MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

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Experiment 2: Faraday Ice Pail

OBJECTIVES

1. To explore the charging of objects by friction and by contact.
2. To explore the charging of objects by electrostatic induction.
3. To explore the concept of electrostatic shielding.

PRE-LAB READING

INTRODUCTION

When a charged object is placed near a conductor, electric fields exert forces on the free charge carriers in the conductor which cause them to move. This process occurs rapidly, and ends when there is no longer an electric field inside the conductor ($\mathbf{E}_{\text{inside conductor}}=0$). The surface of the conductor ends up with regions where there is an excess of one type of charge over the other. For example, if a positive charge is placed near a metal, electrons will move to the surface nearest the charge, leaving a net positive charge on the opposite surface[1]. This charge distribution is called an *induced charge distribution*. The process of separating positive from negative charges on a conductor by the presence of a charged object is called *electrostatic induction*.

Michael Faraday used a metal ice pail as a conducting object to study how charges distributed themselves when a charged object was brought inside the pail. Suppose we lower a positively charged metal ball into the pail ***without touching it to the pail***. When we do this, positive charges move as far away from the ball as possible – to the outer surface of the pail, leaving a net negative charge on the inner surface. If at this point we provide some way for the positive charges to flow away from the pail, for example by touching our hand to it, they will run off through our hand. If we then remove our hand from the pail and then remove the positively charged metal ball from inside the pail, the pail will be left with a net negative charge. This is called *charging by induction*.

In contrast, if we touch the positively charged ball to the uncharged pail, electrons flow from the pail into the ball, trying to neutralize the positive charge on it. This leaves the pail with a net positive charge. This is called *charging by contact*.

Finally, when a positively charged ball approaches the ice pail from outside of the pail, charges will redistribute themselves on the outside surface of the pail and will exactly cancel the electric field inside the pail. This is called *electrostatic shielding*.

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[1] We will typically say that "positive charge flows outward" even though in metals it's really electrons moving inward. This is a completely equivalent way of thinking about it for our purposes.

You will investigate all three of these phenomena—charging by induction, charging by contact, and electrostatic shielding—in this experiment.

The Details: Gauss's Law

In the above situations, the excess charge on the conductor resides entirely on the surface, a fact that may be explained by Gauss's Law. Gauss's Law[2] states that the electric flux through any closed surface is proportional to the charge enclosed inside that surface,

$$\oiint_{\substack{\text{closed}\\\text{surface}}} \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q_{\text{enc}}}{\varepsilon_0} . \tag{2.1}$$

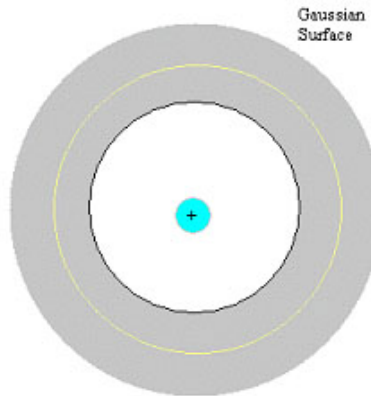Consider a mathematical, closed Gaussian surface that is *inside* the ice pail:

Figure 1 Top View of Gaussian surface for the Faraday Ice Pail (a thick walled cylinder)

Once static equilibrium has been reached, the electric field inside the conducting metal walls of the ice pail is zero. Since the Gaussian surface is in a conducting region where there is zero electric field, the electric flux through the Gaussian surface is zero. Therefore, by Gauss's Law, the net charge inside the Gaussian surface must be zero. For the Faraday ice pail, the positively charged ball is inside the Gaussian surface. Therefore, there must be an additional induced negative charge on the inner surface of the ice pail that exactly cancels the positive charge on the ball. It must reside on the surface because we could make the same argument with any Gaussian surface, including one which is just barely outside the inner surface. Since the pail is uncharged, by charge conservation there must be a positive induced charge on the pail which has the same magnitude as the negative induced charge. This positive charge must reside outside the Gaussian surface, hence on the outer surface of the ice pail.

Note that the electric field in the hollow region inside the ice pail is not zero due to the presence of the charged ball, and that the electric field outside the pail is also not zero, due to the positive charge on its outer surface.

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[2] For more details on Gauss's Law, see Chapter 4 of the *Course Note*, Section 4.3 for info on conductors.

Now suppose the ice pail is connected to a large conducting object ("ground"):
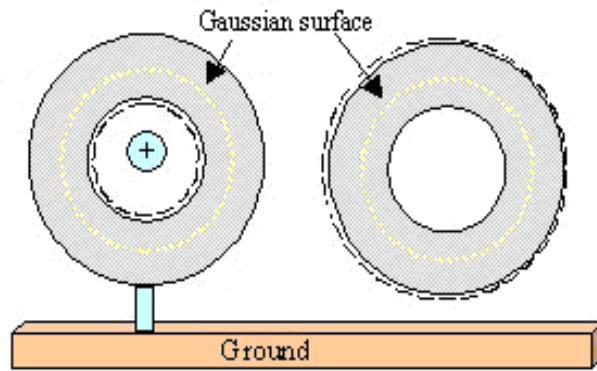

Figure 2 Grounding the ice pail (left) and after removing the ground & ball (right)

Now the positive charges that had moved to the surface of the ice pail can get even further away from the positively charged metal ball by flowing into the ground. Now that there are no charges on the outer surface of the pail, the electric field outside the pail is zero and the pail is at the same "zero" potential as the ground (and infinity). If the wire to ground is then disconnected, the pail will be left with an overall negative charge. Once the positively charged ball is removed, this negative charge will redistribute itself over the outer surface of the pail.

Finally, when a charged ball approaches the ice pail from outside of the pail, charges will redistribute themselves *on the outside surface* of the pail while the electric field inside the pail will remain zero, cut-off from any knowledge of what is going on outside by the enforced zero electric field inside the conductor. This effect is called shielding or "screening" and explains popular science demonstrations in which a person sits safely inside a cage while an enormous voltage is applied to the cage. This same effect explains why metal boxes are used to screen out undesirable electric fields from sensitive equipment.

APPARATUS

1. Ice Pail

Our primary apparatus consists of two concentric wire-mesh cylinders. The inner cylinder (the "pail") is electrically isolated by three insulating rods. The outer cylinder (the "shield") will be attached to ground – charge can flow to or from it as necessary. This cylinder will act both as a screen to eliminate the effect of any external charges and other external fields and as a "zero potential" point, relative to which you will measure the potential of the pail.

Figure 3 The Ice Pail

2. Charge Producers

To replace the positively charged metal ball of Faraday's experiment, you will use charge producers (Figure 4). When rubbed together a net positive charge will move to one of them and a net negative charge to the other.

Figure 4 One of two charge producers (the other has a blue charged pad)

3. Charge Sensor

The Charge Sensor does not directly measure charge, but instead measures the voltage difference between its positive (red) and negative (black) leads. Furthermore, it connects the black lead to ground, meaning that as much charge can flow into or out of that lead as is necessary to keep it at "zero potential" (ideally the same voltage as at infinity).
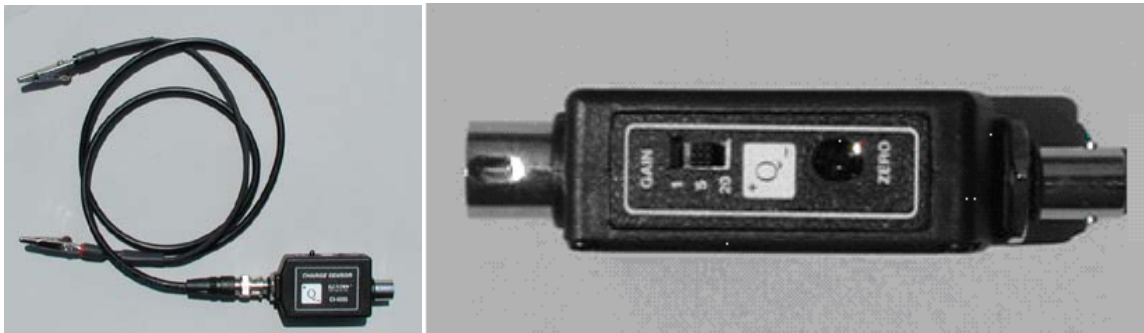

Figure 5 Charge Sensor – measures voltage difference between its red and black leads. Left: Shown attached to the lead assembly. Right: The gain switch (used to amplify small signals) should be set at 1. The zero button sets the output signal to zero.

The red lead is free to be at any potential, although by pushing the "zero" button on the sensor (Fig. 5, right), it too can be attached to ground (the potential difference between the red and black leads is set to zero).

Even though this is really a potential difference sensor, we none-the-less call it a "Charge Sensor" because the voltages measured arise from the presence of charges on the ice pail, as you will calculate in Pre-Lab problem 1.

4. Science Workshop 750 Interface

In this lab we will for the first time use the Science Workshop 750 interface (Fig. 6). This allows signal measurements (in this lab, from the charge sensor) to be sent to the computer where they can be recorded and plotted.

Figure 6 The *Science Workshop* 750 Interface.

GENERALIZED PROCEDURE

This lab consists of four main parts. In each you will measure the voltage between the inner and outer cylinder to determine what is happening on the inner cylinder.

Part 1: Determine Polarity of (Sign of Charge on) Charge Producers
Here you will lower the charge producers into the center of the pail (the inner cylinder) and determine which producer is positively charged and which is negatively charged

Part 2: Charging by Contact
You will now rub the charge producer against the inner surface of the pail and see if the charge is transferred to it.

Part 3: Charging by Induction
In this part you will not let the charge producer touch the pail, but will instead briefly ground the pail by connecting it to the shield (the outer cylinder) while the charge producer is inside. Then you will remove the charge producer and observe the induced charge on the pail.

Part 4: Electrostatic Shielding
In this part you will measure the effects of placing a charge producer outside of the grounded shield.

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END OF PRE-LAB READING

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Experiment 2: Faraday Ice Pail Pre-Lab Questions

Answer these questions on a separate sheet of paper and turn them in before the lab

1. Capacitance of our Experimental Set-Up

In this experiment we will measure the potential difference between the pail and the shield, and make statements about the charge on the pail based on this. Here you will calculate the relationship between charge and potential.

Consider two nested cylindrical conductors of height h and radii a & b respectively. A charge $+Q$ is evenly distributed on the outer surface of the pail (the inner cylinder), $-Q$ on the inner surface of the shield (the outer cylinder).
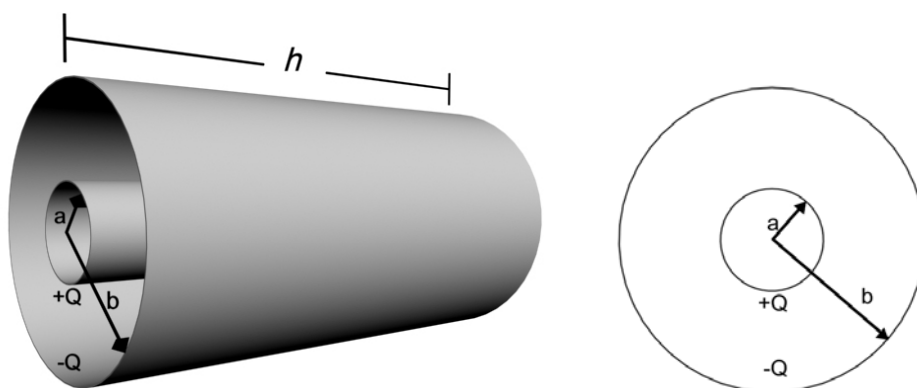
(a) Calculate the electric field between the two cylinders ($a < r < b$).

(b) Calculate the potential difference between the two cylinders:
$$\Delta V = V(a) - V(b)$$

(c) Calculate the capacitance of this system, $C = Q/\Delta V$

(d) Numerically evaluate the capacitance for your experimental setup, given:
$h \cong 15$ cm, $a \cong 4.75$ cm and $b \cong 7.25$ cm

The capacitance should be given in Farads (1 F = 1 Coulomb/Volt) or some fraction thereof (mF, μF, …) ***Write this number in your notes***, as you will use it to convert from the measured voltage difference ΔV to a charge on the outer surface of the pail (inner cylinder) Q, using $Q = C \Delta V$

2. What about charge on other surface?

In the previous problem we assumed that charge was located on the outer surface of the inner cylinder and the inner surface of the outer one, in other words, if both cylinders were charged. What if instead the cylinders were both neutral but exhibited charge separation due to the presence of a positive charge Q sitting in the interior of the inner cylinder? What now is the potential difference between the two cylinders?

For the next three questions you are asked to sketch potential difference versus time as you move charges into or around the system. You should mark the given actions on the time axis (assume they are each done very quickly but with some time in between) and indicate what happens to the potential difference when each action is made. In each case the potential difference should start at zero volts. NOTE: Of course you can't give any numbers, we just want you to indicate if the potential increases or decreases or goes to zero or back to some previous value.

3. Prediction: Charging by Contact

Sketch your prediction for the graph of potential difference vs. time for part 2 of this experiment. Indicate the following events on the time axis:
   (a)   Insert positive charge producer into pail
   (b)   Rub charge producer against inner surface of pail
   (c)   Remove charge producer

4. Prediction: Charging by Induction

Sketch your prediction for the graph of potential difference vs. time for part 3 of this experiment. Indicate the following events on the time axis:
   (a)   Insert positive charge producer into pail
   (b)   Ground pail to shield
   (c)   Remove ground contact between pail and shield
   (d)   Remove charge producer

5. Prediction: Electrostatic Shielding

Sketch your prediction for the graph of potential difference vs. time for part 4 of this experiment. Indicate the following events on the time axis:
   (a)   Bring positive charge producer near (but outside of) shield
   (b)   Move charge producer away

IN-LAB ACTIVITIES

EXPERIMENTAL SETUP
1. Download the LabView file from the web and save the file to your desktop (right click on the link and choose "Save Target As" to the desktop. Overwrite any file by this name that is already there). Start LabView by double clicking on this file.

2. Using the multi-pin cable, connect the Charge Sensor to Analog Channel A on the 750 Interface. The cable runs from the left end of the sensor (in Fig. 5) to Channel A.

3. Connect the lead assembly to the BNC port on the Charge Sensor (right end of the sensor in Fig. 5). Line up the connector on the end of the cable with the pin on the BNC port. Push the connector onto the port and twist it clockwise about one-quarter turn until it clicks into place. Set the Charge Sensor gain to 1x.

4. Connect the charge sensor input lead (red alligator clip) to the pail (the inner wire mesh cylinder), and the ground lead (black alligator clip) to the shield (the outer wire mesh cylinder).

MEASUREMENTS

Important Notes:

The charge producers are delicate. When rubbing them together do so briskly but gently.

Each experiment should begin with completely discharged cylinders. **To discharge them, ground the pail by touching both it and the shield at the same time with a conductor (e.g. the finger of one hand). You also will always want to zero the charge sensor before starting by pressing the "Zero" button.**

Part 1: Polarity of the Charge Producers

1. Ground the pail and zero the charge sensor
2. Start recording data. (Press the green "Go" button above the graph).
3. Rub the blue and white surfaces of the charge producers together several times.
4. Without touching the pail, lower the white charge producer into the pail.
5. Remove the white charge producer and then lower in the blue charge producer

Question 1 (Don't forget to submit answers in the software!):

What are the polarities of the white and the blue charge producers?

Note: There may be some variations in this from group to group.

Part 2: Charging By Contact

Part 2A: Using the White Charge Producer

1. Ground & zero; Start recording; Rub the producers
2. Lower the *white* charge producer into the pail
3. Rub the charge producer against the inner surface of the pail
4. Remove the charge producer

Question 2: Sketch the plot of voltage vs. time and indicate the charge on the inner and outer surfaces of the pail after each of the above steps

Answer:

ΔV

time

Charge on inner & outer surfaces of the inner cylinder (indicate sign, and use a variable like q for non-zero magnitudes – do NOT simply record numerical values)

After Step 1: $Q_{inner} =$ $Q_{outer} =$

After Step 2: $Q_{inner} =$ $Q_{outer} =$

After Step 3: $Q_{inner} =$ $Q_{outer} =$

After Step 4: $Q_{inner} =$ $Q_{outer} =$

Part 2B: Using the Blue Charge Producer

1. Ground & zero; Start recording; Rub the producers
2. Lower the *blue* charge producer into the inner cylinder
3. Rub the charge producer against the inner surface of the inner cylinder
4. Remove the charge producer

Question 3:

What happens to the charge on the pail when you rub it with the blue charge producer?

## Part 3: Charging By Induction

Part 3A: Using the White Charge Producer

1. Ground & zero; Start recording; Rub the producers
2. Lower the *white* charge producer into the pail, without touching it
3. Ground the pail by connecting it to the shield with your finger
4. Remove the ground connection (your finger)
5. Remove the charge producer

Question 4:

Sketch the plot of voltage vs. time and indicate the charge on the inner and outer surfaces of the pail after each of the above steps

Answer:
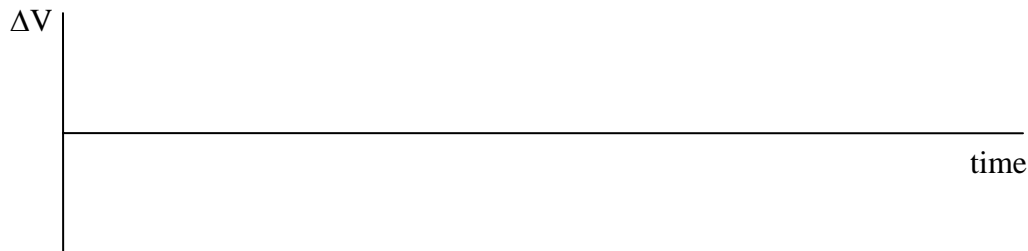
Charge on inner & outer surfaces of the inner cylinder (indicate sign, and use a variable like q for non-zero magnitudes – do NOT simply record numerical values)

After Step 1: $Q_{inner} =$ $Q_{outer} =$

After Step 2: $Q_{inner} =$ $Q_{outer} =$

After Step 3: $Q_{inner} =$ $Q_{outer} =$

After Step 4: $Q_{inner} =$ $Q_{outer} =$

After Step 5: $Q_{inner} =$ $Q_{outer} =$

3B: Using the Blue Charge Producer

1. Ground & zero; Start recording; Rub the producers
2. Lower the *white* charge producer into the pail, without touching it
3. Ground the pail by connecting it to the shield with your finger
4. Remove the ground connection (your finger)
5. Remove the charge producer

Question 5:

What happens to the charge on the pail when you do the above steps?

Part 4: Testing the shield

1. Ground & zero; Start recording; Rub the producers
2. Bring the *white* charge producer to just outside the shield (the outer cylinder)
      Do Not Touch it!
3. Repeat, bringing the *blue* charge producer just outside the shield.

Question 6:

What happens to the charge on the pail when the white charge producer is placed just outside the shield? Will an induced charge distribution appear on the pail? Explain your reasoning. Will an induced charge distribution appear on the shield? Are we sensitive to this? What about the blue charge producer?

Further Questions (for experiment, thought, future exam questions…)

- What happens if we repeat the above measurements with the ground (black clip) attached to the pail and the red clip attached to the shield? Does anything change aside from the sign of the voltage difference?
- What happens if in part 2 we touch the charge producer to the outside of the pail rather than the inside?
- What happens if we place the charge producer between the pail & shield rather than inside the pail?
- What happens if we put both the white & blue charge producers inside the pail together (not touching, just both inside). Is the cancellation exact? Should it be?
- What if in part 2 we touch the white producer and then the blue producer to the pail? What if we touch the white producer, then recharge it and touch again? Doing this repeatedly, is there a difference between touching the inside of the pail and the outside of the pail?