Introduction: In 1686 Newton presented his work, *Mathematical Principles of Natural Philosophy*. He revealed two objects with masses $m_1$ and $m_2$ exert an attractive force on each other given by $F = G \frac{m_1 m_2}{r^2}$. It would take another hundred years until Charles-Augustin de Coulomb formulated that the force law for charges $F = \frac{q_1 q_2}{r^2}$. These two force laws are among the most important discoveries ever made. With respect to their relative importance, one may note that an astronaut can exist in space in the absence of appreciable gravitation, but if the electrostatic force were to suddenly cease, he or she would disintegrate in a matter of $10^{-12}$ seconds as the atoms that compose cells, tissues, bones, and DNA disassociate. The electrostatic force is responsible for everything from chemical bonds to the annoying shock you get from grabbing a doorknob after walking on carpet. Just as Newton’s Law describes the gravitational force, Coulomb’s Law can be used to quantify the electrostatic force. After these experiments, you should have a deeper understanding of the manner in which charge is transferred from one material to another. You will understand the relative strengths of gravitational and electrical forces, and you will see the relationship between charge and force. By the end of this lab, you should:

- Understand when the electrostatic force occurs
- Know how to quantify this force through Coulomb’s Law
- Understand how Coulomb’s Law is applied in practical devices

Materials:

- hair/fur
- Balloon
- acrylic (clear) friction rod
- teflon (white) friction rod
- plastic bag
- tissue paper
- hairdryer
- CCD camera
- frame grabber
- graph paper
- pith electroscope
- laser printer
- ruler
- 0.001 g scale
Experiment 1: Shocking Balloons

Some materials “like” electrons while others do not. This “electron affinity” of compounds has been characterized with an electronegativity scale. Chlorine, for example, has a high electronegativity since it wants one more electron to have a complete valence shell, while sodium has a low electronegativity since it is one electron in excess of a complete valence shell. Electronegativity is critical to understand how atoms share electrons and form chemical bonds. Since there is a large difference in electronegativity between Na and Cl, the Cl atom effectively takes one electron from Na atom and a NaCl molecule is formed. The electrostatic force between Cl- and Na+ ionically binds the atoms together. In a molecule such as CO, the relative difference in electronegativity is much less. The result is that the oxygen is not able to completely pull the electrons away, and the two atoms share the electrons in what is known as a covalent bond. More complicated materials exhibit the similar properties, as they too are composed of atoms.

The table at right shows the relative electron affinities of popular materials and an absolute scale for several atoms. The items towards the positive end donate electrons just as the sodium did above. Similarly the materials towards the negative end accept electrons, just like chlorine. The farther apart materials are the greater their relative differences in electron affinity, and thus more likely that charge will be transferred when the two come into contact. By rubbing two materials of differing electron affinity together, friction can provide the energy needed to transfer the electrons from a electron donor to acceptor. This is called triboelectric charging, or charging by friction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electronegativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>0.93</td>
</tr>
<tr>
<td>Cl</td>
<td>3.16</td>
</tr>
<tr>
<td>C</td>
<td>2.55</td>
</tr>
<tr>
<td>O</td>
<td>3.44</td>
</tr>
</tbody>
</table>

Table: Electronegativity scaling for various elements

![Figure: The transfer of the electron from the Na donor to the Cl acceptor is shown. The ionic bond formed results from the attraction between Na+ and Cl-.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electronegativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Human Hair</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Nylon</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Silk</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Fur</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Aluminum</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Paper</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Cotton</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Copper</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Rubber</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>PVC</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Teflon</td>
<td>+ + + + +</td>
</tr>
</tbody>
</table>
You can see the electrostatic force in action using nothing more than a balloon and your head. Try rubbing the balloon back and forth on your head five or six times to triboelectrically transfer negative charge from your hair to the latex rubber balloon. Can you feel the force between the charges on head and the balloon? (Since water from humidity conducts electricity, you may need to use a hair-dryer to dry the balloon and your hair to get effective charging.)

Then:

- Charge the balloon by rubbing until it is able to attract a piece of paper or any other material you can think of.
- Could the gravity due to the mass of the balloon be responsible for lifting these objects?
- Can the Coulomb force on the balloon be greater than the gravitational attraction of the earth?

![Diagram of charged balloon and fur](image)

_Figure: Triboelectric charging of a latex rubber balloon and fur (a),(b) results in a transfer of negative charge to the balloon from the fur. This accumulated charge is shown in (c) exerting a force on thin copper wire._
**Experiment 2: Pith Ball Electroscope**

In this experiment you will quantify the Coulomb force you qualitatively observed earlier. Coulomb’s law predicts that two objects with the same charge will have a repulsive force between them. In an electroscope (see figure) two small conductors (pith balls) are suspended by insulating threads. Triboelectrically charge the Teflon friction rod using your hair and transfer the charge from the Teflon to the pith balls by touching to rod to the pith ball. You may also want to explore charging the device with the balloon. Charge the pith balls one at a time. Once charged, they can touch each other, but they must not touch your hand or the stand as the charge will be transferred away. Also avoid getting the threads tangled. Both objects should now have a mass and a charge. Normally, the apparatus will discharge in a few minutes. You may need to use the hair dryer to get effective charging (do not overheat objects or they may melt you only need to dry them lightly).

Draw a detailed free-body diagram for the pith balls. Label all the pertinent forces from the mass and charge on the two pith balls. For a quantitative analysis, you will need to measure the mass of the objects with a balance. Explain, in detail, the physics behind this experiment. What are the competing forces? Using the camera and the frame-grabbing software, **determine the separation distance d between the pith balls.** In order to obtain an accurate distance, include a piece of graph paper at the same distance from the camera for a reference point (see figure). Weigh the pith balls with the very sensitive scale. The pith balls detach from the electroscope with the finger tight top screw. With this information:

- Determine the Coulomb force between the pith balls assuming the charge is equally shared.
- How many electrons reside on each pith ball?
- What is the gravitational attraction between the two pith balls and how does this compare to the electrostatic force?
Experiment 3: Physics of a Laser Printer

Copiers and laser printers rely on the Coulomb force between charged toner particles and a charged printing drum. Triboelectric charge transfer is not used to create the charge on the printing drum. Rather, the drum is made of a photoconductive element like selenium. In a laser printer, the negative charges accumulate on the drum anywhere light hits it. So when a laser “writes” the image to be printed, that area becomes negatively charged, and attracts positively charged toner particles that are nearby.

In order to transfer the toner particles from the drum to the paper, a corona wire is placed below the paper. The corona wire has a higher charge on it than the drum so it attracts the toner from the drum. With a piece of paper inserted between the wire and drum (see diagram) the toner is transferred to the paper. The plastic/carbon toner particles are fused to the paper by heating to a high temperature – which is why new copies are always warm.

The electrostatic image written on the drum by the laser normally reaches a charge of $-1 \times 10^{-7} \text{C/cm}^2$. An average toner particle has a charge of about $4.5 \times 10^{-10} \text{C}$. The corona wire is normally given a line charge density of $-3 \times 10^{-6} \text{C/m}$.

Related Internet Resources and Information:

You may explore the workings of the printer in this lab by taking a piece of paper, and allowing it to feed into the printer (do a test print for example), but stopping the printing process midway by opening the top of the printer to the position shown in the figure. You should locate the printing drum, corona wire, toner cartridge, paper, etc. Examine the toner particles on the paper and the drum. With this information, the help of your text and the internet resources at the end of the lab answer the following questions:

- Using internet resources and looking at the printer in your group, explain quantitatively how the laser printer works. Give a detailed description of the printer and include important dimensions that are relevant to the physics concepts (i.e. what is the distance between charged objects).

- Try to locate the corona wire in the printer, capture the image using your CCD camera and frame grabber. Include the picture in your lab with the corona wire indicated.

- Design a laser printer with the same printing drum and yet requires 30% less charge on the corona wire to exert the same force on the toner particle and pull it from the drum to the paper.

Figure: Laser printer with the top open. The paper is shown as well as the photoconductive drum (in green/yellow). Notice the carbon on the drum that has not been transferred to the paper.

Figure: Inside of a laser printer showing the paper in the process of having the toner transferred to it from the printer drum.