ECET 3000

Electrical Principles

Introduction

1

Electric Principles?

Even though this course is simply named "**Electric Principles**", I am often asked what topics will be covered during the course, to which I reply:

"**anything and everything related to electricity**."

And I'm always surprised by how many people seem to accept that answer without further question, because I'm sure they've gained no useful information about the course based purely on my response.

Why not? Well, not only was my answer extremely vague… in almost every instance I would have bet $100 that they couldn't provide me with a simple definition for the term "**electricity**".

In case you're wondering, I always provide additional information beyond just:
"anything and everything related to electricity,"
but first I pause long enough to gauge their acceptance of that useless response.

2

Electricity

I'm not saying that the person doesn't at least have some general concept in their head regarding **electricity**, especially since they utilize it daily and begrudgingly pay for it monthly when their power bill* arrives.

*** I'll discuss this soon!**

But, if pressed for a definition that a 5th grader could understand, or even a college senior, the average person is **unable** to provide a suitable response.

The same can also be said regarding a simple definition for the term **voltage** which, along with **current**, is one of the most common things that people associate with electricity.

Btw - the most common definition for voltage that I've received from electrical engineering students that I've taught in the past, if they're even willing to volunteer one when asked, is that:

"A voltage is a potential difference"

My usual response: "When I was young, I heard a teacher tell my parents that I had potential, but when later asked how I compared to the other students, the teacher paused and then casually replied 'well, he's different'…"

So, was I a voltage?

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What is Electricity?

So, what is **electricity**?

According to **Wikipedia**, the most trusted and utilized source of information:

"***Electricity is the set of physical phenomena associated with the presence and motion of matter that has a property of electric charge.***"

https://en.wikipedia.org/wiki/Electricity

Really? What the **h$☹K̶**! ***"the set of physical phenomena…?"***

Btw – h$☹K̶ ≡ Heck?

I have no idea what that means!?! Wikipedia, you've let me down!

Okay, when all else fails, I know that everyone trusts the government, so how about a definition from the US Energy Information Administration:

"***Electricity is the flow of electrical power or charge.***"

https://www.eia.gov/energyexplained/electricity/

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A definition… of electricity… please!

So… ***Electricity is the flow of electrical power or charge?***

That definition **seems** better. It's short, concise, and it doesn't utilize the word "phenomena"! But something seems wrong; the **flow** of electrical **power**?

The American Heritage® Science Dictionary defines **power** as:
"***The rate at which work is done, or energy is expended, per unit of time.***"

If I substitute that for "power" then, according to the US EIA:
"Electricity is the flow of the (electrical?) rate at which work is done…"

That's even worse! Things flow at a rate, but **a rate doesn't flow**!

Beginning to wonder what point I'm trying to make? Well, I don't remember!

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The Bigger Picture?

In **Electric Principles**, we will cover a variety of topics that span the entire range from theoretical concept to practical application, all of which are associated with the field of **Electrical Engineering**.

In fact, we'll cover as many topics as can be squeezed into a single semester!

Ideally that would fill you with excitement and anticipation, but in reality it probably invokes more of a sense of foreboding or dread.

Why?
- Perceived difficulty?
- Heavy workload?
- Lack of interest in the subject?
- You wanted a different professor?

I am fully aware that **none** of you are studying to be electrical engineers, and that the majority of you are enrolled only because it's required, but…

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As this Course Begins…

You are studying to be **engineers**, and an important characteristic that's common among successful engineers is **a desire**, if not a passion, **to learn** everything possible about the world that surrounds them!

If you worry about the difficulty of this course or the required workload, I promise you that all of the material presented during this course is relatively easy to understand, and that **you are fully capable of mastering the material** with a reasonable amount of continuous effort that, for most, is typically less than the effort exerted in one of their major courses.

If you lack interest in the subject… that I can fix. But you have to enter this course with an **open mind** and a **commitment for success**. I assure you that we will cover material that will benefit you both during your career as an engineer and in your personal life, but only if you're **willing to learn**.

With that said…

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What is Electrical Engineering?

Electrical Engineering is a field of engineering that relates to the study and application of electricity, electronics, and electromagnetism.

Together, **electromagnetic theory** and **electric circuit theory** comprise the foundation upon which all of the different branches of electrical engineering are built.

₪

We will begin this course by focusing on **electric circuit theory**, which is based on the **existence or motion of <u>electric charge</u>**.

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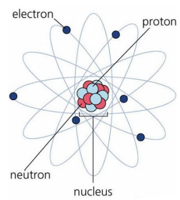
Electric Charge and Atoms

There are two types of **electric charge**:

- **positive charge**, and
- **negative charge**.

All ordinary matter is composed of **atoms** that, in-turn, are composed of three, differently-charged, particles:



- **Protons** (**positively**-charged particles)
- **Electrons** (**negatively**-charged particles)
- **Neutrons** (**neutrally**-charged particles)

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Electric Charge and Atoms

The **elementary charge**, ***e***, is defined as the charge carried by a **single proton**, which is equal in magnitude, but opposite in polarity, to that carried by a single electron.

Based on this definition:

- **Protons** are typically given the symbol "p^+" and assigned a net (**positive**) charge of **+1*e***.
- **Electrons** are typically given the symbol "e^-" and assigned a net (**negative**) charge of **–1*e*.**
- **Neutrons** are typically given the symbol "***n***" and have <u>no</u> net electric charge (i.e. – they are assigned a charge of **0*e***).

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Electric Charge

The SI* derived <u>unit</u> of electric charge, q, is the **coulomb** (C).

*** SI ≡ Système International (The International System of Units)**

1 coulomb of charge is equivalent to the total charge contained by:

$6.242 \; x \; 10^{18}$ protons.

Thus, the **elementary charge**, e or q_e, contained by a **single electron** is equivalent to:

$$e = \frac{-1}{6.242 \; x \; 10^{18}} = -1.602 \times \; 10^{-19} \; coulombs.$$

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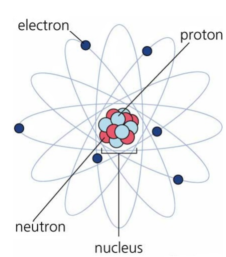
The Structure of Atoms

The basic structure of an **atom** consists of a dense central **nucleus** that is surrounded by a "cloud" of (negatively charged) electrons that orbit the nucleus.

The **nucleus** contains a mix of (positively-charged) protons and (neutrally-charged) neutrons.



Atoms typically contain an equal number of protons and electrons, and thus contain a net neutral charge ($q_{net} = 0e$).

Note that a <u>molecule</u> is an electrically-neutral group of two or more atoms that are held together by chemical bonds.

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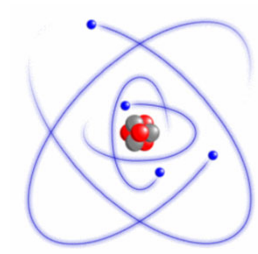
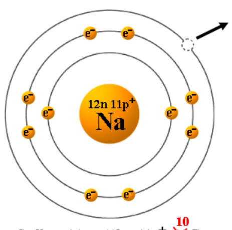
The Structure of Atoms

The **protons** and **neutrons** that are contained within the nucleus are tightly bound, while the orbiting **electrons** are more loosely bound to the atom.



Additionally, the **mass** of an **electron** is only $^{1}/_{1386}$ times that of a proton.



Sodium Atom (12n, 11p$^+$, ~~11~~ 10e$^-$)

Compared to the protons that are bound within the nucleus, it is **much easier to move electrons** from one atom to another due to both their loose bonding structure and smaller mass.

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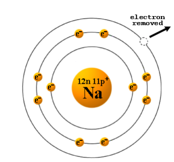
Ions

Ions are atoms (or molecules) that contain a different number of protons and electrons, and thus have a non-neutral net charge.

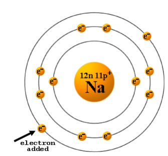
Sodium atoms (Na) contain 12n, 11p$^+$ and 11e$^-$.

If a sodium atom loses an electron, it becomes a **sodium ion** with a net positive charge of **+1*e***.
$[q_{net} = +11e + -10e = +1e]$



Sodium Ion (q_{net} = +11e + -10e = +1e)

If a sodium atom gains an electron, it becomes a **sodium ion** with a net negative charge of **–1*e***.
$[q_{net} = +11e + -12e = -1e]$



Sodium Ion (q_{net} = +11e + -12e = -1e)

In terms of the NET CHARGE that results from "x" electrons being removed from a material, theoretically the same result would be occur if instead "x" protons are added to that same material.

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Coulomb's Law

Coulomb's Law states that an **electrostatic force** will exist between two point charges that is directly proportional to the magnitude of the charges and inversely proportional to the square of the distance between the charges:

$$F = k_e \frac{q_1 q_2}{r^2} \text{ (N)}$$

where: $\boldsymbol{q_1}$ and $\boldsymbol{q_2}$ are the **charge magnitudes** in coulombs, and $\boldsymbol{r}$ is the **distance** between the point charges.

Note that Coulomb's Law can be extended in order to determine the electrostatic force will exist between any combination of charged **particles**, charged **bodies**, and/or **regions** of charge.

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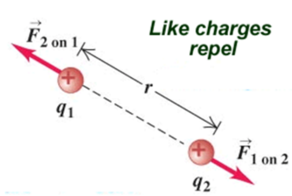
Force Between Charged Particles

When calculated using Coulombs Law, a **positive force** (***F***) relates to a repulsive force between the charges and a **negative force** (***F***) relates to an attractive force between the charges:

$$F = k_e \frac{q_1 q_2}{r^2} \text{ (N)}$$

Thus, **similarly-charged** particles are **repelled** from each other while **oppositely-charged** particles are **attracted** towards each other.



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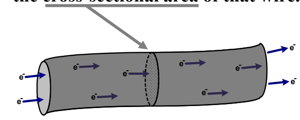
Electric Current

Electric Current, ***i***, is the rate at which electric charge crosses a specific surface or (in circuits) the rate at which charge flows past a point in an electric circuit, as defined by:

$$i = \frac{dq}{dt}$$

where: ***q*** is **charge** in coulombs (C), ***t*** is **time** in seconds (s), and ***i*** is **current** in Amperes (A).

For example, the amount of current that flows through a wire is defined by the rate that charge passes through the cross-sectional area of that wire.



Note that an **Ampere** is a SI base unit that is equivalent to:

$$Amps = \frac{coulombs}{seconds}$$

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Characterizing Electric Current

Electric Current is often classified by whether the rate of charge flow is constant or time varying.

- **Direct Current** (**DC**) is used to describe steady-state currents that remain constant in time (both magnitude and direction).
  - an **upper-case** variable "***I***" is typically used for DC (constant) currents (and for the magnitude of time-varying current).
- **Alternating Current** (**AC**) is used to describe steady-state currents that vary with time (in magnitude and/or direction).
  - a **lower-case** variable "***i***" is typically used for AC (time-varying) currents and is often expressed as "***i(t)***".

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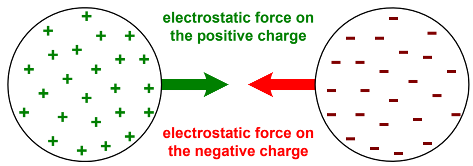
"Source" of Electric Current

The are many different **mechanisms** that can create **current***, such as the **electrostatic force** that exists between charges.

* the flow of charge

If two spheres with **opposite net charge** are in close proximity:



$$F = k_e \frac{q_1 q_2}{r^2}$$

then an **electrostatic force** will exist upon those charges that attracts the opposing charges towards each other.

For this example, assume that the spheres were (somehow) initially charged by removing electrons from the atoms of one sphere and depositing them on the other.

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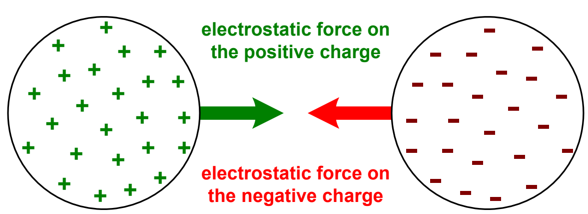
Opposition to Electric Current

Although the **electrostatic force** provides a mechanism for the potential motion of charge, if the region separating the spheres provides an **ideal barrier** that prevents the motion of charge, then the charges will remain in place despite the force present.



Media that prevents or opposes the motion of charge is an insulator, while media through which charge can easily flow is a conductor.

Note that, unless "ideal", even good conductor will still provide some minor opposition to the flow of charge, although it is often neglected.

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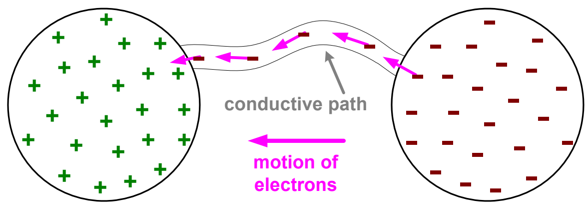
Current in a Conductive Path

If a “**conductive**” **path** is provided between the spheres, then the negative charge will flow back to the positively-charged sphere, the rate of which will depend on the actual conductivity of the material used to create the path.



The positive charge does not readily move because the protons are tightly-bound to within the nuclei of their atoms.

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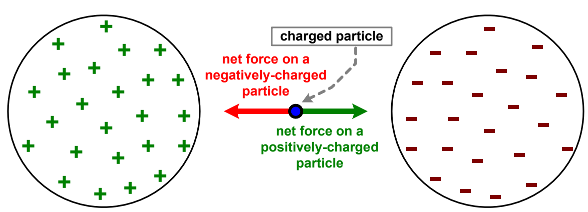
Characterizing the Coulomb Force

If a **charged particle** is placed in the region between the spheres, then a **force** will be exerted on the particle such that it will be:

- “**repelled**” from the similarly-charged sphere, and
- “**attracted**” towards the oppositely-charged sphere.



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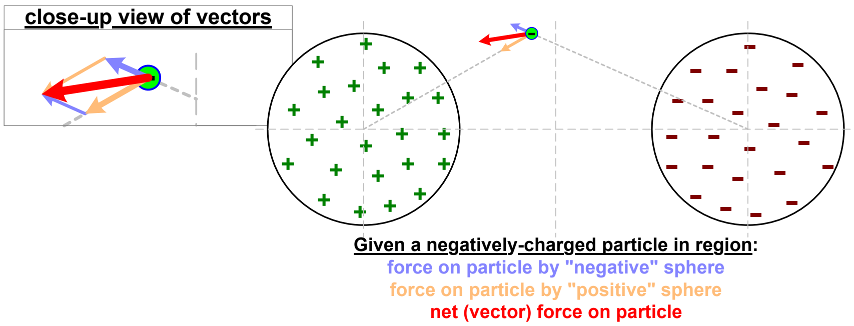
Characterizing the Coulomb Force

And the **net force** on that particle will be a **vector quantity** having a magnitude and direction that both depend on the charge type and the exact position of the particle within the regions :



This figure displays both the individual electrostatic forces developed by each charged sphere on a negatively-charged particle and the net (vector sum) force experienced by the particle.

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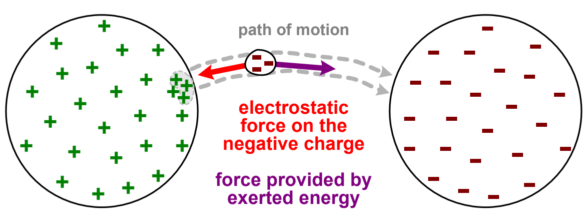
Energy Required to Move Charge

In order to pull **negative charge** from the positively-charged sphere and then move it to the negatively-charged sphere, **energy** must be exerted to overcome the Coulomb force that opposes such motion.



Note that the electrostatic forces will increase slightly as the charge is moved due to the increase in the magnitude of the charge difference that results from the transport of additional electrons to the "negative" region.

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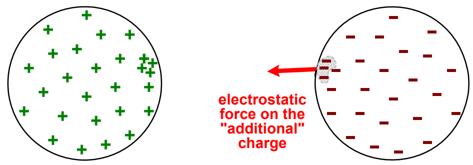
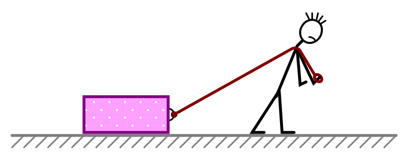
Potential Energy of the Stored Charge

Yet, after the movement of the charge is complete, the electrostatic forces will still "try" to push/pull the negative charge back to the positively-charged sphere.



This is very different than that which occurs if a mass is pulled from one location to another. It takes energy to move the mass, but once moved, there is no force present that will try to move the mass back to its original position.



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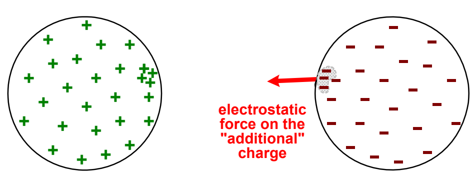
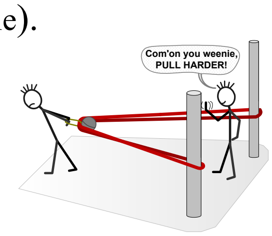
Potential Energy of the Stored Charge

For the case of the transported charge, assuming 100% efficiency of motion*, the energy exerted to move the charge was in-turn transferred to the charge in the form of a **potential energy** that remains available to return the charge to the positive sphere if the opportunity arises (i.e. – if a path becomes available).

*** all of the exerted energy was used to overcome only the electrostatic force.**





This is similar to the case of an "ideal" spring, such that the energy exerted to stretch a spring is imparted to the spring in the form of a potential energy that is used to return the spring to its original length once released.

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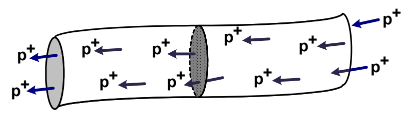
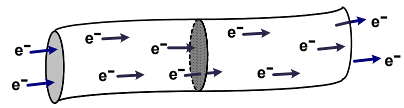
Positive vs. Negative Charge Flow

Classical Electric Circuit Theory characterizes current as the flow of positive charge (i.e. – the movement of protons).



Classical Electromagnetism is also based on the concept of positive charge flow.

Yet, as previously discussed, it is actually the **electrons** that are mobile and thus function almost exclusively as charge carriers.



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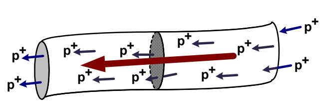
Positive vs. Negative Charge Flow

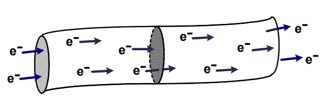
Since the **same effect*** can theoretically be accomplished either by moving a net positive charge from point $\boldsymbol{a} \rightarrow \boldsymbol{b}$ or by moving the same net negative charge from point $\boldsymbol{b} \rightarrow \boldsymbol{a}$, this oversight only provides a convention issue.

* such as the creation of two oppositely-charged spheres

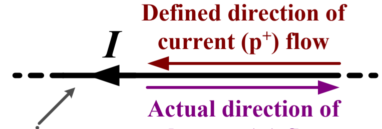
Thus, if **current**, ***I***, is defined to flow in a direction through the wire of an electric circuit, there are actually **electrons** flowing in the **opposite direction**.



Classical Current Flow



Actual Electron Flow



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Voltage

Voltage is defined by the work per unit of charge that is required to move that charge from one location to another, such that:

$$V = \frac{W}{Q} \quad (\mathrm{V})$$

where: ***W*** is **energy** in Joules, and
Q is **charge** in Coulombs.

The SI derived unit of voltage is **volts** (**V**), where:

$$Volts = \frac{Joules}{Coulomb}$$

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Voltage

Based on the definition of **voltage**:

A voltage of **1 volt** exists between points ***a*** and ***b*** if
1 joule of energy is required to move
1 coulomb of charge from point ***b*** to point ***a.***

Since the work required to move the charge is dependent on the starting and ending locations, **voltage** provides a measure of the **difference in the electric potential** (of the charge as it moves) between those two points.

This is the reason that voltage is often referred to as a "potential difference".

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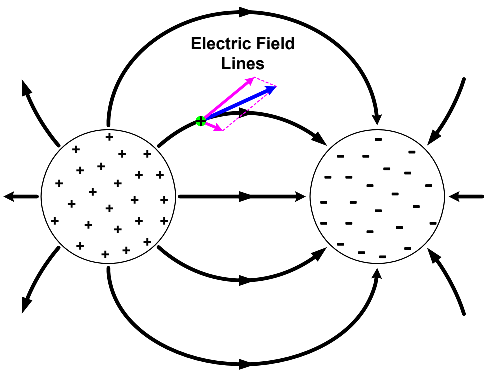
Electric Fields

An **Electric Field**, $\overline{E}$, is a representation of the **electrostatic force** experienced by a unit of motionless, positive charge at any point in space relative to the source(s) of that force.



Electric field lines are drawn such that the direction of the electrostatic force on a positive charge at any location is tangent to the line passing through that point.

Thus, an electric field represents a **vector quantity** that can also vary with location.

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Electric Fields

If an **electric field** represents the electrostatic force per unit charge, then the derived standard units for an electric field are:

$$\bar{E} = \frac{\bar{F}}{q} \quad \rightarrow \quad \frac{newtons}{coulomb}$$

And since **1 joule** of energy relates to a force of **1 newton** exerted over a distance of **1 meter**, the units of **electric field** can also be expressed as:

$$\frac{newtons}{coulomb} \equiv \frac{\frac{joules}{meter}}{coulomb} \equiv \frac{joules}{coulomb} \cdot \frac{1}{meters} \equiv \frac{volts}{meter}$$

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Voltage and Electric Fields

Furthermore, if an **electric field**, $\overline{E}$, has units of:

$$\frac{volts}{meter}$$

then the line integral of an electric field along any path will have the unit of **volts**.

Thus, the **voltage** (potential difference), $\boldsymbol{V_{ab}}$, that exists between points ***b*** and ***a*** can be determined by the equation:

$$V_{ab} = \int_b^a \overline{E} \cdot dl$$

where: $\overline{E}$ is the **electric field** that exists along any path from point ***b*** to point ***a***.

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Simple Concept of a Voltage

If an electric field represents an electrostatic force per unit charge, and voltage is the integral the electric field that exists between two points (or regions), then for the case of a "source of current", **voltage** provides a measure of the potential force provided by that source in order to create the flow of current.

And, when considered for the case of charge moving from one location to another (i.e. – current) along a path that is not lossless*, **voltage** provides a measure of the oppositional force provided by the path (load) that "tries" to prevent the flow of current.

*** We will discuss the concept further during an upcoming lecture.**

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Voltage Sources

A **voltage source** is a device that internally develops a potential difference across two terminals (electrical connection points), thus allowing for that voltage to be applied across two points in an electric circuit as a potential source for the creation of current.

An **ideal voltage source** is a voltage source that can maintain a constant voltage potential across its terminals independent of the amount of current that is flowing out of the source.

Although there are no true "ideal" sources, under certain conditions, a "**practical**" voltage source can act ideal.

One such commonly-used voltage source is a **battery**.

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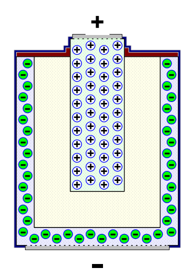
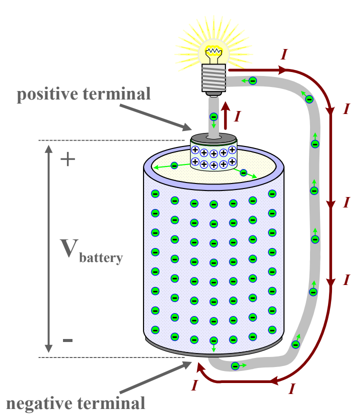
Batteries

A **battery** is an **electrochemical device** that utilizes the energy released during a chemical reaction as the means for developing a charge difference between two regions within the battery.





The **terminals** of the battery provide an external connection to its charged regions in order to allow for the **developed voltage** to be used as a source of **current** that will flow <u>out of the positive terminal</u>, through an externally-connected electric circuit, and back <u>into the negative terminal</u>.

Remember that electrons and current flow in opposite directions.

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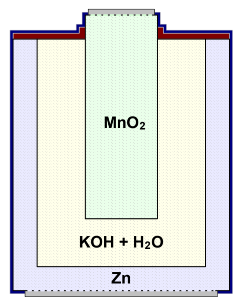
Battery Composition (Alkaline)

Internally, a typical **battery** is composed of **two** different **metals** that are separated by an **electrolyte**, which is a substance that ionizes when dissolved in water, thus providing a conductive material through which electrons can flow.

<u>FOR EXAMPLE</u>:

A standard "**alkaline battery**" utilizes **manganese dioxide** and **zinc** for the two metals and a **potassium hydroxide** solution for the electrolyte.



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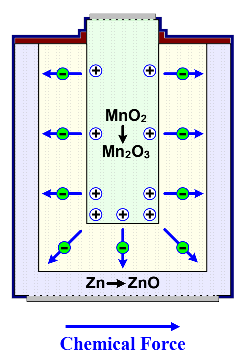
Chemical Reaction in an Alkaline Battery

When the components are all combined together, a pair of **chemical** half-**reactions** begin to occur between each of the metals and the electrolyte:

$$Zn_{(s)} + 2OH^{-}_{(aq)} \rightarrow ZnO_{(s)} + H_2O_{(l)} + 2e^{-} \; [e° = 1.28 \text{ V}]$$

$$2MnO_{2(s)} + H_2O_{(l)} + 2e^{-} \rightarrow Mn_2O_{3(s)} + 2OH^{-}_{(aq)} \; [e° = +0.15 \text{ V}]$$



The reactions are balanced such that the <u>electrolyte is not consumed</u>.

You do <u>not</u> need to know this!

But, a key effect occurs with this reaction:

- ♦ **Electrons** are pulled from the "**manganese**" region and deposited in the "**zinc**" region.

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Build-Up of Charge in a Battery

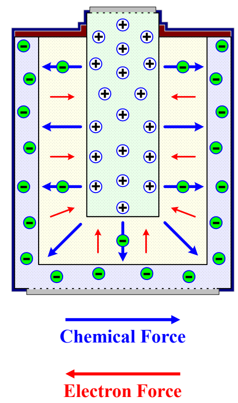
As the reaction continues, the "**zinc**" region builds-up a net **negative charge** and the "**manganese**" region builds-up a net **positive charge**.

In-turn, an **electrostatic force** is created by the charge difference between the regions, opposing the (chemical) "reaction force" and thus slowing down the chemical reaction.

But provided the:

reaction force > electrostatic force

the reaction will continue.



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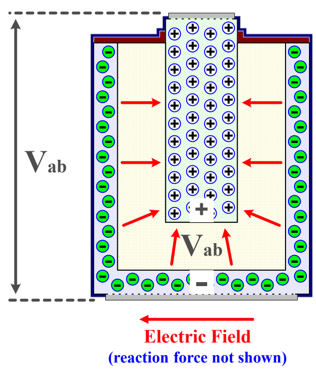
Battery Voltage Potential

Keep in mind that the electrostatic force resulting from the charge difference can be represented by an **electric field**, $\tilde{E}$.

Furthermore, a **voltage** can be defined between the two charged regions, and in-turn the battery's terminals, as the integral of electric field:

$$V_{ab} = \int_b^a \overline{E} \cdot dl$$

Thus, as the charge-difference increases, so does the **voltage** (potential difference) across the battery's terminals.



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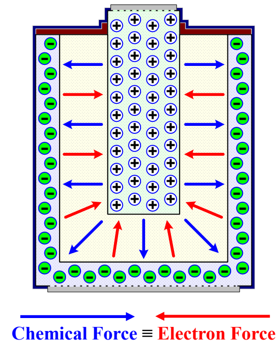
Battery Equilibrium

Eventually, the charge difference between the "**zinc**" and "**manganese**" regions increases to the point at which the electrostatic force is equal but opposite to the reaction force.



Equilibrium is reached when this occurs, and the **reaction stops** because it can't overcome the electrostatic force in order to transport more charge across through the electrolyte.

Similarly, the electrostatic force cannot pull the electrons back through the electrolyte due to the still-present reaction force.

Note that this is the state of a battery when it is newly purchased from a store.

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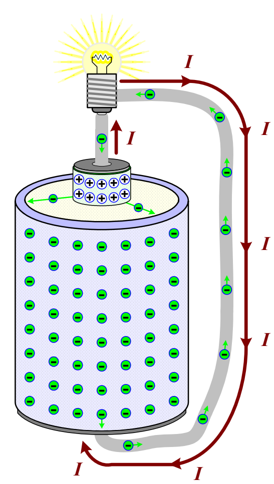
Current Flow from a Battery

Although the negative charge cannot pass backwards (on its own) through the electrolyte due to the reaction force, if an **external path** is available for the electrons to travel to the positive terminal, then the **potential difference** between the charged regions provides the necessary motivational force required to push the electrons through that external path.



And it is this external flow of charge, when represented as **current***, that forms the basic concept of an **electric circuit**.

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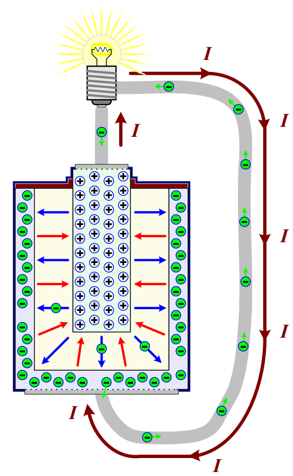
Battery Discharge During Using

Note – as electrons travel externally from negative to positive terminal, the **charge difference** between the two regions **begins to decrease**, in-turn **decreasing** both the **electrostatic force** and the **voltage** developed by the battery.

The decreasing electrostatic force allows the **chemical reaction** to **begin again** and transport additional the electrons through the electrolyte in order to **replace those traveling externally** back to the positive region, <u>ideall</u>y without a "noticeable" drop in battery's voltage.



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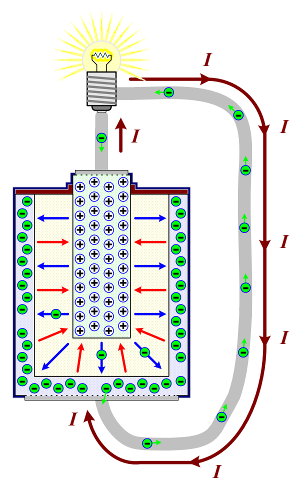
Continued Use of a Battery

After continued use, the reaction will **consume** most of the chemicals, causing the reaction to slow down to the point that it can no longer compensate for the flow of current.

When this occurs, the voltage present across the terminals of the battery will begin to drop, in-turn decreasing the amount of current that the battery is able to provide.

Even in a new battery, if the external flow of current is too large, the chemical reaction will <u>not</u> be able to replenish the charge fast enough and the battery's voltage will notably decrease.

This effect is often seen in a car battery when starting the engine due to the excessive current drawn by the starter motor.



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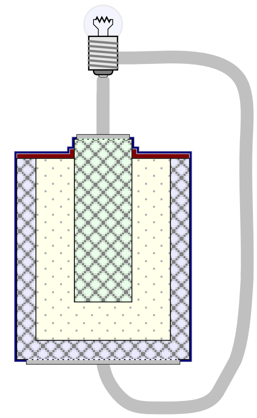
All Good Things Come to an End?

Eventually the chemicals will be fully depleted, the reaction will stop, and the battery will be "**completely discharged**".

At this point, the battery is considered to be **dead** because it is no longer able to supply current.

If it is a "**primary battery**" (disposable), then its lifespan is over.

But if it's a a "**secondary battery**" (rechargeable)… well, then there's still a story left to tell, but not during this lecture!



Although I do want to consider one final aspect relating to batteries…

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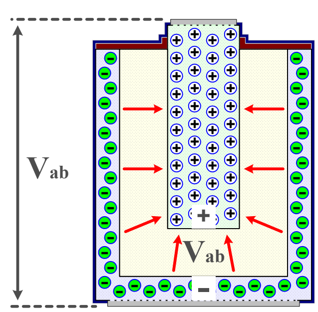
The Voltage Potential of a Battery

Since the force required to separate the charges is provided by the chemical reaction, and the strength of the reaction is based on the materials (metals and electrolyte) chosen for the battery, **different types of batteries** will provide **different voltages**.

Nominal Voltage based on Battery Type			
Battery Type	Primary Materials		$V_{nominal}$
Alkaline	Zn	MnO_2	1.5
Carbon-Zinc	Zn	MnO_2	1.5
Lead-Acid	Pb(s)	$PbO_2(s)$	2
Lithium-ion	Li_xC_6	$Li_{(1-x)}CoO_2$	4.1
Lithium-Iron	Li	FeS_2	1.5
Lithium-Metal	Li	MnO_2	3.0
Nickle-Cadmium	2NiO(OH)	Cd	1.2
Nickle-Metal Hydride	Intermetallic Compound	$Ni(OH)_2$	1.2
Silver-oxide	Zn	Ag_2O	1.85
Zinc-Air	Zn	O_2	1.6



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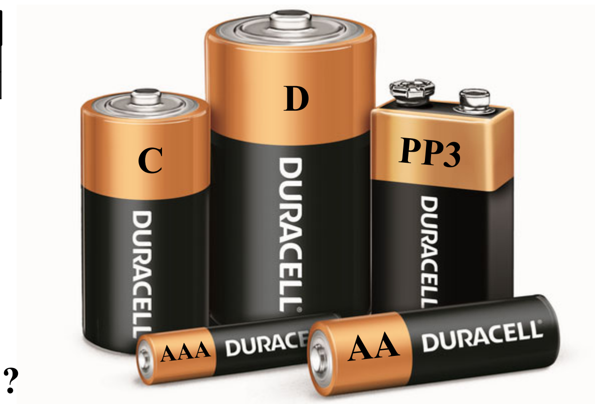
The Voltage Potential of a Battery

Thus, it should make sense that batteries constructed using the same materials should all **develop the same voltage**, as shown for a variety of different-sized, Duracell, alkaline batteries:

Nominal Voltage based on Battery Type			
Battery Type	Primary Materials		$V_{nominal}$
Alkaline	Zn	MnO_2	1.5

SIZE	VOLTAGE
D	1.5V
C	1.5V
AA	1.5V
AAA	1.5V
PP3	9V ← ?!?



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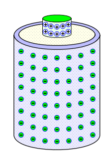
The Voltage Potential of a Battery

The answer to the mystery of the **9V** alkaline battery involves a common misuse of terminology between **cell** and **battery**.

A cell is a single electrochemical unit that produces a voltage based on chemistry and the chosen materials.



cell

A **battery** is a device that contains one or more cells, along with the terminals and packaging required for proper utilization of the voltage(s) produced by the cell(s).

Internally, a 9V battery contains **six** individual **cells**, each the size of a AAAA battery, that are wired together to produce a total of 9V.

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