Force Fields Visualized

(An Electricity and Magnetism (E&M) primer for electronics students)

Force Fields Visualized

First Edition

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Introduction

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Chapter 1
Gravitational Fields

When you let go of a ball, it falls to the ground. We do not see anything pushing it. The force accelerating it is invisible. The force is gravity, and it accelerates the ball to the ground or actually towards center of the earth. We represent this force field with lines radiating out from the center of earth. The force of gravity is a vector that points inward toward the earth's center or more correctly toward the center of gravity of the earth. Actually all matter or mass exhibits a gravitational attraction. Two stationary baseballs in deep space will begin to move towards each other due to a mutual gravitational attraction. **Click Number 35** to learn more about gravity.

In the late 16^{th} century Tycho Brahe documented the elliptical paths of planets. Johannes Kepler developed a geometrical description for all planetary motion, but it was Newton who first discovered the force of gravity that made the planets and projectiles move the way they do. Newton theorized that all objects with mass exert a force of attraction on each other.

$$\underline{\mathbf{F}}_{gravity} = \mathbf{G}\, m_1 m_2 / r^2$$

G is very small: 6.67×10^{-11} newtons [Using SI Units]
Where: **G = gravitational constant, m = mass in kilograms,**
r = distance between center of each mass in meters.

This means two one hundred-kilogram balls of lead a meter apart would only exert a gravitation force 6.67×10^{-7} **N** (Newton) on each other.

Click Number 51 and look over entire page. Then learn what it is like to fly a spaceship in a weak gravitational field. By clicking the " ***Test Drive a Spaceship in a Gravitational Field***" button. Then Click 52, and dock a spaceship in the variable gravitational field of a six trillion-kilogram space station (actually a simulation of a heavy sphere.)

Chapter 2

Electrostatic Field around Sphere with a Uniform Distribution of Positive Charge

Click number 1 and select " ***Electric Field Lines of a Point Charge."***

We can also represent the electrostatic force field around a sphere with an electric charge on it using lines of force. The total number of lines emanating from the sphere will be proportional to the charge on the sphere. Like charges and spheres with like charges will repulse each other. Observing the animation on screen, we see an electrostatic force field (or flux) emanating from the center of a positively charged small sphere. The field is represented with outward pointing lines.

Magnitude of Electrostatic Force

Coulomb's Law

$$\underline{\mathbf{F}}_{\mathbf{electostatic}} = \boldsymbol{k} q_1 q_2 / r^2$$

k is very large: 9.0 X 10^9 newtons [Using SI Units]

Where: ***k* = constant, m = mass in kilograms,**

r = distance between center of masses in meters.

Let us assume an ion propulsion produces a .1 ampere positive ion beam (not neutralized) for a period of ten seconds. One-tenth ampere means one tenth of coulomb per second by definition. Thus, after ten seconds an ion cloud with a positive charge of one coulomb would be behind the space ship. Assume that both the center of gravity and charge of the positive ion cloud was 1000 meters behind the spaceship. The spaceship now also as a charge of negative one coulomb due to an excess of electrons. Calculate the force of attraction between the ion cloud and the space ship force.

$$\underline{\mathbf{F}}_{\mathbf{electostatic}} = \boldsymbol{k} q_1 q_2 / r^2 = k\,(1/1000^2) = k/10^6 = 9.0 \text{ X } 10^9 / 10^6 = 9000$$

Answer 9000 newtons of force of attraction

Ion propulsion engines neutralize positive ion beams with electrons as they leave the engine. Today's ion propulsion engines have high specific impulse but have a thrust less than one Newton. If the charge were not neutralized, then the strong force of attraction would pull the positive charge and the negatively charged spaceship back together, and the ship will not go anywhere.

Click number 59 and the hyperlinks on that page to learn more about Ion propulsion engines.

Chapter 3

Matter and Electricity

Click number 2!

If we place a small positive test charge near the surface of the positively charged sphere, it will be pushed away from the sphere. Thus, the electrostatic force field emanating from the center of the sphere is outward. We can visualize this force as an outward pointing vector (**E**). The test charge moves in the direction of the E field.

We can also charge a sphere to a negative potential. When we place the positive test charge a distance from the surface of the negatively charged sphere, it will be pulled towards the surface of the sphere. We represent the electrostatic field around negatively charged sphere with lines of force that point inward or toward the center of the sphere. Note that positive test charge is being accelerated in the direction the **E** field. Note that we have selected a small positive charge to map or define the force field. [Go to the bottom of the web page you are viewing and select "***electric field mapping***".] This follows the mathematical convention established when we selected positive mass to map the direction of gravitational fields, or the common convention of assuming a quantity is positive unless negative is specified (x = +x by virtue of identity). If we placed a small negative charge or an electron in this E field it would be propelled away from the negatively charged sphere. Note the electron is accelerated in the opposite direction of the E field. Note that positive ion would be propelled in the direction of the E field and that a negative ion would move against the **E** field. A positive ion is an atom with one or more electrons missing. A negative ion is an atom with one or more extra electrons. Note the first scientists to investigate electricity knew nothing of electrons and ions. However, they knew how to charge objects making them either negative or positive by rubbing them with a cloth. **Click number 3,** and watch movie**!**

An electron placed near the surface of the positive charged sphere will be accelerated towards the center of the sphere in the opposite direction of the field line pointer. Electrons always flow in the opposite direction of the E field.

Chapter 4

Atoms and Ions

Click number 7 and select "*All About Atoms*"

Let us briefly consider ions. Ions are atoms with missing or extra electrons. If positive ions (ions with missing electrons) were suspended in space they would still experience a gravitational attraction for each other; however, positive ions would experience a far greater repulsive electrostatic force between them. The electrostatic force is far greater than the gravitational force. Even large molecules with just one electron missing would repel each other, because the electrostatic force vector (**E**) is far greater than the gravitational force.

We represent the electrostatic **E** field with invisible lines of force in the same manner as the gravitational field is represented, except that the force vectors point outward not inward. The electrostatic lines radiate outward from the center of the positive ion. (Atoms that are missing electrons are called positive ions.)

Atoms that are missing electrons are called positive ions. Atoms that have extra electrons are called negative ions. Ions with like charges repel each other. Ions with opposite charges are attracted to each other. Ions with like charges still experience gravitational attraction, but the electrostatic force is much stronger than the gravitational attraction. The gravitational force is so weak that when we hold two steel balls close to each other we cannot even feel the gravitational attraction. If we hung a steel ball on a string and placed another steel ball next to it, we could not see or induce any visible motion in the hanging ball even though a very weak gravitational attractive force exists between the balls. Static clean on clothes removed from a dryer is very visible and can be felt. Yet gravity in the down (towards earth's center) direction feels very strong. That is due to the extremely large mass of the earth. We feel the pull of the earth's gravity, but no one feels the sideways pull of a large mountain or a huge ship. **Click number 26** to learn the strength of gravitational field on other planets.

Chapter 5

The Electroscope

Click number 5 and select " ***An Electroscope*** "

Electrostatic force is measurable using an electroscope. The electroscope takes advantage of the repulsive nature of charge. That is it takes advantage of the fact that like charges repel each other. They force the pointers of the electroscope apart when the electroscope is charged either positive or negative. Next select " C*harging an Electroscope*". Here, you can see how an electroscope is charged with a positively charged rod. Use the animation to charge the electroscope by first touching and then rubbing the rod on the electroscope terminal. First charge the electroscope by touching. Note the motion of electrons as the rod approaches the electroscope. The positive nuclei in the metal of the electroscope cannot move (or flow). Atom position is fixed in a solid. Atoms are free to move about in gases and liquids. Many chemicals ionize in water. For example salt in water. The ions in water make it conductive. When a gas is fully ionized, we refer to it as plasma. In the electroscope, the electrons are free to move and start moving when the rod approaches the electroscope. The rod induces an electron flow in the metal of the electroscope causing the charge to become unevenly distributed. This leaves both the metal arms of the electroscope with like charge. The repulsive force of like the charges causes separation of electroscope pointers.

Note that when the rod touches the electroscope a single unit of negative charge (an electron) travels to the electroscope, and neutralizes a single unit of positively charged atoms at the point of contact. We can imagine a single electron neutralizes a single atom. However, in the real world even point contact would involve many atoms. The reason that more electrons do not flow onto the glass rod is that glass rod is an insulator. Rubbing the rod on the electroscope transfers more charge to electroscope.

Chapter 6

Inverse Square Laws

Click number 6 and select " *Field Lines* " and view animation that shows two views of flux density.

The ***Inverse Square Law*** states that a physical quantity such as an electrostatic field, gravitational field, light or electromagnetic radiation decreases with the square of the distance from the point of origin. Imagine a candle at the center of a sphere with an area of 10 square meters. Each square meter of the sphere would be illuminated to an intensity of **.1** candlepower. Now double the radius of the sphere. The area of the sphere is now 40 square meters and the surface illumination is reduced to **.025** candlepower. Likewise the electrostatic field around a point charge or the gravitational field around the center of gravity of a spherical mass also follow the inverse square law. If you visualize the rays of light, electrostatic field, or the gravitational field as lines radiating out from a central point you can see that they spread in three dimensional space, and the inverse square law simply reflects the geometry of three dimensional space.

$\underline{\mathbf{F}}(\text{gravity}) = GM_1M_2/ r^2$ where G is a gravitational constant.

$\underline{\mathbf{F}}(\text{electrostatic}) = k(q_1q_2)/ r^2$ where k is a function of the permittivity of free space.

The above equations are for point like masses and charges respectively. However, the center of gravity of a spherical mass and the geometric center of a sphere with an even distribution of charge can also be used in the equations.

Chapter 7
Voltage and Current

This Chapter will show the relationship between the vectors **E** and **H** and the scalars V (Voltage) and I (Current) respectively**.**

Click number 36! Read the paragraphs that deal with wax and wool diagrams. Next, I want you to imagine that the wool and the wax were in a vacuum, and some negative ions were placed near the arrow adjacent to the wax. Also imagine some positive ions were placed in the vicinity of the arrow adjacent to the wool. Note that an electrostatic field **E** exists between the wool and the wax. The **E** Vector points from the wool cloth toward the wax. The negative ions introduced in the vicinity of the wax will be accelerated from left to right in the **opposite** direction of the **E** vector. The positive ions introduced in the vicinity of the wool will be accelerated from right to left in the **same** direction of the **E** vector. Next, I would like you make a fist with left hand and point your thump in the direction as the negative ion flow. Now make a fist with your right hand and point your thump in the same direction as the positive ion flow. Note that your thumps now point towards each other. Touch the tips of your thumps together and note that your fingers curl in the same direction. The curl of your fingers point in the direction of the magnetic field **H** (vector) that is generated when electrons or ions are set into motion by an **E** field. Note that even though the positive and negative ions move in the opposite direction, their respective magnetic field curl in the same direction. Therefore, the current generating the field can be represented only using the right hand rule. Note that it is the right hand thumb that points in the same direction as the **E** field. Thus, the current vector **I** points in the direction of the **E** field.

Summary

Gravity Field (g) points from up to down.(Center of Earth)
Water flow (current) goes from up to down.
Electrostatic **E** field points from + charge to - charge.
Current flows in the direction of the **E** field.
Right Hand Rule gives direction of Curl.
Electrons move in opposite direction of current.

Voltage and Current continued**.**

This relationship between current and magnetic fields was actually first observed by placing a compass next to a wire carrying a current. **Click number 4** and select "***Magnetic Field of a Straight Current-Carrying Wire*** in the ***Electrodynamics***" simulation listings**.** Note the direction of the current "**I"** and use your right hand rule to determine direction of the magnetic curl around the wire. Note that the red North Pole of the compass points in the direction of the magnetic field lines.

Click number 36!

View the lower diagram showing the wax and cloth connected by the wire. The wire allows electrons to flow from the wax to wool. Thus, we have a current **I** flow from wool to wax in the direction of **E** field. Remember the vector (**I)** is a measure of magnetic field strength and is independent of polarity of the charge carrier and proportional to and in the same direction as vector (**E**). Current is not usually spoken of as a vector. Current in a wire is not thought of as a vector because it usually follows path of the wire. The wire in the diagram is parallel to the **E** field lines. Thus, the current is in the direction of the electrostatic field. Now imagine a 10-foot long wire from the wool that loops out of the screen around your chair and back to the wax. This wire is obviously not aligned with the **E** field. This does not effect the current magnitude at all. Electrons will flow from the wax to wool.

Lets go back to point where we have finished rubbing the wool and wax together. The wool and wax are charged, but are still in contact and thus at the same potential. Now, I pull the wool and wax apart. To do this I most apply force greater than the electrostatic force of attraction. The further I pull them a part, the more work I must do (Work = Force times Distance). This work translates into a greater potential difference measured in volts. Thus, the potential difference is a function of the distance between cloth and the wax. The potential difference is measured in volts (a volt is a non-vector). The current is a measured in ampere (amperes are also a non-vector or scalar quantity.) This current follows the path of the conductor.

I realize I started talking about current as a vector pointing from the wool to the wax. Now I am saying that current is a scalar that follows the path of a wire. It can be both. Lighting striking a tall building starts as a vector that you can actually see, than it hits a lighting rod and follows the path of the grounding wire to ground. We refer to the current vector as an arc or a beam. But most of electrical engineering and electronics deal with current that follows the path of wires. **Click number 24! and number 55**!

Click number 40!

The water at the top of the fall has potential due to the force of gravity and its distance from the center of the earth. Its distance above sea level is the practical way of describing the waters absolute potential. Nothing falls all the way to the center of the earth. The potential difference between the river at the top of waterfall and the turbine in the power station located a short distance down river from the bottom of the waterfall makes power generation possible. This potential difference can be measured as pressure at the input of the turbine. Pressure is scalar not a vector quantity. The velocity of the water at the bottom of the fall is a vector pointing in the direction of earth's gravitational field. I have to admit that I selected this analogy in order to advertise our latest publication, the ***Energy Matrix*** e-zine. I recommend that you bookmark this site. **Click number 41** and bookmark the ***Energy Matrix***.

Chapter 8

Magnetism

Click number 37!

When a wire is wound as a coil, it will produce a magnetic field similar to that of a permanent magnet. The field around the coil is the vector sum of the circular field about each element (very short length of wire). The diagram you are viewing should make it intuitively clear how circular fields produce the resultant vector sum you are viewing. The wire in coils is usually insulated so that the wire loops can be wrapped tightly in overlapping layers and not short circuit with each other. Note that if you had a 100 loop coil and loop 20 shorted to loop 80 you would effectively have a 40-loop coil. The magnetic field strength of an electromagnet with 60% of its coils shorted out would be decreased by 60%. This is significant for electronic troubleshooters, because such coil failure could result in an inductor changing value. If a coil wire broke, it would simply make the coil an open circuit. Open circuits and total shorts are easier to locate than changes in the value of components.

Click number 38 and see how the polarity of magnetic poles is determined using right hand rule. **Click Number 39!** Activate the animation for Oersted's experiment and observe. Perform virtual experiment that Oersted performed in 1820.

Magnets

The orbital motion of electrons around the nucleus of an atom create a magnetic field in the same manner that current in a wire loop does. We will learn in Quantum mechanics that electrons do not orbit the nucleus of an atom in accordance to the laws of classical physics that govern the motion of the planets, but are governed by quantum mechanics, which describes the status of electrons in terms of energy levels. In Quantum mechanics electrons are described as tiny spinning tops, and spinning charge creates a magnetic field of its own. Generally electrons with opposite spins pair up with each other and produce no net magnetic field. In some material like iron a magnetic field forces a majority of the spins to align with the magnetic field. After the external field is removed some magnetism will remain in the iron. **Click number 25,** and **number 9,** to learn more about magnets and the history of magnets.

Chapter 9

Generators and Motors

Click number 14!

When the loop moves the density of the flux in the loop increases and than decreases. The change in magnetic flux or change in the total number of magnetic force lines contained in loop results in an induced Electromagnetic Force (*EMF). *The *EMF* is expressed in volts and is proportional to the change in the number of lines contained in the loop. If you loop the wire again so that there were two loops than the *EMF* of the moving loops would double.

There is a difference between *EMF* and voltage. The *EMF* is strictly a function of the time rate of change of magnetic flux passing through the loop. The needle on meter is moving because current flowing through the loop and the meter. When electrons flow in a wire loop, they strike molecules and generate heat, and this results in a small voltage drop in each loop. This voltage drop is referred to as a "current/resistance (or IR) drop." Resistance is similar to friction in mechanical and hydraulic systems. Thus, the voltage output of each loop is slightly less than the *EMF*. Thus if the output of a generator is 120 volts when there is no load (no current being drawn from generator), then the output of a generator will be less than 120 volts when a load is connected (such as a light being turned on). When there is no load on the generator, then and only then does *EMF* = Voltage Output.

In the case of a 12-volt battery, the total *EMF* of the six 2-volt cells is 12 volts. That is the voltage output of the battery is 12 volts when no current is flowing and the engine is not running. If you turn the headlights on the voltage output at the battery terminal will drop below 12 volts. Positive and negative ion flow in the acid results in some heating of the acid and chemicals that generate the EMF. Thus, the internal resistance of a battery cell is distributed throughout chemicals and plates of a battery. When you engage the starter a large current (over a hundred amperes is typical) results in the output voltage of the battery to drop several volts. Your car headlights dim noticeably when you engage the car starter due to this **IR** drop.

Generators and Motors continued**.**

Click number 15!

In 1831 Faraday discovered that moving a magnet through a coil induced a voltage. Crude generators can be made this way. I suspect non-battery **LED** flashlights that you shake to produce light use this principle. Spinning a coil in a magnetic field was a far more practical way of generating voltage and current. Steam Engines with large flywheels could drive generators with a constant angular velocity resulting in a sinusoidal output. Note that in order to produce electricity, power had to be applied to the system. The greater the current draw, the greater the force required to turn the generator. If you were hand-cranking a generator that was connected to a light via a switch, the generator would turn easily when the switch was open and would be hard to turn when the light was switched on. U.S power companies regulate the frequency of turbine/generators to produce a precise 60 Hz perfect sine wave. The standard frequency in Europe is 50 Hz.

This process of generating electricity is reversible. A generator takes power from a turbine or engine and converts it to electricity. A motor inputs electricity and outputs power. Thus, electricity is a method of power transmission. In the 19th Century factories used belts to transfer power from a small steam engine to a steel shaft. The shaft would transfer power from the boiler room to a machine shop where belts would transfer the power to the saws, laths, drills and other machines. **Click Number 42!** With the advent electricity it was possible to have a large steam engine driven generators produce electricity and transmit that electricity to factories miles away. A large electric motor in the factory could now replace the dangerous high-pressure steam boiler and engine in the manufacturing facilities. Wires replaced the shaft that linked the power output of the steam engine to the factory machinery. The generator/motor transmission of power was one of the great benefits of electricity. The combination of generator and light got the most attention at this historic juncture. Edison was able to power an entire district of Manhattan with low voltage direct current electricity. With the advent of Alternating Current power could be transmitted at high voltage for hundreds of miles. Within a couple decades the whole of New York city was powered with AC electricity from Niagara Falls, except for a small portion of Manhattan that was powered by steam generated direct current well into the 1950's. **Click Number 41!** You are not looking at Niagara Falls, but like Niagara Falls this river is both tourist attraction and a hydroelectric project. **Click Number 40!** to see hydroelectric project located downstream**.** AC electricity can be stepped up to High Voltage exceeding 100,000 volts using transformers. The end result is that alternating current makes it possible to transfer power (or work, horsepower) hundreds of miles with only about a 7% energy loss. This is why the relationship between generator and motor is basic to the understanding of the nature of electrical power. The generator/transmission line/motor system allows power to be transmitted from the output of a steam engine or turbine to the input of a motor with only 7% power loss for distances well over a hundred miles. Generators can convert up to 95% of mechanical power to electricity and motors can convert over 90% of electrical energy to mechanical power. Thus, about 80% of output power of a steam engine, turbine, diesel engine, or other type of heat engine can be transmitted to machines hundreds of miles away. Do not confuse this with overall thermal efficiency of the system.

Heat engines or internal combustion engines at best convert 40% of the BTUs in fuel to mechanical power. About 7% of power is lost by transmission lines. Thus, a baseboard heater or electric furnace only delivers about 1/3 of the energy of coal or natural gas burnt at the power plant to your home. If you burnt natural gas or oil in your home furnace, heating efficiencies over 90% can be achieved. About 10% of the heat from a home furnace go out the chimney.
Click Number 50! Read about the latest on combined heat and power for the single family home.

Chapter 10
Inductors

Click number 38!

We showed earlier that a magnetic field curls around a current carrying wire, and the strength of magnetic field is proportional to the current. This magnetic field is proportional to current flowing in the wire at any point on the wire. Let us assume one ampere is flowing through a wire. Let us set the number of lines of force around a one-millimeter length of wire carrying one ampere to ten lines of force. A two-millimeter wire would than have twenty lines of force curling around it. A meter length of wire would have ten thousand lines of force curling around it, and a kilometer long straight wire would have ten million lines of force around it. We have the same current flowing in the short wire and the long wire. So what is the difference between the long wire and short wire? The answer is the amount of energy stored in the magnetic field. The energy stored in the magnetic field is proportional to the total number of lines of force. Thus, there is more energy stored in the magnetic field of a long wire carrying one ampere than there is in a short wire carrying one ampere. The difference between the short wire and the long wire is called inductance.

Click number 43!

Let us analyze the difference between the meter wire with ten thousand lines of force and the kilometer wire with ten million lines of force. A long wire appears to have many more lines of force around it than a short wire. If the number of lines of force in a plane perpendicular to the wire represents current (I), what does the total number of lines of force represent? The answer is energy (E). The energy stored in the magnetic field is directly proportional to the total number of lines of force in the magnetic field. We call this ability to store magnetic energy *inductance* (L).

$$E = LI^2/2$$

Inductance is really the property of a current loop. We could connect a light to a battery using a single long straight wire; however, to complete the circuit we would have to ground one terminal of the battery and one end of the light. Then earth ground would complete our circuit. Ground rods are expensive and have to be hammered several meters deep. Therefore, two wires would be used to carry power from a battery to a light. One line would be positive and one negative. One wire would carry current to the light and one would return current to the battery. On most cars, the steel chassis of the car is used as the return line. The Negative terminal of battery is connected to the chassis of American cars with a heavy-duty cable. I believe only the British ground the positive terminal to the car chassis.

Inductors are manufactured by looping wire around a core. The inductance of the inductor will be proportional to the number of loops (**N**) and the Area (A) of loop.

$$L = uNA$$

u is dependent on the material of the core of the coil.

Actually the above formula is somewhat simplified. Fortunately after coils are manufactured they are tested and labeled with correct inductance value. That is all that an electronic technician really needs to know. A rigorous treatment of inductors requires calculus and is beyond the scope of this e-book. For technicians who wish to build an inductor, tables are available to help you design inductors. **Click number 54** to learn about Coil Calculators.

Now let us consider the magnetic field around a straight long wire carrying a current from the positive terminal to a light, and a return wire carrying current back to the negative terminal of a battery. Both wires have a magnetic field curling around them; however, since the current are in opposite directions their magnetic flux will also curl in opposite directions, and they will cancel each other out. If the insulated wires wire adjacent to each other, the H fields curling around each wire would almost completely cancel the other out. Since the magnetic flux is reduced to near zero, the energy in the magnetic flux is reduced to near zero, therefore the inductance goes to near zero. Ordinary power cords and extension cords keep their inductance small by placing their wires adjacent two each other. Inexpensive audio cables use twisted pairs to transmit audio to speakers.

$$E = LI^2/2 \text{ or } L = 2E/ I^2$$

Where E = energy, I = current, and L = inductance by definition.

Inductors continued

Click number 45!

The high-tension wires have a large space between them. Thus, their magnetic fields do not completely overlap and do not entirely cancel each other out. High-tension wires would arc if they were not separated. **Click number 55** to see picture of arc!

Click number 45!

Look at two of the three phase wires and imagine an **E** vector going from one wire to the next. Also imagine an **H** field around one of the wires. Note that the **H** field intersects the E vector, and at that point the **H** and **E** field are perpendicular to each other. The energy transmitted by the power lines is contained in the **E** and **H** field in the space around the wires and propagates down the power lines at the speed of light. Some of the energy escapes into space as electromagnetic waves consisting of oscillating **E** and **H** fields. When **E** (the potential energy field) is at a maximum, **H** the kinetic energy field is zero. This oscillation between kinetic and potential energy will continue until the wave reaches past the stars and on to the edge of the universe. It is this escaped energy that we hear on our car radios as we pass high voltage power lines. The sound is referred too as 60-cycle hum.

Click number 10 and select "***Electromagnetic Wave".***

Chapter 11

Electromagnetic Radiation

Click number 1!

View the 3 animations in the "***Electric Field Lines***" section. Note that the first animation shows how the electrostatic field of a single charge fills all of space. The second animation shows how a dipole (two separated charges) produce a magnetic field that also fills all of space. The third animation shows how separating the charges change the field filling all of space. Note that it takes work to separate the charges; therefore, the longer field lines of the more separated charges indicate that the field has greater potential or electrostatic energy. **Click number 5** and select "***Electric Field of a Dipole***" from the "***Electric Field***" section. Move the charges closer and further apart and note that the field changes right up to the edge of the Java simulation. Of course we know that the field changes beyond the edge of the animation. The electrostatic field extends out into space. We can imagine that the field changes extend 186 thousand miles ($3X10^8$ meters) into space. If we imagine that field change occurs instantaneously throughout space we would be making an error. Nothing travels faster than light and that includes field lines. Thus it will take one second for the field to change 186 thousand-miles away. One hundred and eighty six thousand miles is the distance light travels in one second.

Click number 58 and view animations of electromagnetic fields produced by a dipole with a constantly changing voltage applied. Note that the frequency of the signal is high enough so that several wavelengths appear in animation window. You can also view this animation as a large dipole viewed from a great distance. **Click number 4** and select "***Electromagnetic Wave*** "from Electrodynamics section and view wave fields. Next select "***Electromagnetic Oscillating Circuit***" and run animation. Compare the phase relationship of fields in the circuit with those in the wave.

Chapter 12

Capacitors

Click number 19!

A charged capacitor has a positive charge on one plate and a negative charge on the other plate. The charges will attract each other. This results in an attractive force that will try to pull the plates together. **Click number 46** and scroll down to diagram of capacitor and E field. Note that the electrostatic field is uniform except at the edges. If the area of the capacitor plates is kept large and the distance between the plates is kept small, then the capacitor field can be considered to be uniform. To pull the plates apart you will have to apply a force over a distance, this ***work*** that you apply to the capacitor results in an increase in potential energy of the system. This energy is contained in the electrostatic field between the plates of the capacitor. The separating of the two plates results in an increase in voltage between the plates. If we charged the plates of a capacitor with plates separated by one millimeter to 1.5-volt using a battery, then the capacitor plates would retain a charge of 1.5-volt long after battery was disconnected. If we applied a force to separate the plates to ten millimeters, then the voltage between plates would increase to 15-volt dc. If we increased the distance to 11 millimeters, the voltage would increase to 16.5-volt dc. The charge on the capacitor will not change. Therefore, the energy stored in the capacitor is directly proportional to the voltage. The energy is stored in the electrostatic field between the capacitor plates. The **number** of **E** lines of force field is proportional to the charge **Q**, and the voltage is proportional to the length of the lines of force. Note that the energy stored in the capacitor is proportional to Q and V, or the number and length of field lines between the capacitor plates. The number of field lines represents the magnitude of the charge and thus the force of attraction. Thus, the work done to separate the charged plates is simply the product of force times distance. The work done to charge a capacitor with a voltage V is:

$$W \text{ (potential Energy)} = 1/2(QV)$$

Click number 48 and 49 to see why the formula contains a "1/2" in the product.

We have learned that as we separate the two plates (with constant Q) of a capacitor the energy increases in proportion to the distance between the plates. It may not appear obvious that as the energy and voltage increase the capacity decreases. Capacitance is proportional to the amount of charge that can be stored on a capacitor per unit of voltage.

1 farad = 1 coulomb/ 1 volt
$C = Q/V$ or $Q = CV$

The total energy that can be stored in capacitor is proportional to the product of its rated capacitance and its rated voltage.

From above: $W = 1/2\ (QV)$
substituting $Q = CV$ into above results in:
$W = 1/2\ (CV^2)$

In the case of air core capacitor, the closer the plates are placed together the greater the capacitance. However, the closer you placed the plates the more likely arcing will occur. **Click number 55** to see picture of arcing.

Click number 57 and view diagram on page 1 showing the lines of force emanating from the plane. The number of lines is proportional to the charge Q, but the lines are parallel and do not diverge, therefore the force field is constant and do not change with distance from plate. If the plane on the right was infinite and the charge was distributed uniformly, the uniform electrostatic field will also fill the volume of space. Lines of equal length emanating from point in three dimensions fill a sphere, lines of equal length emanating from a plane in one dimension fill a cubic.

Look at the image on the right showing two planes. Note that all the lines of force are between the two plates. Outside the plates the field due to the positive and negative charge cancel each other. The lines of force between the plates of the capacitor fill a volume. This volume of flux represents the energy stored between the plates. The flux density is proportional to the charge per unit area of the plates. Flux density times this volume equals the energy of the capacitor.

Chapter 13
Vacuum Tube Diodes

Click number 32!

We have spoken about how charges move in an electrostatic field and how it requires work to move a unit of charge from one plate to another. It is easy to demonstrate the existence static charge with sparks and the forces charge exerts on balloons, paper, and clothes (static cling). In the laboratory the electroscope could be used to store and measure charge. It was not until the discovery of the vacuum tube that electrons were generated and controlled. A simple tube consists of two plates with an electrostatic field between them. Thus far they are nothing more than a capacitor in a vacuum. When we add a red-hot filament to the system, free electrons are introduced (boiled off the filament) and are accelerated in the opposite direction of the **E** field and conduction takes place. To make the vacuum tube a rectifier only one plate is heated or has red-hot filament adjacent to it. The other plate stays relatively cool. The plate that is heated or has the red-hot filament adjacent to it is called the cathode, and the cool plate is called the anode. The tube only conducts when the anode is positive with respect to the cathode. When the anode is negative with respect to the cathode electrons do not flow from the anode to cathode, because the electrons cannot get off the cool anode. In this reverse bias situation, the free electrons around the cathode are propelled back to the cathode resulting in zero net current.

Chapter 14
Vacuum Tube Amplifiers

Click Number 33!

The Introduction of the grid between the two plates made it possible to control the flow of the electrons from cathode to anode with a low power single on the grid. The British call vacuum tubes "Valves" because they control the flow of electrons much like hydraulic valves control the flow of fluids. Of course it was possible to control current with switches and variable resistors before the vacuum tube. The vacuum tube made it possible to take the small signal produced by a microphone and amplify its power. A voltage of a few mill-volts placed on the grid of the tube would generate a voltage swing on the order of 100 volts on the anode of the tube. The vacuum tube grid would draw very little current so that both voltage and current output were increased; therefore, power not just voltage was multiplied. **Click Number 34** for more about vacuum tubes!

Chapter 15
Semiconductors

Semiconductors replaced the vacuum tube for most applications. Cathode ray tubes, magnetrons, and ion propulsion engines are but a few of the uses that remain for vacuum tubes. Ion propulsion engines electronically accelerate positive ions at speed far greater than the speed of the exhaust of a conventional rocket engine. Today, ion propulsion engines provide thrust with a far greater *specific impulse* than conventional rockets do. They can provide small trusts for very long periods of time. This makes them excellent for maintaining and correcting satellite orbits, and they could also be paired with solar collectors or fission reactors for space travel within the solar system. **Click Number 59** then select one or more links to ion propulsion Webs.

Classical physics and the visualizing of force fields with lines of force do not work well when trying to explain semiconductor physics. Electrons in close proximity to the nucleus of an atom do not orbit like satellites orbit the earth. They are governed by Quantum mechanics. Energy level diagrams will replace the field lines of classical mechanics. Thus, I shall end this e-book. I will end with one note about semi-conductors. Note: the arrow on the transistor and diode schematic symbol point in the direction of conventional current flow and in the opposite direction of electron flow.

Conclusion

I have not included many calculations in this eBook since it is intended specifically as primer for my electronics book. I feel that a qualitative analysis of electricity and magnetism is all that is required by an electronics technician. Electronic technicians do not usually measure static or magnetic forces directly. They make measurements with voltmeters, oscilloscopes, and spectrum analyzers. Electronics students should download my free eBook ***Electronic Concepts*** advertised at Web page **Electricity & Magnetism Slide Show** that you are using in conjunction with this eBook. Physics student should revisit the sites in the **Electricity & Magnetism Slide Show** and study them in greater detail!

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