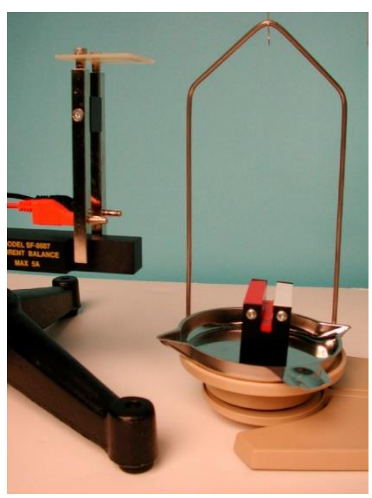


Figure 3: Mass Balance

9. Pull the current loop gently from the arms of the base unit. Replace it with the next current loop and carefully lower the arm to reposition the current loop in the magnetic field.
10. Repeat steps 6-8 for each of the current loops and enter the appropriate data in Table 2.

ANALYSIS

# of Magnets Used: __________
Current Used: ______________
"Mass" with I = 0: ___________

TABLE 2: Calculation of Force

Length (cm)	"Mass" (grams)	"Force" (grams)

1. Subtract the "Mass" value for each of the currents from the "Mass" value for zero current to get the "Force" for each length.
2. Open the DataStudio file, Force_ConductorLength.ds
3. Enter the Lengths used into the Force vs. Length table.
4. Enter the "Force" values into the Force vs. Length table.
5. Observe the shape of the Force vs. Length graph.

QUESTIONS

1. What relationship exists between the magnetic force and length of conductor in the magnetic field?
2. What is the physical meaning of the slope of the Force vs. Length graph?
3. What is the physical meaning of the vertical intercept of the Force vs. Length graph?
4. Can the vertical intercept be attributed to measurement error? Explain.
5. Write a proportionality expression that represents the relationship between Magnetic Force and Length.

EXPERIMENT 12C - FORCE VS. MAGNETIC FIELD

1. Insert one magnet into the magnet holder and center the magnet in the holder.
2. Choose one of the current loops to use throughout the experiment and record the length of the current loop above Table 3.
3. Setup the current balance as shown above.
4. Determine the mass of the magnet holder and magnets with no current flowing. Record this value in the "Mass" I = 0 column in Table 3.
5. Turn on the power supply and set the current between 2.0 and 3.0 Amps. Record this value above Table 3.
6. Determine the new "Mass" of the magnet assembly. Record this value under "Mass" I > 0 in Table 3 below.
7. Turn off the power supply to change the current to zero.
8. Swing the arm of the main unit up, to raise the current loop out of the magnetic field gap.
9. Place an additional magnet into the magnet holder aligning the like poles of the magnets.
10. Place the holder in the back on the balance pan with the North and South poles in the same orientation as the last measurement.
11. Lower the arm of the main unit and reposition the current loop inside the magnetic field gap. Be certain the current loop isn't touching the magnet holder.
12. Determine the mass of the magnet holder and magnets with no current flowing. Record this value in the "Mass" I = 0 column in Table 3.
13. Turn the power supply on to provide current through the loop.
14. Measure the new "Mass" of the magnet assembly and record this value in the "Mass" I >0 column in Table 3.
15. Repeat steps 7-14 for 3, 4, 5 and 6 magnets.

ANALYSIS

Current Used: _______________

Current Loop Used: __________

TABLE 3 Calculation of Force

Magnetic Field (# of magnets)	"Mass" I = 0 (grams)	"Mass" I > 0 (grams)

1. Subtract the "Mass" value for each Magnetic Field from the "Mass" value for zero current to get the "Force" for each field strength.
2. Open the DataStudio file, Force_MagField.ds
3. Enter the Lengths used into the Force vs. Magnetic Field table.
4. Enter the "Force" values into the Force vs. Magnetic Field table.
5. Observe the shape of the Force vs. Magnetic Field graph.

QUESTIONS

1. What relationship exists between the Magnetic Force and Magnetic Field?

2. What is the physical meaning of the slope of the Force vs. Magnetic Field graph?

3. What is the physical meaning of the vertical intercept of the Force vs. Magnetic Field graph?

4. Can the vertical intercept be attributed to measurement error? Explain.

5. Write a proportionality expression that represents the relationship between Magnetic Force and Magnetic Field.

EXPERIMENT 12D -FORCE VS ANGLE

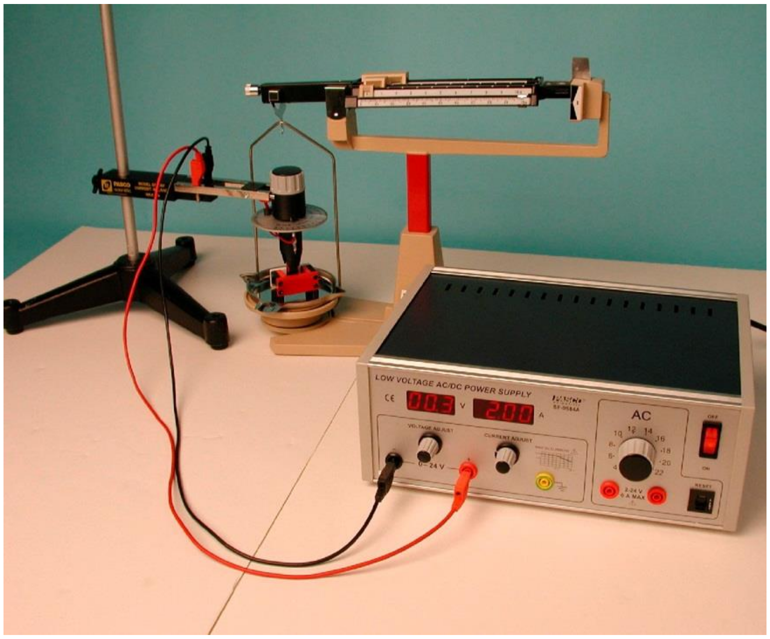


Figure 4: Experimental Setup

1. Place the smaller magnet holder from the Current Balance Accessory on the mass tray of the balance. (See Figure 4)
2. Attach the Current Balance Accessory to the arm of the current balance and lower the coil into the magnetic field of the magnet holder. The coil should not be touching the magnet holder.
3. Setup the current balance as shown above.
4. Set the angle to 0º such that the coils are facing the shorter dimension of the magnet holder (see photo below Figures 5).

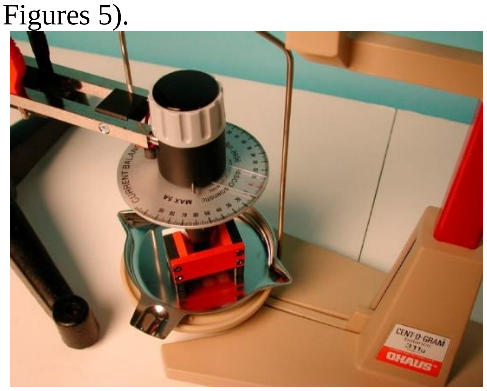


Figure 5: Set up for angle

5. Determine the mass of the magnet holder and magnets with no current flowing. Record this value above Table 4.
6. Turn on the power supply and set the current between 2.0 and 3.0 Amps. Record this value above Table 4.
7. Determine the new "Mass" of the magnet assembly. Record this value under "Mass" I > 0 in Table 4 below.
8. Change the angle by 10º increments up to 90º, each time repeating steps 5 – 7. Record the measurements in Table 4.

9. Repeat steps 5 – 7 for angles between 0º and -90º and record the measurements in Table 4.

ANALYSIS

"Mass" with I = 0: ___________

Current Used: _______________

Current Loop Used: __________

TABLE 4 Calculation of Angle

Angle (degrees)	"Mass" I > 0 (grams)	Force (grams)
0		
10		
20		
30		
40		
50		
60		
70		
80		
90		
-10		
-20		
-30		
-40		
-50		
-60		
-70		
-80		
-90		

1. Subtract the “Mass” value for each Magnetic Field from the “Mass” value for zero current to get the “Force” for each angle.
2. Open the DataStudio file, Force_Angle.ds
3. Enter the Angles used into the Force vs. Angle table.
4. Enter the “Force” values into the Force vs. Angle table.
5. Observe the shape of the Force vs. Angle graph.
6. Print a copy of the Force vs. Angle graph.

POST LAB QUESTIONS

1. Describe the relationship between Magnetic Force and Angle.
2. Which trigonometric function best fits the data? Explain your choice.
3. Draw this fit on the printout of the graph and write the proportionality expression between Magnetic Force and Angle.

FINAL ANALYSIS

1. Combine the proportionality expressions for all four experiments into one expression. Force should be on the left side of the expression and the other variables on the right side of the expression.

2. Write a few sentences explaining the relationship between Magnetic Force, Length, Current, Magnetic Field and Angle.

3. How would you convert this expression into an equation?

4. What is the constant of proportionality for this equation? Explain.

5. How could such an equation be used?

EXPERIMENT # 13

To calculate induced e.m.f in a circuit by Faraday's law of induction.

EQUIPMENT

INCLUDED:

1	Induction Wand	EM-8099
1	Variable Gap Lab Magnet	EM-8641
1	Large Rod Stand	ME-8735
2	45 cm Long Steel Rod	ME-8736
1	Multi Clamp	SE-9442
1	Voltage Sensor	CI-6503
1	Magnetic Field Sensor	CI-6520A
1	Rotary Motion Sensor	CI-6538
1	Mass Balance	SE-8723
1	Meter Stick	SE-7333
1	ScienceWorkshop 500 Interface	CI-6400
1	DataStudio Software	CI-6870

INTRODUCTION

A voltage is induced in a coil swinging through a magnetic field. Faraday's Law and Lenz' Law are examined and the energy dissipated in a load resistor is compared to the loss of amplitude of the coil pendulum.

A rigid pendulum with coil at its end swings through a horseshoe magnet. A resistive load is connected across the coil and the induced voltage is recorded using a Voltage Sensor and the angle is measured with a Rotary Motion Sensor that also acts as a pivot for the pendulum. The induced voltage is plotted versus time and angle. The power dissipated in the resistor is calculated from the voltage and the energy converted to thermal energy is determined by finding the area under the power versus time curve. This energy is compared to the loss of potential energy determined from the amplitude of the pendulum. Faraday's Law is used to estimate the magnetic field of the magnet from the maximum induced voltage. Also, the direction of the induced voltage as the coil enters and leaves the magnetic field is examined and analyzed using Lenz' Law.

Part I: Induced emf

THEORY

According to Faraday's Law of Induction, a changing magnetic flux through a coil induces an emf given by

$$E = -N\frac{d\Phi}{dt} \qquad (1)$$

where $\Phi = \int \vec{B} \cdot d\vec{A} = BA$ for a magnetic field (B) which is constant over the area (A) and perpendicular to the area. N is the number of turns of wire in the coil. For this experiment, the area of the coil is constant and as the coil passes into or out of the magnetic field, there is an average emf given by

$$E = -NA\frac{\Delta B}{\Delta t} \ . \qquad (2)$$

SET UP

1. Put a rod in the stand and clamp the cross-rod to it as shown in Figure 1. Put the Rotary Motion Sensor at the end of the cross-rod.

2. Attach the coil wand to the Rotary Motion Sensor with the tabs on the 3-step pulley just to the sides of the wand as shown in Figure 2.

3. Put the pole plates on the magnet as shown in Figure 3. Adjust the gap between the magnet poles so the coil wand will be able to pass through but put the magnet poles as close together as possible.

Figure 1: Rod Stand

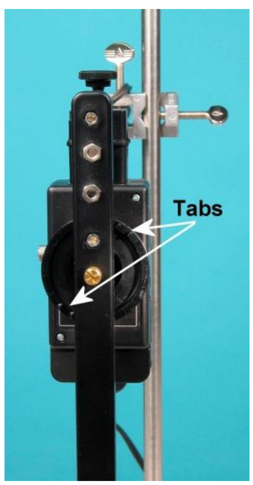


Figure 2: Tabs

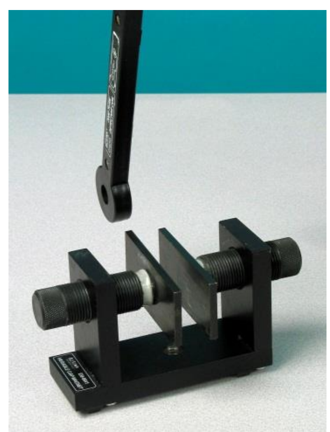


Figure 3: Magnet Pole Plates

4. Adjust the height of the coil so it is in the middle of the magnet. Align the wand from side-to-side so it will swing through the magnet without hitting it.

5. Plug the Voltage Sensor into Channel A of the ScienceWorkshop 500 interface. Plug the Rotary Motion Sensor into Channels 1 and 2. Plug the Magnetic Field Sensor into Channel B.

6. Plug the Voltage Sensor banana plugs into the banana jacks on the end of the coil wand. Drape the Voltage Sensor wires over the rods as shown in Figure 1 so the wires will not exert a torque on the coil as it swings. It helps to hold the wires up while recording data.

7. Open the DataStudio file called "Induced emf".

PROCEDURE

1. Click START. With the pole plates on the magnet, use the Magnetic Field Sensor to measure the magnetic field strength between the magnet poles. Click STOP. Note which pole of the magnet is the north pole.

2. Click START and pull the coil wand back and let it swing through the magnet. Then click STOP.

3. Use the Magnifier Tool to enlarge the portion of the voltage vs. time graph where the coil passed through the magnet.

4. Use the mouse to highlight the first peak and find the average voltage.

5. Use the Smart Cursor to determine the difference in time from the beginning to the end of the first peak.

Figure 4: Coil Passes through Magnet

ANALYSIS

1. Calculate the value of the average emf using Equation (2). Compare this value to the value measured from the graph.

2. Identify on the graph where the coil is entering the magnet and where the coil is leaving the magnet.

3. Is the emf of the first peak positive or negative? Taking into account the direction the wire is wrapped around the coil, does the sign of the emf correspond to the direction expected using Lenz's Law?

4. Why is the sign of the emf of the second peak opposite to the sign of the first peak?

5. Why is the emf zero when the coil is passing through the exact center of the magnet?

EXPERIMENT # 14

Magnetic Fields of Coils

EQUIPMENT

INCLUDED:

1	Helmholtz Coil Base	EM-6715
2	Field Coil (2)	EM-6711
1	Primary and Secondary Coils	SE-8653
1	Patch Cords (set of 5)	SE-9750
1	Patch Cords (set of 5)	SE-9751
1	60 cm Optics Bench	OS-8541
1	Dynamics Track Mount	CI-6692
1	20 g hooked mass (Hooked Mass Set)	SE-8759
2	Small Base and Support Rod (2)	SE-9451
2	Optics Bench Rod Clamps (2)	648-06569
1	DC Power Supply	SE-9720
1	Digital Multimeter	SE-9786
1	Magnetic Field Sensor	CI-6520A
1	Rotary Motion Sensor	CI-6538
1	ScienceWorkshop 500 or 750 Interface	CI-6400
1	DataStudio Software	CI-6870

INTRODUCTION

The magnetic fields of various coils are plotted versus position as the Magnetic Field Sensor is passed through the coils, guided by a track. The position is recorded by a string attached to the Magnetic Field Sensor that passes over the Rotary Motion Sensor pulley to a hanging mass.

It is particularly interesting to compare the field from Helmholtz coils at the proper separation of the coil radius to the field from coils separated at less than or more than the coil radius. The magnetic field inside a solenoid can be examined in both the radial and axial directions.

THEORY

Single Coil

For a coil of wire having radius R and N turns of wire (Figure 1), the magnetic field along the perpendicular axis through the center of the coil is given by:

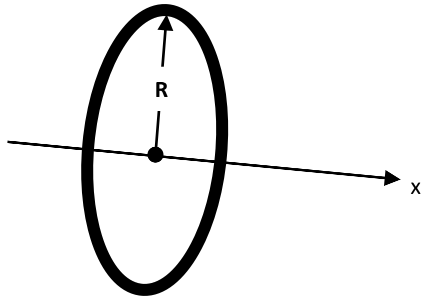


Figure 1: Single Coil

$$B = \frac{\mu_o N I R^2}{2\left(x^2 + R^2\right)^{\frac{3}{2}}} \qquad (1)$$

Two Coils

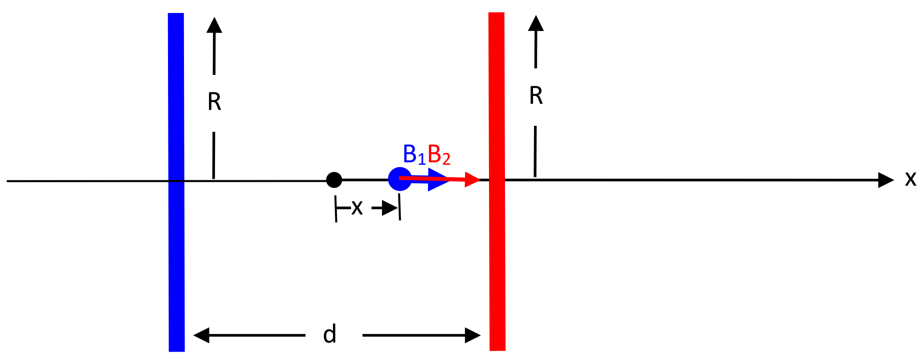
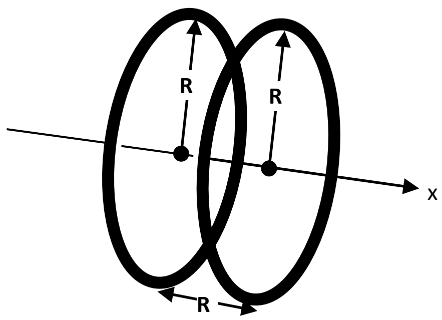


Figure 2: Two Coils with Arbitrary Separation

For two coils (Figure 2), the total magnetic field is the sum of the magnetic fields from each of the coils.

$$\vec{B} = \vec{B}_1 + \vec{B}_2 = \frac{\mu_o N I R^2}{\left(\left[\frac{d}{2} - x\right]^2 + R^2\right)^{\frac{3}{2}}}\hat{x} + \frac{\mu_o N I R^2}{\left(\left[\frac{d}{2} + x\right]^2 + R^2\right)^{\frac{3}{2}}}\hat{x} \qquad (2)$$



For Helmholtz coils, the coil separation (d) equals the radius (R) of the coils. This coil separation gives a uniform magnetic field between the coils. Plugging in

x = 0 gives the magnetic field at a point on the x-axis centered between the two coils:

$$\vec{B} = \frac{8\mu_o NI}{\sqrt{125}R}\hat{x} \qquad (3)$$

Figure 3: Helmholtz Coils

Solenoid

For a solenoid (Figure 4) with n turns per unit length, the magnetic field is $B = \mu_o nI$. (4)

The direction of the field is straight down the axis of the solenoid.

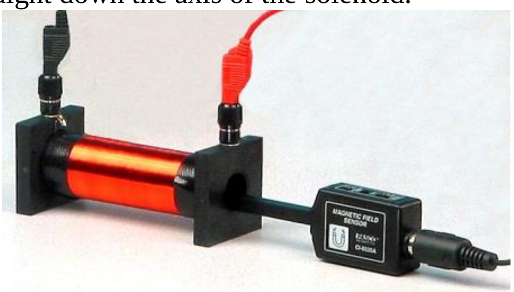


Figure 4: A solenoid with the sensor

SET UP

1. Attach a single coil to the Helmholtz Base. Connect the DC power supply directly across the coil (not across the coil's internal resistor). To measure the current through the coil, connect the digital ammeter in series with the power supply and the coil. See Figure 5.

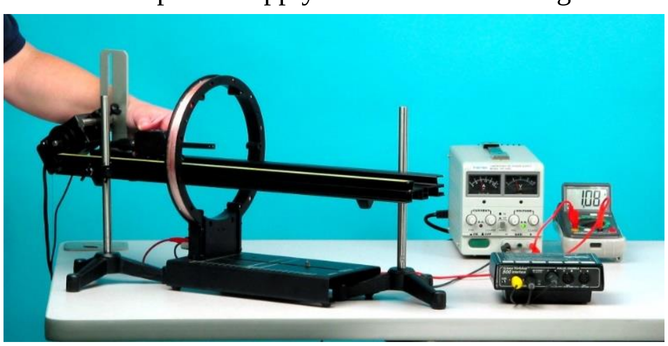


Figure 5: Single Coil Setup

2. Pass the optics track through the coil and support the two ends of the track with the support rods. Level the track and adjust the height so the Magnetic Field Sensor probe will pass through the center of the coil when it is pushed along the surface of the track.

3. Attach the Rotary Motion Sensor to the track using the bracket. Cut a piece of thread long enough to reach from the floor to the track. Tape one end of the thread to the side of the Magnetic Field Sensor and pass the other end of the thread over the middle step of the Rotary Motion Sensor pulley and attach the 20-g mass. Place the Magnetic Field Sensor in the center of the track and adjust the position of the Rotary Motion Sensor so the thread is aligned with the middle step pulley.

4. Plug the Magnetic Field Sensor into Channel A of the ScienceWorkshop 500 interface. Plug the Rotary Motion Sensor into Channels 1 and 2. Note that the Rotary Motion Sensor plugs can be reversed in Channels 1 and 2 to change which direction of rotation is positive.

5. Turn on the DC power supply and adjust the voltage so about 1 Amp flows through the coil. Turn the DC power supply off at the switch.

6. Open the DataStudio program called "Mag Field Coils".

SINGLE COIL PROCEDURE

1. Find the radius of the coil by measuring the diameter from the center of the windings on one side across to the center of the windings on the other side.

2. Set the Magnetic Field Sensor switch on Axial and x10 gain. With the DC power supply off, set the Magnetic Field Sensor in the middle of the track about 15 cm from the coil. Press the tare button.

3. Turn on the DC power supply. Click on START in DataStudio and slowly move the Magnetic Field Sensor along the center of the track, keeping the probe parallel to the track, until the end of the sensor is about 15 cm past the coil. Then click on STOP.

4. Use the Smart Cursor on the graph to measure the position of the peak. Click on the DataStudio calculator and enter the peak position in for the constant (c) in the equation for the distance. This will center the peak on zero on the graph.

5. Click on FIT at the top of the graph and choose User Fit. Type in the theoretical equation for the magnetic field and enter in the current, the coil radius, and number of turns in the coil.

6. Does the theoretical equation fit everywhere? If not, why not?

HELMHOLTZ COILS PROCEDURE

1. Attach a second coil to the Helmholtz Base at a distance from the other coil equal to the radius of the coil. Make sure the coils are parallel to each other. See Figure 6.

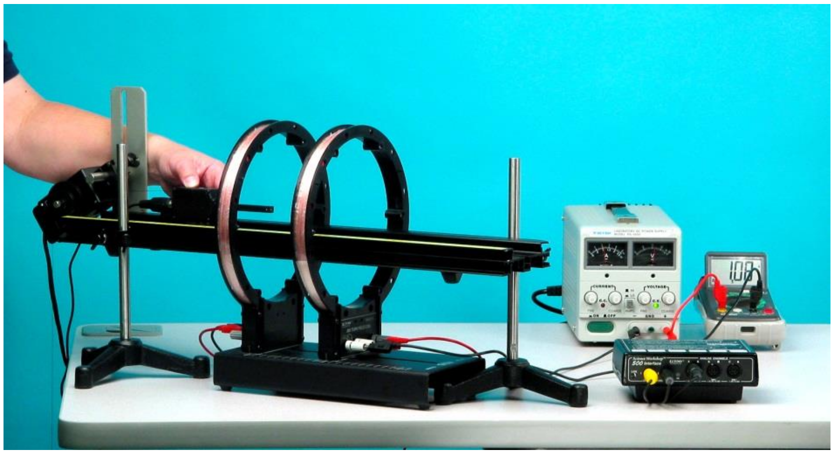


Figure 6: Helmholtz Coils

2. Connect the second coil in series with the first coil.

   See Figure 7.

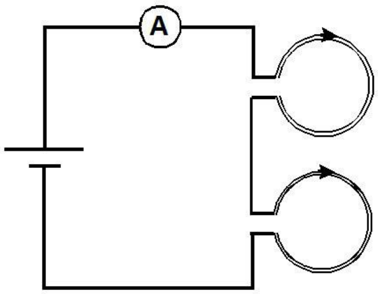


Figure 7: Helmholtz Wiring

3. Set the Magnetic Field Sensor switch on Axial and x10 gain. With the DC power supply off, set the Magnetic Field Sensor in the middle of the track about 5 cm from the first coil. Press the tare button.

4. Turn on the DC power supply. Click on START in DataStudio and slowly move the Magnetic Field Sensor along the center of the track, keeping the probe parallel to the track, until the end of the sensor is about 5 cm past the second coil. Then click on STOP.

5. Use the Smart Cursor on the graph to measure the position of the center of the peak. Click on the DataStudio calculator and enter the peak position in for the constant (c) in the equation for the distance. This will center the peak on zero on the graph.

6. Click on the annotation button at the top of the graph and put a note showing the position of each coil on the graph. Is the magnetic field strength constant between the coils?

7. Calculate the theoretical value for the magnetic field between the coils and compare it to the measured value on the graph.

8. Now change the separation between the coils to 1.5 times the radius of the coils. Repeat steps 3 through 6.

9. Now change the separation between the coils to half the radius of the coils. Repeat steps 3 through 6.

SOLENOID PROCEDURE

1. Connect the DC power supply in series with the digital ammeter and the solenoid.

2. Set the Magnetic Field Sensor switch on Axial and x10 gain. With the DC power supply off, put the Magnetic Field Sensor inside the solenoid (see Figure 4). Press the tare button.

3. Turn on the DC power supply and adjust it until the ammeter reads about 100 mA.

4. Click on START and measure the magnetic field at various points all over the inside of the solenoid, keeping the sensor probe parallel to the long axis of the solenoid.

5. Is the field inside the solenoid constant? What happens near the end of the solenoid?

6. Measure the length of the coil and using the given number of winds in the coil, calculate the theoretical value of the magnetic field. Compare this value to the value at the center at the coil.

7. Set the Magnetic Field Sensor switch on Radial and x10 gain. With the DC power switched off, put the Magnetic Field Sensor inside the solenoid. Press the tare button.

8. Turn on the DC power supply with the same current as before.

9. Click on START and measure the magnetic field at various points all over the inside of the solenoid, keeping the sensor probe parallel to the long axis of the solenoid.

10. Is the field inside the solenoid constant? What happens near the end of the solenoid?

Appendix A: Lab Evaluation Criteria

Evaluation	**Weightage (%)**
Quizzes	**15**
Laboratory Work	**30**
Laboratory Reports/ Assignment	**20**
Final Examination	**35**

Notice:

Copying and plagiarism of lab reports is a serious academic misconduct. First instance of copying may entail ZERO in that experiment. Second instance of copying may be reported to DC. This may result in awarding FAIL in the lab course.

Appendix B: Safety around Electricity

In all the Electrical Engineering (EE) labs, with an aim to prevent any unforeseen accidents during conduct of lab experiments, following preventive measures and safe practices shall be adopted:

- Remember that the voltage of the electricity and the available electrical current in EE labs has enough power to cause death/injury by electrocution. It is around 50V/10 mA that the "cannot let go" level is reached. "The key to survival is to decrease our exposure to energized circuits."
- If a person touches an energized bare wire or faulty equipment while grounded, electricity will instantly pass through the body to the ground, causing a harmful, potentially fatal, shock.
- Each circuit must be protected by a fuse or circuit breaker that will blow or "trip" when its safe carrying capacity is surpassed. If a fuse blows or circuit breaker trips repeatedly while in normal use (not overloaded), check for shorts and other faults in the line or devices. Do not resume use until the trouble is fixed.
- It is hazardous to overload electrical circuits by using extension cords and multi-plug outlets. Use extension cords only when necessary and make sure they are heavy enough for the job. Avoid creating an "octopus" by inserting several plugs into a multi-plug outlet connected to a single wall outlet. Extension cords should ONLY be used on a temporary basis in situations where fixed wiring is not feasible.
- Dimmed lights, reduced output from heaters and poor monitor pictures are all symptoms of an overloaded circuit. Keep the total load at any one time safely below maximum capacity.
- If wires are exposed, they may cause a shock to a person who comes into contact with them. Cords should not be hung on nails, run over or wrapped around objects, knotted or twisted. This may break the wire or insulation. Short circuits are usually caused by bare wires touching due to breakdown of insulation. Electrical tape or any other kind of tape is not adequate for insulation!
- Electrical cords should be examined visually before use for external defects such as: Fraying (worn out) and exposed wiring, loose parts, deformed or missing parts, damage to outer jacket or insulation, evidence of internal damage such as pinched or crushed outer jacket. If any defects are found the electric cords should be removed from service immediately.
- Pull the plug not the cord. Pulling the cord could break a wire, causing a short circuit.
- Plug your heavy current consuming or any other large appliances into an outlet that is not shared with other appliances. Do not tamper with fuses as this is a potential fire hazard. Do not overload circuits as this may cause the wires to heat and ignite insulation or other combustibles.
- Keep lab equipment properly cleaned and maintained.
- Ensure lamps are free from contact with flammable material. Always use lights bulbs with the recommended wattage for your lamp and equipment.
- Be aware of the odor of burning plastic or wire.

- ALWAYS follow the manufacturer recommendations when using or installing new lab equipment. Wiring installations should always be made by a licensed electrician or other qualified person. All electrical lab equipment should have the label of a testing laboratory.
- Be aware of missing ground prong and outlet cover, pinched wires, damaged casings on electrical outlets.
- Inform Lab engineer / Lab assistant of any failure of safety preventive measures and safe practices as soon you notice it. Be alert and proceed with caution at all times in the laboratory.
- Conduct yourself in a responsible manner at all times in the EE Labs.
- Follow all written and verbal instructions carefully. If you do not understand a direction or part of a procedure, ASK YOUR LAB ENGINEER / LAB ASSISTANT BEFORE PROCEEDING WITH THE ACTIVITY.
- Never work alone in the laboratory. No student may work in EE Labs without the presence of the Lab engineer / Lab assistant.
- Perform only those experiments authorized by your teacher. Carefully follow all instructions, both written and oral. Unauthorized experiments are not allowed.
- Be prepared for your work in the EE Labs. Read all procedures thoroughly before entering the laboratory. Never fool around in the laboratory. Horseplay, practical jokes, and pranks are dangerous and prohibited.
- Always work in a well-ventilated area.
- Observe good housekeeping practices. Work areas should be kept clean and tidy at all times.
- Experiments must be personally monitored at all times. Do not wander around the room, distract other students, startle other students or interfere with the laboratory experiments of others.
- Dress properly during a laboratory activity. Long hair, dangling jewelry, and loose or baggy clothing are a hazard in the laboratory. Long hair must be tied back, and dangling jewelry and baggy clothing must be secured. Shoes must completely cover the foot.
- Know the locations and operating procedures of all safety equipment including fire extinguisher. Know what to do if there is a fire during a lab period; “Turn off equipment, if possible and exit EE lab immediately.”

Appendix C: Guidelines on Preparing Lab Reports

Each student will maintain a lab notebook for each lab course. He will write a report for each experiment he performs in his notebook. A format has been developed for writing these lab reports.

Lab Report Format:
For hardware based labs, the format of the report will include:

1. **Introduction**: Introduce area explored in the experiment.
2. **Objective**: What are the learning goals of the experiment?
3. **Measurements**: In your own words write how the experiment is performed (Do not copy/paste the procedure).
    a. **Issues**: Which technical issues were faced during the performance of the experiment and how they were resolved?
    b. **Graphs**, if any
4. **Conclusions**: What conclusions can be drawn from the measurements?
5. **Applications**: Suggest a real world application where this experiment may apply.
6. Answers to post lab questions (if any).

Sample Lab Report:

Introduction

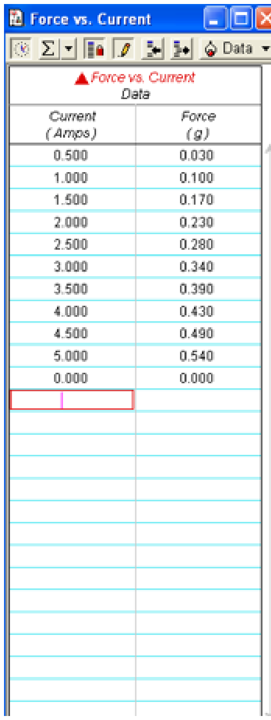
Since an electric current is just a bunch of moving charges, wires carrying current will be subject to a force when in a magnetic field. When dealing with a current in a wire, we obviously can't use units of q and v. However, qv can equally be expressed in terms of Il, where I is the current in a wire, and l is the length, in meters, of the wire—both qv and Il are expressed in units of C · m/s. So we can reformulate the equation for the magnitude of a magnetic force in order to apply it to a current-carrying wire:

$$F = I\ell B \sin\theta$$

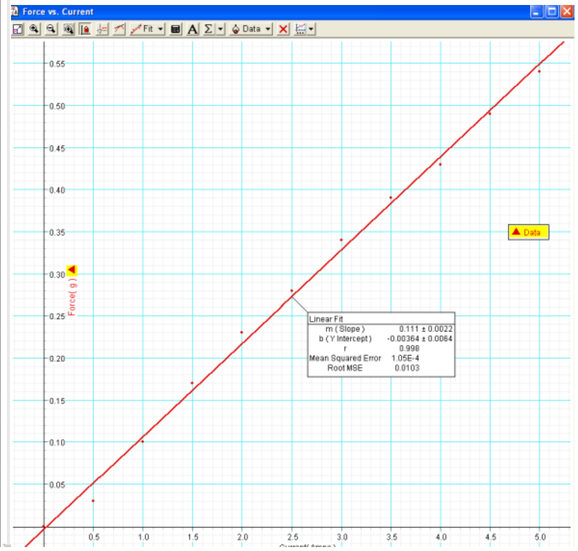
Objective:

The purpose of this lab experiment is to investigate the magnetic force of a current-carrying wire. In this experiment we will investigate the effect of length of wire on the magnetic force.

Measurements/Calculations/Graphs:



Current (Amps)	Force (g)
0.500	0.030
1.000	0.100
1.500	0.170
2.000	0.230
2.500	0.280
3.000	0.340
3.500	0.390
4.000	0.430
4.500	0.490
5.000	0.540
0.000	0.000



Issues:

Mention any issue(s) you encountered during the experiment and how they were resolved

Conclusions:

A linear relationship exists between magnetic force with conductor's length, current and strength of the magnetic field.

Applications:

Magneto hydrodynamics, Electromagnetism etc.