Physics II: Electricity and Magnetism

Lecture 1: Electric Charges and Forces – Coulomb's Law – Polarization

Electricity and magnetism is all around us.

- we have electric lights, electric clocks microphones, calculators, televisions, VCRs, radio, and computers
- Light itself is an electromagnetic phenomenon
  - also radio waves
- The colors of the rainbow are due to electricity

Horses need electricity cuz they have muscles

- Muscle contraction require electricity
- Your ~~nervous~~ central nerve system uses electricity
- you cannot see without electricity

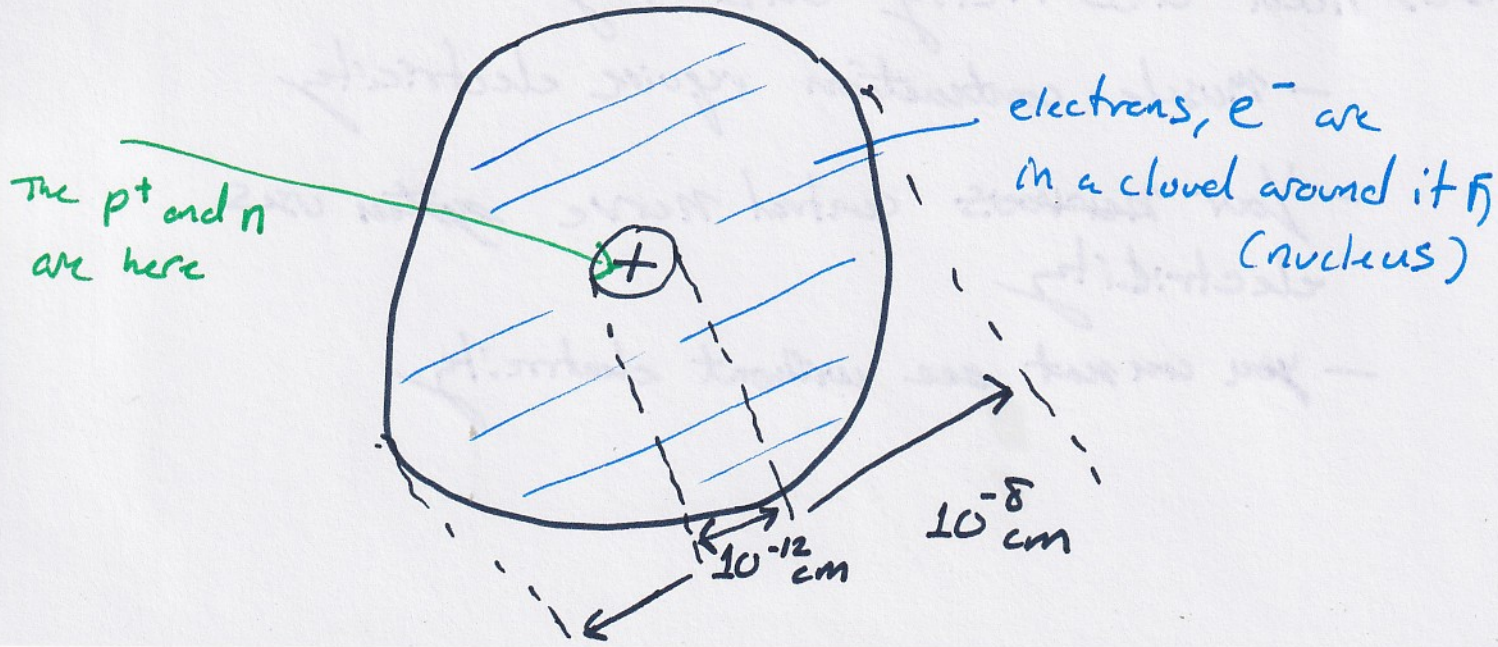
Modern Atom

- The nucleus of the atom is very small compared to the size of the atom.

Nucleus

- The nucleus has protons (p^+)
  - We write the '+' because the proton is positively charged
- The nucleus has neutrons (n)
  - Neutrons have no charge
- The mass of the proton is approximately the same as the mass of the ~~electrons~~ neutron

$$m_p \approx m_n \approx 1.7 \times 10^{-27}\ kg$$



If the atom is neutral, the number of electrons and the number of protons is the same.

- If you take off one e^-
  - you have a positive Ion
- If you add an e^-
  - you get a negative Ion

$$\left|\begin{matrix}\text{charge of} \\ \text{an } e^-\end{matrix}\right| = \left|\begin{matrix}\text{charge of} \\ a\ p^+\end{matrix}\right|$$

- neutral atoms have # of e^- = # of p^+

Mass of e^- → $m_e = 9.11 \times 10^{-31}$ kg

$$\approx 1830 \times m_e = m_p$$

- Generally, we consider m_e as negligible

Therefore, All of the Mass of an atom is in the nucleus

If you have 7 billion atoms lined up together adjacently, you get a length ≈ 70cm

(7 billion people on Earth)

Atom is 10,000 times larger than Nucleus

History of Electric Charge

In 600 BC, they knew if you rub amber, it can attract pieces of dry leaves.

- The Greek word for amber is 'electron'
  - That is where electricity got its name from.

Glass and sulfur also did this, we had these in the 16th century.

When bored at a party, women would rub their amber jewelry and touch frogs. The frogs would then jump!

- They though this was fun. They didn't know what was happening to the amber or frogs

In the 18th century, it was discovered there were two types of electricity

- One for rubbing glass
- Another for rubbing rubber or amber

Let's call one of them A, the other B.

- A repels A, B repels B
- A attracts B

Benjamin Franklin (didn't know about e^- or p^+)

- said all substances are penetrated w/ electric fluid, electric fire.
- He said if you have too much fire, you're positively charged
- If you have a deficiency of that fire, then you're negatively charged

Franklin Introduced the sign convention

- If you rub glass, you have an excess of fire He called it positive, (The glass rod is positively charged after being rubbed.)

If you can transfer electric fluid from a neutral object to another neutral object, the second object becomes positively charged and the first object becomes negatively charged.

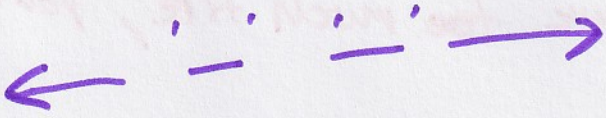
— According to Benjamin Franklin

That's the Big Idea behind The conservation of charge

- You cannot create charge

If you create positive charge, you create minus

positive charges repel



negative charges repel

positive / minus attract

→ The more fire you have, the stronger the force, closer they are, the stronger too!

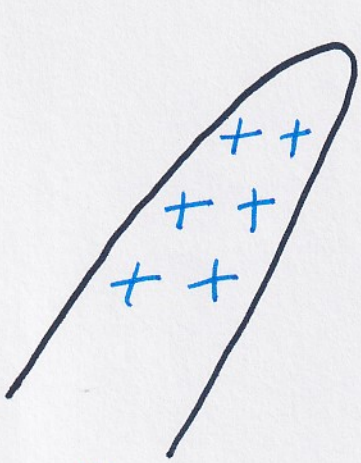
Franklin also noticed there are some substances that conduct this fluid, they are Conductors

If I have a glass rod, and rub it ~~with~~ with some silk, it will be positively charged.

Conductors (metals) have a small fraction of their e^-'s unbound to atoms and can freely move around in the conductor.

Non-Conductors all e^-'s are ~~feel~~ fixed to individual atoms

What happens when a charged rod is brought close to a conductor? *



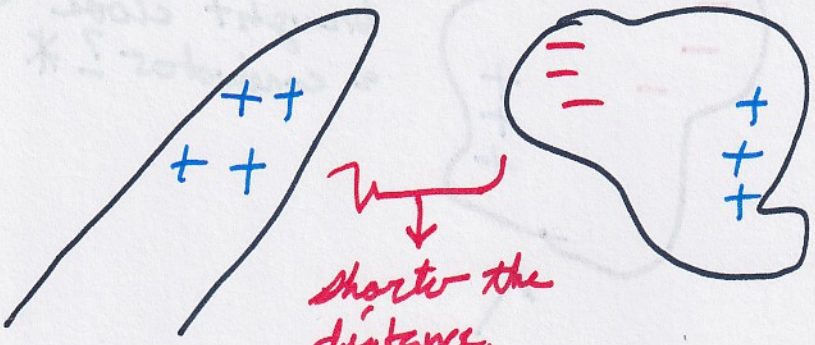
glass rod rubbed with silk

conductor

* plus and minus are attracted to each other!
- The e^-s will move around to get closer to the '+'
- The other parts of the conductor will lose some of those e^-s. → so those parts are '+' charged!

→ This is called Induction
- you get a polarization (division of charges)
- perhaps a $|10^{-13}|$ of charge is displaced, that's all it takes!

So what is happening to the Forces?
- There is an attraction force and a repelling force



shorter the distance, stronger the force

Franklin noticed this

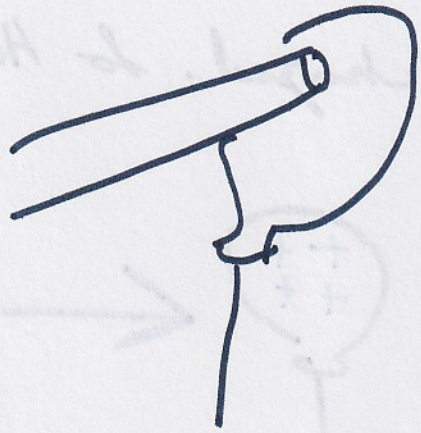
Demonstration with a Helium balloon

The balloon has a conductive surface

Rub the glass rod with silk rag, rod will become '+' charged! Bring the rod close to the ballon → what happens?

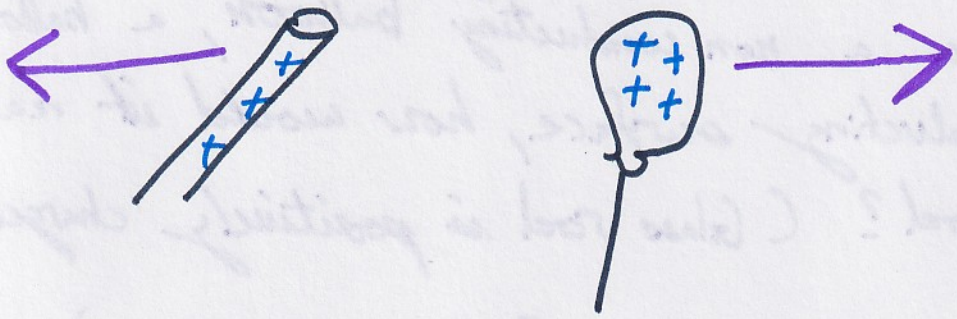
They are attracted to each other!

with a positively charged rod, rub the rod onto the balloon. What happens?



The balloon is now positively charged!

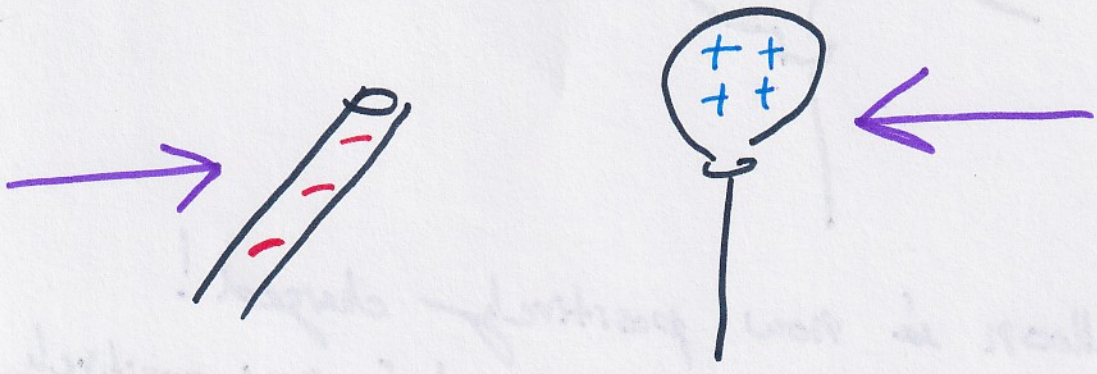
If you rub the rod again, the rod is now positively charged! What happens when you move the rod closer to the balloon?



They want to repel! The rod wont move because it's in your hand.

Two kinds of Electricity

If we rub a rubber rod with cat fur It becomes negatively charged. So How will the balloon react?



The balloon is attracted

Polarization

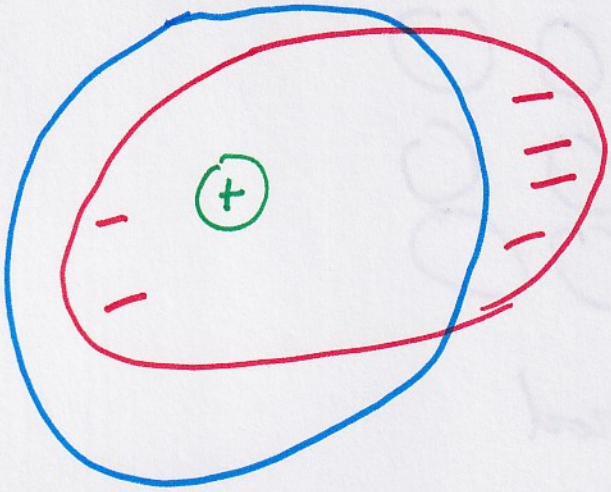
If we have a non conducting balloon, a balloon with a non conducting surface, how would it react to the glass rod? (Glass rod is positively charged)

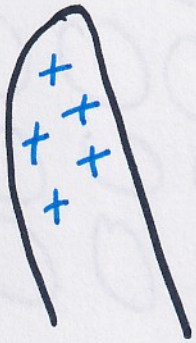
Do you get Induction? (polarization)

One may think 'No' But that's not the case!

At the Atomic scale, there is quite a bit going on.

you have a positive nucleus you have a cloud of e^-s





When you bring a glass rod (positively charged) nearby, the electrons are stuck to the atom, e^-s can't move freely as they could in conductors.

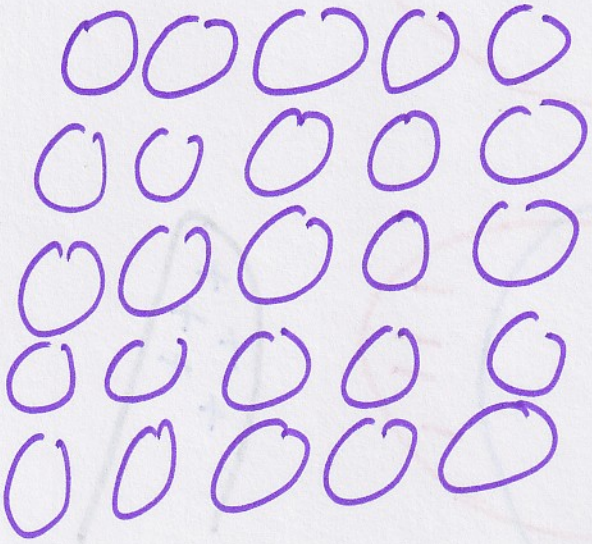
- A spherical atom will be deformed because the e^-s will spend more time closer to the glass rod ('+' charged)
- The nuclei is ~~repelled~~ repelled

Essentially, the atom itself is polarized.

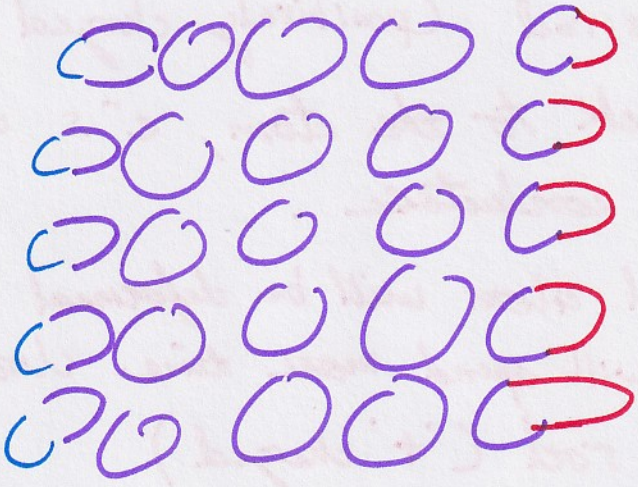
- The right side is more negative than the Left side (Induction)

A structure with compact-Adjacent Atoms behave this way too!

neutral atoms

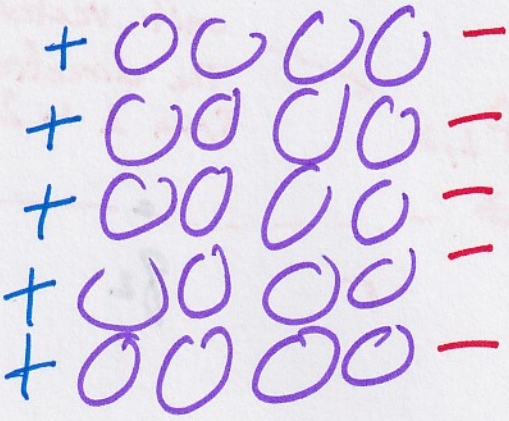


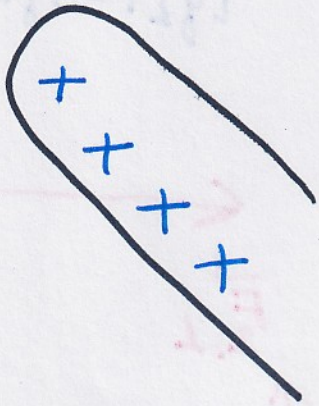
when we add a glass rod



we have polarized ~~this~~ this structure of atoms!

Effectively, we have created a negative Layer and a positive Layer





→ Induction!

Demonstration: Polarization of a non-conducting balloon

Demonstration: charged balloon stick to a blackboard

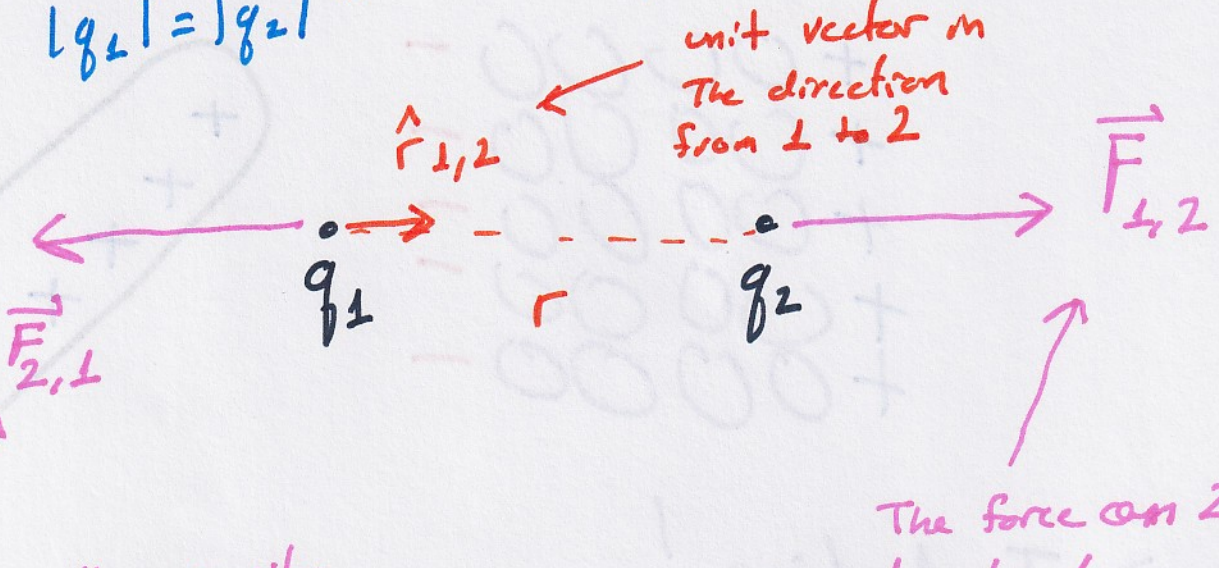
Demonstration: discharge lights up a neon flash tube

Demonstration: Confetti Vandegraaff

Electric Force

We have charges q_1, q_2. Same Polarity

$|q_1| = |q_2|$



We have the opposite Force. $\vec{F}_{2,1} = |\vec{F}_{1,2}|(-1)$

The force on 2 due to 1

Coulomb (French physicist) 19th, 18th century

Coulomb found the following relationship

→ The force is ~~twice~~ proportional to the product of the two charges multiplied by a constant!

$$\vec{F}_{1,2} = \frac{K q_1 q_2}{r^2} \hat{r}_{1,2}$$

The force is in the direction of the unit vector.

This is the force on charge 2 due to charge 1.

If the charges had opposite polarization, then

$$\vec{F}_{1,2} = -\frac{K q_1 q_2}{r^2} \hat{r}_{1,2} = \frac{K q_1 q_2}{r^2} \hat{r}_{2,1}$$

because, $q_1 q_2 = -|q_1||q_2|$

If both charges were negative, the minus signs would still cancel out.

SI units: we use Coulomb! as unit of charge

One Coulomb is a lot of charge.

- Usually see micro Coulombs

We may note that (magnitude)

$$q_{p+} = q_{e-} = 1.6 \times 10^{-19} \text{ C}$$

an electron will have -1.6×10^{-19} C

We have Coulomb's constant

$$K = 9 \times 10^9 \ \frac{N\text{-}m^2}{C^2}$$

We can derive the units of K from $\vec{F} = \frac{K q_1 q_2}{r^2} \hat{r}$

$$\rightarrow \frac{[?]C\text{-}C}{m^2} = Newtons$$

But No one thinks of K in this way

We think of it Like this

$$K = \frac{1}{4\pi \epsilon_0} = 9 \times 10^9$$

for historical purposes

ϵ_0 is the permittivity of free space

Notice, there's a parallel with gravity

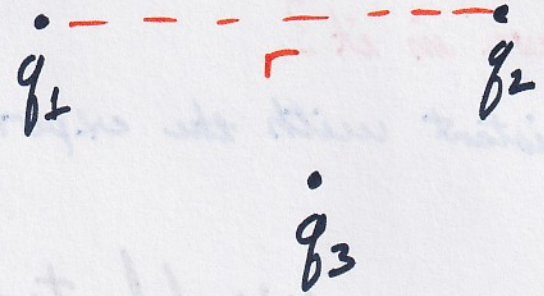
$$\vec{F} = G \frac{m_1 m_2}{r^2} \hat{r}$$

G is the gravitational constant

Newton's Law of gravity

The force of gravity is always attracting, gravity never repels.

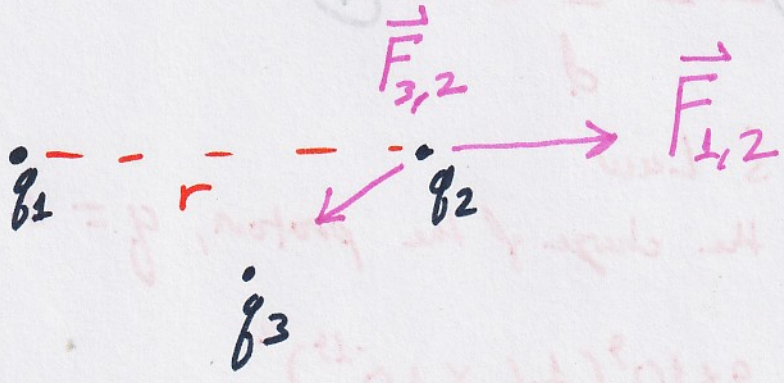
Say we have another charge q_3



If we want to know what is the force on q_2, we use the superposition principle.

→ The Net force on q_2 is due to the contribution of $\vec{F}_{1,2}$ and $\vec{F}_{3,2}$

Let $|q_1| = |q_2| = |q_3|$. Let q_1 and q_2 be positive and q_3 be negative.



Is it obvious that the superposition principle works?

— No. It's not at all obvious

But we believe in it.

Why do we believe in it?

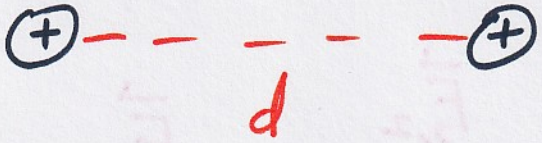
Because it's consistant with the experiments

So what holds our world together?

~~Electrical~~

Electric Forces are way more powerful than gravitational forces

Example 2 protons



Use Coulomb's Law

We have the charge of the proton, $q = 1.6 \times 10^{-19}\ C$

So $F_c = \dfrac{9\times10^{9}(1.6\times10^{-19})^{2}}{d^{2}}$

To get the Gravitational Force

Mass of proton → $m_p = 1.7 \times 10^{-27}$ kg

and $G = 6.7 \times 10^{-11} \frac{N-m^2}{kg^2}$

to

$$F_g = \frac{G m_1 m_2}{d^2} = \frac{(6.7 \times 10^{-11})(1.7 \times 10^{-27})^2}{d^2}$$

Notice that when we Look at the ratio

$$\frac{F_e}{F_g} \approx 10^{36}$$

→ The electric Force is 36 orders of Magnitude more potent than the gravitational attraction

What if These forces were the only forces acting on the protons? Lets say you get these protons and you bring them in an atom's nucleus. The nucleus has a size of 10^{-12} cm.

What's the ∉ acceleration the proton will experience?

Never forget $F = ma$

since we are inside the nucleus, $d = 10^{-12}\,cm = 10^{-14}\,m$

$$\rightarrow \frac{F_c}{m_p} = a_c = 1.35 \times 10^{27}\ \frac{m}{s^2} \qquad (F_c = 2.3\ N)$$

For comparison

$$\frac{F_g}{m_p} = a_g = 1.14 \times 10^{-9}\ \frac{m}{s^2} \qquad (F_g = 1.93 \times 10^{-36}\ N)$$

So what the Hell holds the nucleus together?
There are tremendous forces, so what keep it together?

Nuclear forces hold them together, and we do not fully understand them.

for the nuclear scale, 10^{-12} cm
— we have nuclear forces holding it together

from the atomic scale to (thru) thousands of kilometers
— Electric forces hold our world together

On a galactic scale (planets, stars, galaxy)
— The gravitational forces hold our world together

You may argue and complain that I just said F_e is 36 orders of magnitude larger than F_g in our comparisons of the forces concerning two protons.

Lucky for me, most objects are neutral or close to neutral. And it's unlikely Earth as a whole would have a charge of more than 10 Coulombs.

Example

Let's say the Earth has 10 Coulombs of charge and the Moon has -10 Coulombs. What is the ratio of Gravitational force to Electric force?

$$F_e = \frac{K(-10)(10)}{R^2}$$

Mass of Earth = 5.97×10^{24} Kg

Mass of Moon = 7.35×10^{22} Kg

$$F_g = \frac{G M_E M_m}{R^2}$$

$$\rightarrow \frac{F_g}{F_e} = \frac{G M_E M_m}{K(-10)(10)} = 3.26 \times 10^{25}$$

The Electric force is Negligible

$$F_e = 6.09 \times 10^{-6} \text{ N}$$

And the Gravitational Force is big League

$$F_g = 1.99 \times 10^{20} \text{ N}$$

The Gravitational Force is larger than the Electric force by orders of Magnitude 25.

Electric Forces hold our surrounding together.

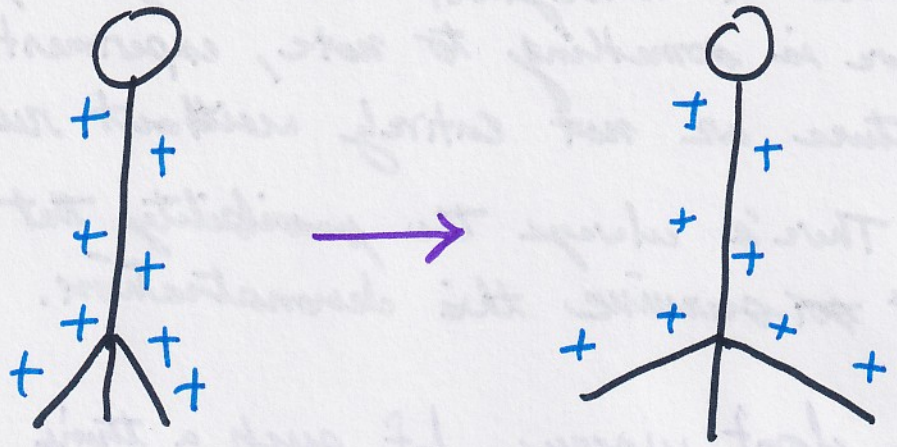
But on the galactic scale, we have Gravitational forces that hold our world together.

Electro Scope

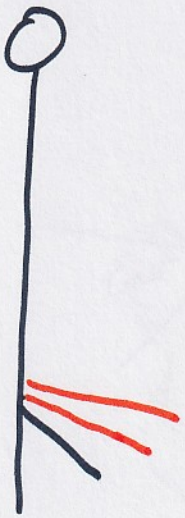
The electro Scope is a conducting rod, at the end is two pieces of tinsel (could be aluminum)

← we have a knob.

If we touch the knob with a charged object, then the electro scope will become charged.



The tinsel will be positively charged (for example) and thus will have a more acute angle with respect to the Electroscope.



The greater the angle of the tinsel leaf gives us an idea of the strength of the charge.

Demonstration: Human Electroscope

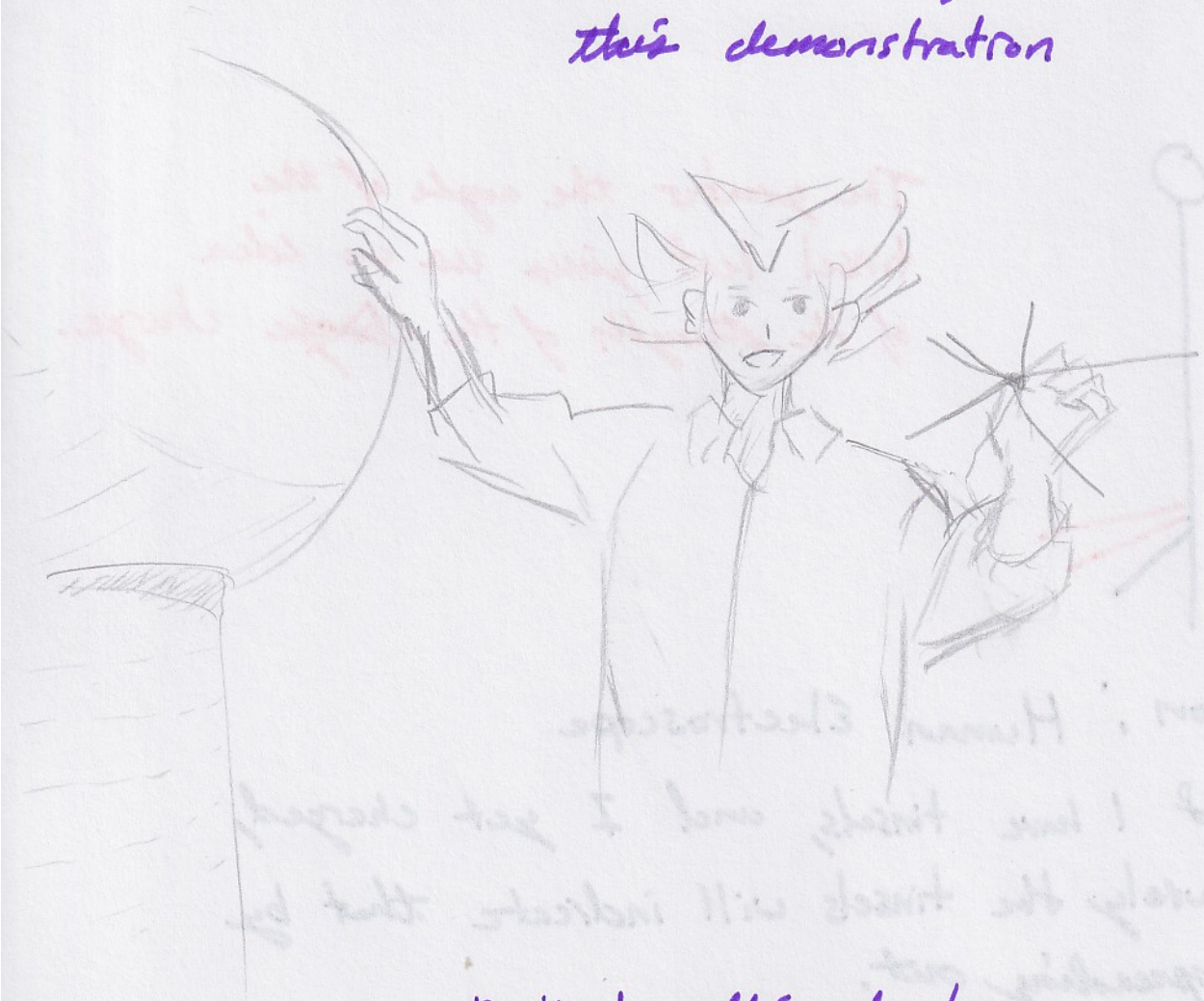
If I have tinsels, and I get charged, Surely the tinsels will indicate that by spreading out.

We can use a Vandegraaf to charge myself. But there is something to note, experiments of this nature are not entirely without risk

There's always the possibility that I won't ~~not~~ survive this demonstration.

– don't worry. If such a thing were to occur, you would get someone else to lecture you.

– But ~~that guy is not li~~ he's not likely to show this demonstration



Don't try this at home