Electrostatics (Chapter 22)

Electrostatics is the studying of electric charge that is not accelerating.

Comparing Gravitational and Electric Forces

To get a “feel” for what an electrical force is, I want to compare it to gravity, which is somewhat more familiar to us. The way I will do this is by answer the following four questions:

1. What is the cause of the force?
2. How many types of forces are there?
3. What is the law that describes the force?
4. What is the strength (proportionality constant) of this force

Gravitational Forces

Gravitation is the force that affects objects that have mass. So if an object has mass then it has a gravitational force.

1. The cause of the gravitational force is MASS
2. Because there is only one type of mass (matter and antimatter have the same mass characteristic), there is only one gravitational force, and this force is ATTRACTIVE. (Have you felt an extra pull when you were next someone – you’re right in thinking so because gravitation is at work!)
3. Newton’s Universal Law of Gravitation (inverse square law): The farther two objects get from each other, the weaker the force of attraction between the two masses.

\[ F_g = \frac{G(mass-1)(mass-2)}{(distance)^2} \]

4. The gravitational strength constant \( G \) tells us about the strength of the gravitational force. That is, it tells us how strong gravity is. This number is \( G \approx 10^{-11} \) (units are ignored)

Because this number is very small, it means that gravity is a very weak force.

Aside:
- This law is what is used to land space probes on the moon and mars – it is that accurate. However, it has been found that this law has been replaced by a more accurate one – Einstein’s General Theory of Relativity.
- Newtonian vs. Einsteinium view of gravity

Electrical Forces

The electrical force affects objects that have electric charge.

1. The cause of the electric force is electric charge.
   There are two kinds:
   - Positive (proton)
   - Negative (electron)

2. Since there are two types of charges, there are two types of electric forces: attractive or repulsive.
3. Coulomb’s law (inverse square law): The farther two objects get from each other, the weaker the force of attraction between two electric charges.

\[ F_{\text{Coulomb}} = F_e = k \frac{(\text{charge-1})(\text{charge-2})}{(\text{distance})^2} \]

4. The electrical strength constant \( k \) tells us about the strength of the electric force. This number is \( k \approx 10^{-9} \) (units are ignored).

To compare this number with the gravitational strength constant, one immediately see that electrical forces are much, much stronger than gravitational forces. That is, electrical forces are \( 10^{20} \) times stronger than gravity:

\[ \frac{k}{G} \approx 10^{20} \]

However, this is not a complete picture of the comparison between the two forces. The standard comparison between these two forces is to compare the gravitational and electrical attraction between a proton and electron.

Here is the difference in the two forces:

Gravitational force: 1 N
Electrical force: \( 1,000,000,000,000,000,000,000,000,000,000 \) N (This is equivalent to the weight of 23 battle ships)

Why is it that we are NOT dominated by electrical forces?
Microscopically, human senses are dominated by electric forces since touching, seeing, feeling, and thinking are due to electric impulses within the body. Macroscopically however, people and objects in general are neutral to a very high degree. If there is no excess of electric charge, then there is no electrical forces that are felt two neutral objects. Once again, we do not feel electrical forces because to a very high degree we are neutral.

**Electrons, Conductors and Insulators**

Because the nucleus is positive and the electrons are negative, there is an electrical attractive force between these two that binds them together. The binding energy (a form of PE) is the work required to bind (or hold) the electron to the nucleus. If we look at a Copper atom (\( ^{64}_{29} \text{Cu} \)), it has its 29th electron in the 4th shell all by itself. Coulomb’s law tells us that electrons closest to the nucleus will “feel” a stronger electrical attractive force compared to the 29th electron since it is the farthest – there is a distance effect. In other words, one has to work a lot harder to remove electrons from the inner shells than the outer shells. Furthermore, there is something called charge screening: outer electrons “see less” charge than inner electrons since the inner electrons screen the charge, reducing the charge the outer electrons see. In summary,

- The outer most electrons are WEAKLY BOUND
- Only a small amount of work (or binding energy) is required to remove this weakly bound electron from the atom
Once these weakly bound electrons are removed, they travel between overlapping atomic orbitals. This rapid exchange of electrons among the metal atoms holds the structure together in a process known as **metallic bonding**.

**Protons and the Strong (or Color) Force**

The nucleus is composed of protons and neutrons. Since protons have the same charge and are confined inside the nucleus, the nucleus is inherently unstable due to the repulsive nature of positive charges. Clearly, there must be some other kind of force that binds the nucleus together that is different from the electric force – this is called the **Strong Nuclear (or Color) Force**. The strong nuclear force binds the protons and neutrons inside the nucleus and is about 1000 times stronger than $F_E$ at the energy range of 1000 GeV. Since $F_{\text{strong}} > F_{\text{El}}$, protons are bound and unable to escape this binding energy unless lots of energy is used (need a thermonuclear reaction). Under normal conditions, the protons do not get outside the nucleus. **When electric charge is transferred, it is electrons that are transferred, NOT the protons.**

**Conductors and Insulators**

We all have a pretty good idea of what a conductor and insulator is. Analogy: **When a metal poker is used to move coals around in a fire**, as you know, the metal poker gets really hot – why? We say that metal is a good conductor of heat, but again, why? Heat energy is transferred from the fire and loosens weakly bound electrons. The weakly bound electrons now have KE that move up the poker to the other end (mass transfer of electrons). Since KE is a form of heat energy, these weakly bound electron heat up your hand and you say “aye chiwawa.” **Good conductors allow weakly bound electrons to move. If instead now one uses a wood poker to move the coals in the fire**, as you know it does not get hot for a long time – why? We say that wood is not a good conductor of heat. That means that there are relatively very few weakly bound electrons in the wood. Even though the weakly bound electron get the same KE, there are relatively very few of them, and therefore, do not feel the heat at the other end of the wood poker.

Here is an analogy (that is, it is an approximation but it captures the essence) to determine whether an object is a conductor or an insulator; there are 3 things to look at:

i. **A material's binding energies**

ii. **The number of weakly bound electrons of a material**

iii. **The material's band gap.**

![Diagram](image)

i. From the picture above, the binding energy is how far below the weakly bound electrons are from the gap opening in the box. Since the conductor's electrons are much closer to the gap opening, they only need a small amount of energy to escape from the box. On the other hand, the insulator's electrons are far below the gap opening and require a lot more energy to escape through the gap opening.

ii. Conductors have a lot more weakly bound electrons than insulators do. In fact, a perfect insulator would have no weakly bound electrons.

iii. The gap opening in the box is essentially the way weakly bound electrons are transferred from one atom to the next. A larger band gap implies that these atoms are better at moving electrons (like a multi-lane highway) whereas a smaller band gap is not very good at moving electrons (like a single-lane highway).

So to put these three together; as I start shaking these boxes the electrons clearly get energize (acquire energy). Conductors will be able to jump out easier because there are...
more of them, they have a smaller binding energy to overcome and the band gap is larger. Insulators are just the opposite, there are less of them, they have to overcome a larger binding energy and even if they do get out, the band gap is very small so that a really limits charge transfer from one atom to the next.

In summary, whenever there is electric charge around that electric charge must be weakly bound electrons. Furthermore, conductors allow charge to move from one location to another while insulators do not allow charge to move.

**Charging by Friction**
The next step now is to get those weakly bound electrons. The way that is done is a process known as charging by friction. As already stated, we need to overcome the binding energy of electrons to get them out of the box. The most common way to do this in everyday situation is through the work done by friction. When two insulating materials are rubbed together, frictional work gives enough energy to one of the insulators (which has more weakly bound electrons) so that the electrons are transferred to the other insulator (that has very tightly bound electrons). The tightly bound insulator than holds these electrons onto its surface and it becomes charged.

Example: hair on your head and balloon (or fur and a plastic rod). Both of these materials are insulators but your hair is not as good of an insulator as the rubber balloon. Therefore, your hair will give up some of its electrons when they are rubbed together.

**DEMO**: balloon on wall where charge does not move

**Charge Transfer Process: Induction and Polarization**
So through charging by friction, we can now obtain electrically charged insulating rods that are able to hold onto electric charge. The next question is what is the electrical behavior of conductors and insulators when charged rods are brought close to these materials? Because these are two different materials, so there are two different behaviors:

i. Conductors and the process of Induction (or induced charged)

ii. Insulators and the process of polarization

**i. Conductors and Induction**
The main characteristic of conductors is that they allow weakly bound electrons to move. In fact, electrons move by vast migrations from one location to the next. Why?

**DEMO** metal sphere

When the negatively charged rod is brought close to the conducting, metal sphere, the weakly bound electrons feel the repulsive force from the rod, and move as far away from the rod as possible (which is the opposite end of the sphere). We then say that the side that has an excess of electrons is negatively charged while the side closest to the rod is depleted of electrons is more positively charged. **This movement of charge is called**
induction and is the main characteristic of conductors. We say that the negatively charged rod induced a positive charge on the sphere.

**DEMO** pith balls and electric pom-poms

ii. Insulators and Polarization

The main characteristic of insulators is that they do not allow weakly bound electrons to move. Insulators are made up of electric dipoles, which are molecules that have a positive and negative end. To see how an electric dipole can be created, bring a charged rod close to a neutral molecule. The positive nucleus moves closer to the negatively charged rod whereas the negative charged electrons move as far away from the rod as possible. Because of this rearrangement of charge, we call this an electric dipole.

Insulators are made up of atoms that cannot move. So when an electrically charged rod is brought close to the insulator, the neutral atoms inside the insulator form zillion of dipoles. The process of atoms changing their charge orientation is called **Polarization**. We say that the negatively charged rod has polarized a positive charge closest to the rod.

**DEMO** hanging meter stick and balloon (talk about water stream, pieces of paper, clouds)

Examples: plastic wrap and glass vs. metal bowls

**Web Video** friction sliding across car seat at a gas station

http://youtube.com/watch?v=HnSWW7c24fA

Other examples of charging by friction: walking on carpet, changing my son’s diaper at 3:00 am early this morning (as I pulled the tape on the diaper, I saw sparks in the dark due to this charging by friction), getting into your car, etc.

**Interesting point**

1. Soft contact lenses are comfortable to wear because they attract the proteins in the wearer’s tears, incorporating the complex molecules right into the lenses. They become, in a sense, part of the wearer.

2. Some types of makeup exploit this same attractive force to adhere to the skin.

3. A new and extremely sensitive technique for revealing fingerprints has been developed at Los Alamos. It makes use of the fact that unlike charges attract. Negatively charged gold particles adhere to the positively charged proteins, which are always left behind when fingers touch a surface.

**ELECTRIC FORCE FIELD (E-field)**

**Analogy**

Have you ever been approached by someone who is really “coming on to you?” They totally “come into your space.” You feel something in the air even if there is no contact between the two of you. There is an exchange of some sort of information.
DEMO

- If you “like” this person, this exchange may be in the eyes or a smile – (the right “chemistry”). When this happens the interaction between these two people is said to be attractive.
- On the other hand, if this person “vibs you wrong” then the exchange of information leads to the classic giving of the hand, which states “don’t even bother.” The interaction is clearly repulsive. Again, there is some sort of information exchange without any contact.

Physical Interpretation
Gravitational and electric forces act between objects that are NOT in contact with each other. To physically visualize what is going on, physicists use a quantum description to explain the concept of force fields. There are three important points about force fields.
- There is an invasion of one’s space – objects have to be in the vicinity of each other’s force field in order to communicate.
- Exchange of information – “the chemistry” determines what you like or don’t like.
- “The Interaction” (or Force) is the result of interpreting this information and is acted upon – do I perform an attractive or repulsive force?

Summary: for two objects to interact with a force field we must have
- Invasion of space
- Exchange information (Particle physics uses the exchange of particles called bosons. In the case of the EM field, it exchanges photons.)
- Interaction (or force)

Physics wise we say a force field surrounds an object and permeates through all of space. The nature of the force field depends on the individual characteristics of that object (mass, charge …). Only when a second object enters the vicinity of the force field can an interaction take place.

Examples
DEMO: two neodymium magnets
Analogy: Force fields are like the “force” in the Stars War movies. If there is a disturbance in the “force,” Luke senses the presence of Darth Vader.

The E-fields for positive and negative charges are

where the lines are called the lines of force. The line density determines the strength of the E-field:

higher line density ➔ strong E-field ➔ strong E-force
lower line density ➔ weak E-field ➔ weak E-force

There are three important E-field configurations: the E-field between (i) positive & negative charges, (ii) two positive charges, and (iii) a parallel plate.
APPLICATIONS OF ELECTRIC FIELDS
There are four important applications of E-fields: (i) Cancer blood test, (ii) storing E-fields (capacitors), (iii) shielding E-fields (Faraday Cage) and (iv) dielectric breakdown of air.

   This diagnostic procedure relies on color distribution and pattern of liquid crystals in an electrical field. Colors and patterns produced are due to E-field strength values.

   Healthy Blood Plasma

   Healthy "whole blood" test

   Colon Cancer Blood Test

   Ovarian cancer blood test

   Leukemia blood test

   Chronic Leukemia blood test

Leukemia blood test
An electrical field image of a blood plasma sample from a patient with leukemia produces a circles that show a raised red ring narrower than normal; an outer blue area is discolored from its normal blue (high voltage) indicating leukemia.

Colon Cancer Blood Test
The red ring has a wide circumference with clear outline; the blue (high voltage) area is clear blue with no unhealthy discoloration. In cancer, these areas change shape and color. Note that the image on the right has colors and patterns that indicate abnormal plasma – it is in the early
stages of colon cancer. The red ring is a smaller than in normal plasma; the blue (high voltage) area shows some discoloration typical of early cancer.

**Ovarian cancer blood test**
An electrical field image of a blood plasma sample from a female patient with ovarian cancer produces a red ring is narrower than normal and the green area is discolored from normal blue indicating cancer of the ovary.

**Chronic Leukemia blood test**
An electrical field image of a blood plasma sample from a patient with leukemia produces circles of color that are unclear; the outer area (green) is discolored from its normal blue (high voltage) indicating chronic leukemia.

**Healthy "whole blood" test**
Whereas plasma in blood is normally used, a "whole blood" sample is shown here. An electrical current is applied through the wire at centre. Instead of a red ring (near centre) found using plasma it is blue and thin; the light clear blue (high voltage) area shows no unhealthy discoloration.

2. **Storing E-field Energies**
The E-fields between two charged plates can vary in strength depending on the type of material that is place in between the plates (usually call a dielectric).

\[ \begin{array}{c}
- & - \\
- & - \\
+ & + \\
+ & + \\
\end{array} \]

In practice, these are called capacitors.

**DEMO**
Capacitor, light bulb, and power supply

During ventricular fibrillation (a common type of heart attack), the chambers of the heart fail to pump blood because their muscles fibers randomly contract and relax as if the heart’s electrical system went crazy. To save a victim’s life, the heart muscle must be shocked to reestablish its normal rhythm. Capacitors are used to do this burst of stored electrical power.

3. **Electrical Shielding & Faraday Cages**
An important difference between gravitational and electrical fields is that gravitational field cannot be turned off where as the electrical field can. The reason is that gravitational fields are only attractive and there is no component that can oppose the G-field. On the other hand, since E-fields have both attractive and repulsive components, there is a way to literally cancel out electrical influences under special circumstances involving a **hollow conducting shell**.

The special circumstance is that the hollow conductor must be immersed in an external E-field. There are many ways to have an external E-field.
- Cellphone stations emit microwaves. Microwaves (as well as radio waves) are electromagnetic waves, which is composed of external electric and magnetic fields. However, you cellphone is setup to only detect the external E-field from the cellphone station.
- Radio stations emit radio waves, which your car’s antenna detects the external E-field of the radio wave.
- Lightning emits an external E-field

Suppose that a cellphone station is emitting an external E-field (microwaves) that is going to be pick-up by your cellphone.
If a hollow conductor is immersed in this external E-field, then there are two E-field that exists:

- External E-field from the microwaves
- Induced E-field from the hollow conductor

The induced E-field from the hollow conductor is produced when the external E-field (these are the red field lines that are pointing to the right) applies a force on the weakly bound electrons of the hollow conductor. As a result, electrons move towards the positive end of the E-field (to the left) such that the hollow conductor now has an induced positive and negative end of the hollow conductor. These charges produce their own induced E-field (these are the blue field lines that are pointing to the left).

So here is the key point: charges continue to move until these two fields (external and induced fields) cancel each other out. That is, the weakly bound electrons continue to move towards the left until they build up enough induced E-field that it cancels exactly the external E-field. So the net E-field inside the hollow conductor is zero. Since the E-field is zero, the net force anyone will experience inside a hollow conductor is zero! Any shape (square, triangular, ...) of a hollow conductor will act like this. These hollow conductors are known as Faraday Cages. Since the

**DEMO** Cellphone and aluminum foil

**Video** Faraday cage with Tesla coil: [http://www.youtube.com/watch?v=Zi4kXgDBFhw](http://www.youtube.com/watch?v=Zi4kXgDBFhw)

**Examples**

- Trains and cellphones
- MRI rooms
- Automobiles during lighting storms
  - A large spark jumps to the car’s body and then exits across the insulated left front tire (note the flash there), leaving the person inside unharmed.

4. Dielectric Break & Lightning

**Video** Dielectric breakdown of plastic: [http://www.youtube.com/watch?v=FWOst4VwwEU](http://www.youtube.com/watch?v=FWOst4VwwEU)
ELECTRICAL POTENTIAL

I want to first review the work-energy theorem and define what is electrical PE (EPE). I will first remind you how energy can be stored in a spring. When my hand does work on the block (Work = \( F_{\text{hand}} \cdot d \)) it compresses the spring, however, this work is against the spring and consequently, the spring stores this work as spring potential energy. That is, the spring potential energy is "stored work" according to the work-energy theorem: Work = \( \Delta \text{PE} \).

The exact situation occurs when work is done by my hand on a single positive charge (this is called a test charge) and pushes it towards a large positive charge. As I push against the E-field of the large positive charge, my work gets stored in the E-field as electrical potential energy (EPE).

Once again, the work done against the E-field gets stored as EPE.

\[
\begin{align*}
F_{\text{hand}} \quad F_{\text{spring}} \quad d & \quad F_{\text{spring}} \cdot d = \Delta \text{PE} \\
F_{\text{E}} & \quad F_{\text{E}} \cdot d = \Delta \text{EPE}
\end{align*}
\]

Two objects: work is done One object: person has the potential to do work

So let's now get into the details of potential energy. In order to store PE, one has to do work and any type of work requires at least two objects: the one that applies the force and the object that has work done on it. When the stick person pushes on the block, he does work. However, what do you call him before he starts pushing on the block? The person is the potential to do work.

DEMO Power supply and lightbulb

To think of this in terms of electrical work, consider a power supply and a lightbulb. When I turn on the power supply, which lights up the lightbulb, electrical work is done by the power supply. So this involves two objects: the power supply and the lightbulb.

Question: what do you call the power supply before I connect it to the lightbulb? Answer: it is the electrical potential (NOT the electrical PE) because it is only one object.

My goal now is to introduce this new concept of electric potential. This topic is abstract but I will stick to familiar ideas to try and get this concept across to you as clearly as I can. Here is the key point:

the potential to do work describe the landscape that an objects see

So what do I mean by such a statement? The analogy to think about is riding your bike up a hill. Suppose when you are riding your bike you see a small hill up ahead. As you
know it requires work to move up the small hill. So the work you do going up the hill gets stored as gravitational potential energy. However, if there is a larger hill you know that it takes a lot more work to go up that hill.

Question: what do you call the hill before you start going up it?
The Gravitational Potential!
The hill (a single object) represents the gravitational landscape that you see. It is the landscape that tells you how much potential work there is ahead of you. You see the larger hill and it has a larger gravitational potential, whereas seeing the small hill tells you it has a smaller gravitational potential.

Moving onto the electric potential, the most important electrical potential landscape is that of a charged parallel plate. We know that the charged parallel plates have an E-field that goes from the positive to the negative plate. If a test charge is placed in-between the parallel plates, the positive charge moves from the positive plate towards the negative plate because the E-field does work on the test charge. The electric potential describes the electrical landscape that the test charges before it starts to move and it is an electrical incline (or ramp).

Definitions:
• The electrical potential difference is called the Voltage
  \[ \text{Electric Potential} \equiv \text{voltage} = \Delta V \]
• The electric potential of charged parallel plates is an electrical incline
• The height of the electrical incline is the values of the voltage
• The units of measure of voltage is Volts = V

What is the difference between a 1.5-volt and a 9-volt battery? Since the 9-volt battery is 6 times larger, the height of the electrical incline is 6 higher and it can do 6 times as much work as a 2.5-volt battery.

That is,
smaller voltage \(\rightarrow\) lower height \(\rightarrow\) less potential to do work
larger voltage \(\rightarrow\) higher height \(\rightarrow\) more potential to do work
For a battery (that is, the potential to do work), the value of the voltage indicates what is the possible work that it can do if it is connected to a second object. The table below shows this potential to do work.

<table>
<thead>
<tr>
<th>Voltage Source</th>
<th>Voltage</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Body</td>
<td>0.1 V</td>
<td>nerves</td>
</tr>
<tr>
<td>AA</td>
<td>1.5 V</td>
<td>mp3 players, flashlight</td>
</tr>
<tr>
<td>Car Battery</td>
<td>12 V</td>
<td>radio, headlights, defroster</td>
</tr>
<tr>
<td>Household Outlets</td>
<td>120 V, 240 V</td>
<td>refrigerators, dryers</td>
</tr>
<tr>
<td>Moss Landing</td>
<td>25,000 V</td>
<td>small cities</td>
</tr>
<tr>
<td>GRID</td>
<td>500,000 to 1,000,000 V</td>
<td>larger cities and states</td>
</tr>
</tbody>
</table>

Electric Current and Voltage
Just as with water current there is a flow of water molecules; electric current is the flow of electric charge.

**Key conceptual point:** Electric current always flows from a high potential to a low potential.

![Diagram showing electric current from high to low potential]

**DEMO** Van de Graff with a fluorescent light tube.

1. Note that as I hold the tube perpendicular to the Van de Graff, the tube flicker with light. This means that one end of the tube is at a higher electric potential compared to the other end. That is, the Van de Graff does more work on charges closer than ones that are farther.

![Diagram showing voltage to current and no voltage to no current]

2. When I hold the tube such that both ends are equally distanced from the Van de Graff, either end will have a higher potential than the other. In other words, there is no potential difference, and as a result, no current will flow.

Example
Suppose you fell from a bridge and managed to grab onto a high-voltage power line, halting your fall.

- What would happen to you if grab the same high-voltage power line with the both hands?
- What would happen to you if grab a second high-voltage power line of the same voltage?
- What would happen to you if grab a second high-voltage power line with a different voltage?

**Video** Power line workers: [http://www.youtube.com/watch?v=LjiC7DjoVe8](http://www.youtube.com/watch?v=LjiC7DjoVe8)
Example of a semiconductor
There are a wide range of materials that fit in-between a perfect conductor and a perfect insulator – these are called *semiconductors*. As the name suggests, they are both conducting and insulating properties. There are semiconductors that conducts with light is shined on it. This is the premise on how a photocopy machine works: pure selenium is normally a good insulator (charge does not move) and any electric charge build up on its surface will remain there for extended periods in the dark. If the plate is exposed to light, however, selenium becomes a conductor (charge is allowed to move) and the charge leaks away almost immediately. If a charged selenium plate is exposed to a pattern of light, such as the pattern of light and dark that makes up a page, the charge will leak away only from the areas exposed to light.