Physics Around Us: 3

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Electricity and Magnetism

The Atom

• Consists of a nucleus with a positive electric charge
• Surrounded by a cloud of electrons, with a negative charge
• In a neutral atom, the charges cancel exactly.

A stylized model of an atom: not very accurate!

Electricity

• The protons and electrons in each atom carry a quantum property we call charge, which can be one of two “flavours” – positive or negative
• The positive protons in the nucleus are relatively heavy, and cannot get out of the nucleus easily. They do not move much
• The electrons, on the outside of the atom are easier to remove and can move from place to place
• A flow of charge is known as an electric current

Static Electricity

• Sometimes charge is transferred from one object to another, but then can’t flow anywhere.
• We call this static electricity.
• Charge up a balloon by rubbing it on your hair or a sweater

http://www.youtube.com/watch?v=7m-oоф6sO

The Greeks and Electricity

• The ancient Greeks discovered that amber attracted feathers when rubbed by fur

Amber is fossilized tree sap.

In Greek, “elektron” is the word for amber (from “elektor” meaning “beaming sun”)

The Latin word, electricus, means to “produce from amber by friction.”
Electric Field

- All charged particles generate an electric field (E) around them
- We can represent them as field lines
  - Lines start on positive charges
  - Lines end on negative charges

If a charge sits in an electric field generated by another charge, then it feels a force
- A positive charge feels a force in the same direction as the electric field
- A negative charge feels a force in the opposite direction

Like Charges repel each other
Opposite charges attract

Flowing Charge

- There are two types of material
  - Conductors, which allow charge to flow through them
  - Insulators, which prevent charge from moving through them.
- Static electricity builds up on insulating materials (plastics, paper, wood, rubber)
- Conducting materials are usually metals

Electric Current

- Electric current can be made by allowing electrons to flow through conducting materials
- The current is the amount of charge flowing per second and is measured in Amperes, (Amps)
- Copper wire, with an insulating layer is often used to move electricity around in a circuit
- Electricity will not move around the circuit, even if it is connected up, unless there is an incentive.
- The incentive is known as a Potential Difference, better known as a Voltage
Voltage

- Voltage refers to the amount of energy the electrons have as they move around the circuit.
- A voltage source, like a battery, acts as a “pump” to keep the electrons moving.

No battery = No potential
No potential = no flow of electrons,
No flow of electrons = no current

One of the Most Confusing Things in Electricity

- We label the “Conventional current flow” as going from positive to negative terminals
  - This convention was defined by Benjamin Franklin, who assumed that charge was carried by positive charge carriers.
- Unfortunately, much later we found that current is usually carried by negative electrons!
- The actual flow of current is in the opposite direction to the “conventional current flow”

If we have more than one battery, we have to make sure they are trying to send the electrons around the same way, otherwise, the voltage is zero

- If both positive terminals face the same way, then they both drive the current the same way

The Electric Motor

- In the electric motor, the electrons move around a coil which is also inside a magnetic field. This makes the coil rotate.
- This converts electrical energy into mechanical energy of rotation

Current flows around a wire loop in a magnetic field
- The magnetic field exerts a torque on the loop which makes it turn
- To keep it turning in the same direction, the current has to reverse direction after a half-turn (the commutator)

The motor can be operated as a generator, by turning the loop in the magnetic field, this then induces electricity to flow
Hydroelectric Power

- The flow of water turns the motor shaft, and this generates electricity in the coil (the dynamo)
- We have to get the electricity from the point of generation to the point of use (our homes)

Alternating Current and Direct Current

- We can create two types of electric current
  - **Direct Current**, a constant voltage with the current always moving in the same direction
    - This is the preferred method in most small electronic devices, which are battery powered
  - **Alternating Current**, where the current changes direction many times per second
    - This is the best way to send electricity over long distances with the lowest power losses

The Transformer

- A transformer is a device which can change the voltage of an alternating current
- It is two circuits joined by a magnetic field

The transformer does not work with direct current circuits!

Why Use AC?

- By transmitting the electricity over long distances at high potentials (200,000 – 500,000 Volts) using AC, the power losses due to heating in the cables are minimized

Step Down Transformers

- The High Voltage lines have to be stepped down to much lower voltages at local electrical substations.
- This is done using Step Down Transformers.
- It is still Alternating Current when it enters the home

Alternating Current Frequency

- Alternating current supplies are the usual form of electric supply. The frequency (cycles per second, or Hertz) varies by country

60 Hz in North America
50 Hertz in most of the rest of the world
Household Electricity

- When it comes to the wall sockets, the electricity has been stepped down to 110V AC

North American sockets 110V 60 Hz
British Sockets 230V 50 Hz

Changing from AC to DC

- Some devices, like lamps can work with AC supplies.
  - Most electronic devices need to have the voltage stepped down from 110 V to a smaller voltage AND
  - Need the AC converted into DC, by a rectifier circuit

Power Supply

- The black box power supplies are transformers and rectifiers

110 Volt AC in 12 Volt DC out

Natural Permanent Magnets

- Known for at least 2500 years
- Lodestone (magnetite) mined in Turkey, at Magnesia - some of the pieces of this mineral were permanent magnets

Permanent Magnets

- Permanent magnets are magnetic dipoles.
- The two ends have opposite "flavours" which are labelled North and South (compared to the electrostatics labels "positive" and "negative")

Magnetic Field

- The Magnetic Field Lines map out the direction of the magnetic force on a positive charge

A compass will align itself tangentially to the field line. The arrow indicates which way the North on the compass goes

http://www.walter-fendt.de/ph14e/mfbar.htm
Visualizing the Magnetic Field

• The magnetic field can be visualized by putting iron filings near to the magnet

The Earth’s Magnetic Field

• The earth generates a magnetic field, which is approximated by a bar magnet (dipole) near the surface of the earth

Note that what we call the magnetic north pole is actually the south pole of the dipole magnet model!

The Compass

• A compass is a small dipole magnet which is free to rotate
• The compass aligns itself with the earth’s magnetic field
• The north pole of the compass needle points towards the magnetic north pole of the Earth.

The Magnetic North Pole Moves

• The Magnetic North pole moves in the long term
• It is presently leaving Canadian territory and heading to Russia
Magnetic Senses

- Sensing the Earth’s magnetic field provides a directional sense for navigation
- Higher organisms with magnetic senses
  - Homing pigeons
  - Migratory birds
  - Bees
  - Humans (possibly)


Magnetotactic Bacteria

- Live in the Sea
- Have threads of crystals of magnetite inside them
- Magnetic sense helps them navigate
  For Northern hemisphere bacteria, north pole is forwards
  For Southern hemisphere bacteria, south pole is forwards

Magnetic Force

- Like poles repel each other
- Unlike poles attract each other
- The magnetic force will also interact with moving charged particles

Iron filings (and compasses) align themselves in the direction of the magnetic force

Computer Hard Drives

- Stores the data from your computer on a disk of magnetic material

Magnetic Data Storage

- Magnetic tape used to record audio data
- Magnetic stripe on credit cards used to store your account details

Solenoid

- A solenoid is a current carrying multiple loop
- The moving current generates a magnetic field. Inside the loop a uniform magnetic field is produced
**MRI Scanner**

- The Patient is put inside a large solenoid and is thus in a uniform magnetic field

**MRI Images**

- The large magnetic field creates very small changes in the energy of the nucleus of atoms.
- This can be probed with radio frequencies
- Nuclei in different tissue types respond differently

**Magnetism and Electric Charge**

- A magnetic field exerts a force on a moving charge
- A moving charge generates a magnetic field

**Magnetic Field**

- A magnetic field exerts a force at right angles to the direction of motion, and at right angles to the direction of motion

**The Earth’s Magnetic Field**

- The magnetic field generated by the Earth acts on high energy charged particles coming from the sun and deflects them in spiral trajectories towards the polar regions
- The particles collide with oxygen and nitrogen molecules in the upper atmosphere, making them emit blue and green (sometimes red) visible light

**Aurora**

- The spiralling particles create the Northern and Southern Lights
- Aurora Borealis and Aurora Australis
• Southern Lights seen from the International Space Station

Nova Documentary on Earth's Magnetic Field
http://www.youtube.com/watch?v=NJUTUF4WFEY

The Oersted Experiment
• Hans Christian Oersted demonstrated that a compass needle can be deflected by a nearby current
• The current produces a magnetic field, which is stronger than the magnetic field of the Earth, and changes the direction of the needle
http://www.youtube.com/watch?v=w-1-4Xnjuw

The Lorentz Force
• If the current through a floppy wire goes through a magnetic field, the charges in the current feel a magnetic force and push on the wire
http://www.youtube.com/watch?v=_X8jKqZVwoI

The Electric Motor
• The Lorentz Force is what makes the electric motor work
• The current moves around a coil which is inside a magnetic field.
• The Lorentz Force pushes on the current in the coil, which turns the coil

The Electric Motor
• Every half turn, the direction of the current has to be reversed, so that the coil keeps turning in the same direction
• This is done by the Commutator

Ferromagnetic Materials
• Substances which experience a substantial magnetic force when near a magnet
  – Iron, nickel, cobalt, chromium dioxide
• Materials which may be permanent magnets require the electrons to be distributed in a certain way (with unpaired spins)
• Not all materials have this arrangement of electrons
Magnetism at the Electronic Level

• Each electron in an atom acts like a magnet due to
  – Orbiting in a loop around the nucleus
  – An built in magnetic dipole independent of the motion.

http://www.ndt-ed.org/EducationResources/CommunityCollege/MagParticle/Physics/MagneticMatls.htm

• In most materials, the electrons are paired up so the magnetic fields cancel each other out.
• These are non-magnetic materials

• In some materials, there are unpaired electrons, so there is a permanent magnetic field belonging to each atom

Random Alignment

• In paramagnets and diamagnets all of the individual contributions form each electron are randomly aligned

Even in an external magnetic field, the magnetic dipoles tend to remain randomly, or near randomly aligned

Ferromagnetic Materials

• There is a quantum mechanical interaction which tends to align the magnetic dipoles
• This occurs in regions called domains, where all of the dipoles are aligned
• The material may be unmagnetized or magnetized

Unmagnetized Ferromagnet

• The domains in the material have random orientation, so there is no net magnetic interaction with an external magnet

Magnetized Ferromagnet

• If the domains are aligned with each other, then there is an overall magnetic moment

• Magnetising a ferromagnetic material is possible by exposing it to a large magnetic field - changing the magnetic orientation of the domains
Ferrofluids

- Small iron particles suspended in a liquid
- Each particle acts like a tiny magnet in a magnetic field
- So a drop of the fluid takes on the shape of an external magnetic field, if placed near a magnet

Maxwell’s Equations

- Unified the theory of electric and magnetic fields

Maxwell’s Equations

- Electricity and Magnetism are linked by Maxwell’s Equations

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<th>Integral equations</th>
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<td>Gauss’s law</td>
<td>( \int \mathbf{E} \cdot d\mathbf{A} )</td>
<td>( \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} )</td>
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<tr>
<td>Divergence theorem for magnetism</td>
<td>( \int \mathbf{B} \cdot d\mathbf{S} = 0 )</td>
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<td>Maxwell–Faraday equation</td>
<td>( \int \mathbf{E} \cdot d\mathbf{A} = -\frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{S} )</td>
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<tr>
<td>Ampère’s circuital law (with Maxwell’s addition)</td>
<td>( \int \mathbf{H} \cdot d\mathbf{l} = \mu_0 \int \mathbf{J}_0 \cdot d\mathbf{A} + \frac{\partial}{\partial t} \int \mathbf{D} \cdot d\mathbf{A} )</td>
<td>( \nabla \times \mathbf{H} = \mu_0 \mathbf{J} = \mu_0 \mathbf{J}_0 + \frac{\partial \mathbf{D}}{\partial t} )</td>
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