Electric and Magnetic Fields

John C. Bean

Outline

Teaching "E & M" by memorizing equations vs. watching things happen

Our personal experiences with electric fields / The experiences of one British schoolmaster

Electric charge: Two canceling types, attractive to each other, repulsive to themselves

Electric Fields: An abstract way of mapping out the forces between electric charges

Magnetic Fields: Metal filing trails that are NOT force maps

How such non-force-maps can nevertheless explain the forces between magnets

Electro-Magnetism: How charges (driven by Electric Fields) can generate Magnetic Fields

The gravity-defying fall of magnets through non-magnetic metal pipes

Explained by Magnetic Induction = Propulsion of electrons by passing Magnetic Fields

=> Causing their Electro-Magnetism to create an opposing Magnetic Field

Explaining (eventually) metal recycling, maglev trains, electric generators, electric motors . . .

(Written / Revised: July 2019)

Electric and Magnetic Fields

In my introductory note sets, I raised two points:

1) To affect energy, you must study whole Energy SYSTEMS

Why? Because stand-alone technologies can have surprisingly little impact

The prime example? Solar Cells

Which still struggle to provide even 2% of U.S. power!

2) Study of Energy Systems requires a feel for Electricity & Magnetism

Why? Because electricity & magnetism often act in unexpectedly weird ways

Which can make seemingly simple things very **not** simple

Such as the efficient long distance transmission of electrical power

Which impedes adoption of many sustainable energy alternatives!

But what do I mean by "a feel" for electricity & magnetism?

Well, it will be useful to have basic answers to questions such as these:

What ARE Electric and Magnetic Fields?

How are they different (or similar)?

How and when they are created?

What sort of things does each act upon (or not act upon)?

Can they interact with one another?

What constitutes a basic answer? An intuitive sense for how these things work

Which is very different from a complete mathematical answer

(which is instead required to finally **engineer** an Energy System)

*But electricity & magnetism lessons are normally **built** upon mathematics*

Especially in physics classes

Further, those lessons generally START at the END of a very long story

Encapsulating more than a century of investigation in 4 + 1 (cryptic) equations:

Maxwell's Equations:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Where: E = The **Electric Field**

B = The **Magnetic Field**

ρ = Electrical charge / volume

J = The flow of that charge

The Lorentz Force Law:

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} + q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$$

Where: q = The charge on an object

v = That charge's velocity
(relative to the magnetic field)

WHY *do physics teachers teach "E & M" this way?!*

As an applied physics major, I came to suspect that the real reason might be:

TO MAKE US FEEL DUMB!

Because, not only were those equations anything but obvious,

but even after learning them, they could still be devilishly difficult to apply!

Further, I couldn't **imagine** how even the physics gods came to derive them!

But eventually (on my own), I learned that it took a **LOT of physics gods**

and a **LOT of time** (centuries!) to reach such a complete understanding [1]

Which made me feel less dumb but which also left me

feeling decidedly put out with some of my former professors!

1) A somewhat technical account of that history can be found HERE in Resources Webpage for this note set

WE NOW NEED INTUITION - Which is born from personal observation

As, in fact, Maxwell himself depended on a whole LOT of observation

done by a whole LOT of physicists (then called "natural philosophers")

taking whole LOT of time (mid 1700's to early 1900's for full understanding)

The early observations led to a confusingly disconnected set of "laws" & "theorems"

Gauss's Law	Faraday's Law	Lenz's Law
Ampere's Law	Kirchhoff's Law	Snell's Law
Joules's Law	Biot-Savart Law	Lorentz Force Law
Curie's Law	Superposition Theorem	Reciprocity Theorem
Coulomb's Theorem	Norton's Theorem	Thevenin's Theorem

. . .

Which, only after **long** analysis, were **finally** condensed into Maxwell's Equations

Leading to my novel (downright heretical) plan for this note set:

Let's forget about the final Maxwell Equations

Let's avoid the formality of the Lorentz Force Law

Let's slide by most of those subsidiary "laws" and "theorems"

Let's instead **look at the behavior of electric and magnetic fields**

Drawing on our personal experiences

Drawing upon videos I've found showing electric field behavior

Drawing upon videos **I've now created** showing magnet field behavior

Those observations alone can give us the intuition we now need

Further, our attempts at explaining observed behavior will take us along

the same path that led scientists to invent all of those weird laws!

THUS: What were **our** earliest personal experiences of **electricity**?

I recall these:

A shocking winter experience:

http://www.nachi.org/static-electricity.htm

Toddlers gone wild:

http://joyerickson.wordpress.com/2012/08/05/pull-up-something-cool/

The latter generally seen only for a toddler with freshly cleaned hair

because, somehow, clean fine (and thus light) hair seemed to be essential,

suggesting that **something** was just **barely** overcoming gravity!

These were much more likely if a lot of winter shuffling was involved

Suggesting that the act of shuffling was somehow **transforming** us

"Magic carpet spirits?" "Ancient Aliens?" [1]

However, if you watched REALLY closely, you occasionally saw something more:

One toddler started with **wildly** dancing hair

He/she touched a second toddler with normal hair

Resulting in two toddlers **both** now with **mildly** dancing hair

Suggesting that the first toddler had acquired **something** from the carpet

Which was then shared (and diluted) between the two toddlers

To figure out that **something**, there was a great historical tool: **Pith Balls**

1) To their everlasting shame (I hope!), "Ancient Aliens" is probably a "History Channel" trademark

What the heck are "Pith Balls?"

"Pith" was the name given to the dried stems of vascular plants

Which, due to both the drying and those veins, were exceptionally light

(The modern "pith ball" equivalent: Styrofoam covered by aluminum foil)

"Pith" was cut up into balls ~ 1 cm diameter

Which were hung from fine threads

Then, mirroring our carpet-shuffling experience:

If those balls were touched by glass rods rubbed on various types of fur,

the balls would suddenly dance around (as with the toddler's hair)

But going beyond the behavior of hair:

Individual balls could be touched with rods rubbed on different furs,

And they could be guided to touch one another,

And their resulting movement could be measured

Those "experiments" were first done in 1754:

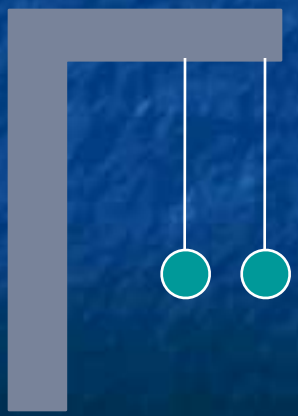
By a **British schoolmaster** named **John Canton**

His "apparatus" (which we now call a **Pith Ball Electroscope)**

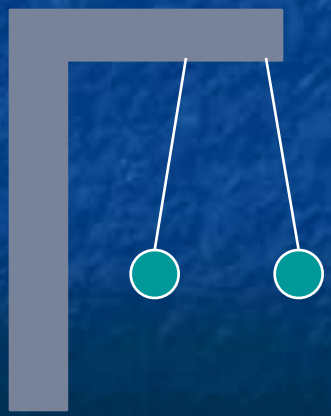
had two pith balls hanging side-by-side from threads

The basic experiment consisted of touching both balls with a glass rod rubbed on fur

BEFORE the pith balls were touched:



AFTER they'd been touched::



Which, as with our toddlers, suggested that:

The fur-rubbed glass rod gave SOMETHING to the pith balls

Which then caused them to repel one another

Canton then set about dissecting this "electric" behavior

By touching electrified balls with un-electrified balls

Or by electrifying balls differently via different rod/fur combinations

And then quantifing results by measuring the Pith Ball's swing

I'd hoped to now replicate Canton's Pith Ball experiments

But it turns out that they work well in only very dry cold conditions

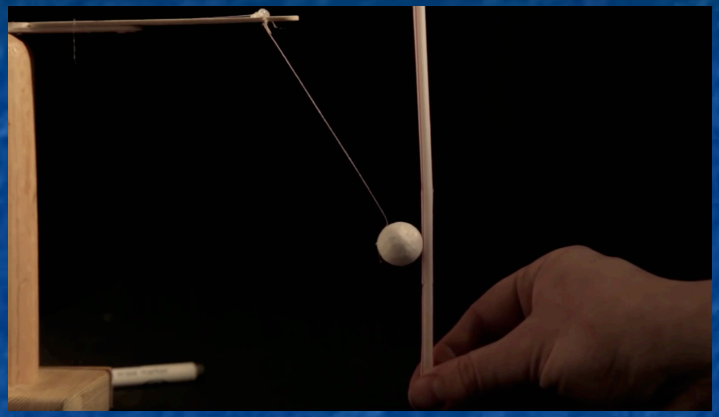
Conditions that are exceedingly hard to replicate in a lecture hall

(Or produce at all . . . at least here in central Virginia!)

In wetter conditions that **SOMETHING** almost immediately leaks away!

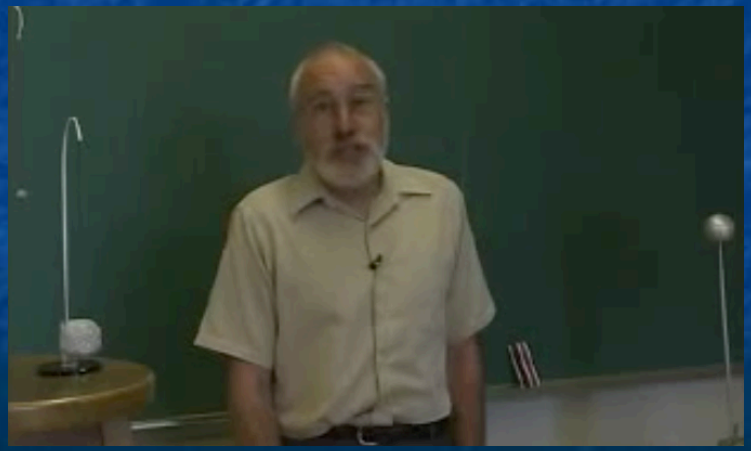
But to prove that it CAN be done, I offer you these YouTube videos:

From the Kahn Academy:



Or from Saint Mary's University:

Or from this gentleman (who notes the difficulty of performing such experiments!):



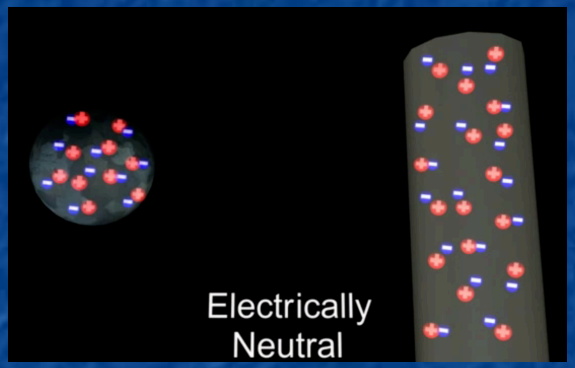
These YouTube videos can be found HERE on the Resources Webpage for this note set

Or a pair of our X-ray vision / virtual reality animations:

Explaining the subtle INNER WORKINGS of Pith Ball experiments we once witnessed:

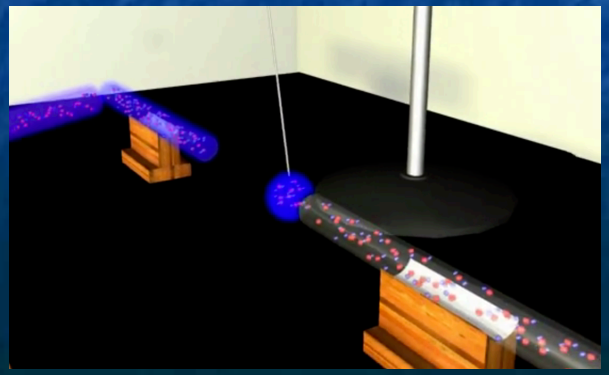
Snapshots from "Pith Ball Basics" (LINK to full X-ray vision animation):

Reality vs. Virtual Reality



Snapshots from "Pith Ball Ping Pong" (LINK to full X-ray vision animation):

Reality vs. Virtual Reality



I'm sorry that I couldn't film a full set of real "Pith Ball" experiments

But I will make it up to you when we turn to the topic of **magnetic fields**

Which turn out to be a whole lot easier to generate and manipulate

Which allowed me to create nine of my own experiments

And to post videos of them on this note set's Resources Webpage

For now:

With credibility added by those YouTube Pith Ball videos, in figures and words,

let me describe Pith Ball experiments that John Canton and his contemporaries

did (or might have done) to develop an understanding of **electric fields**

Proceeding (for now) in virtual reality:

Schoolmaster John Canton's basic experiment confirmed our "shuffling" experience:

Rubbing feet (or glass rods) on rugs (or fur)

captured something which, when shared between light hairs (or Pith Balls),

caused those hairs (or Pith Balls) to repel one another

But what was that SOMETHING? And was it in fact only ONE THING?

Canton certainly had different types of furs and cloth readily available

And it's very likely that he next tried using them *

* Note that I am not particularly concerned with Canton's **exact** experiments

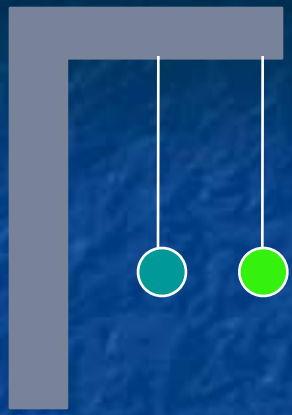
I'm instead trying to put myself (and you) into his shoes

and imagine what we (as scientists) might have done to FigureThisOut

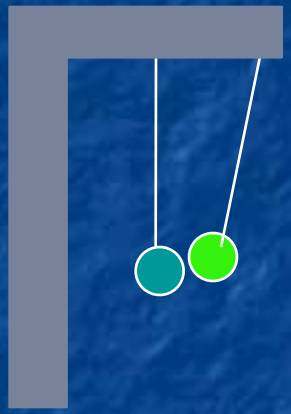
Repeating the experiment but rubbing the rod on different fur or cloth:

Start:

After touching the right ball:

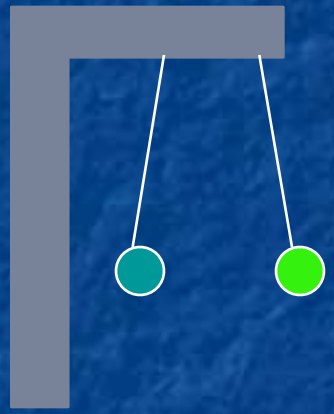


Momentarily push balls together (e.g. w/ glass rod):



Then remove rod

Result:



This SEEMS to be the SAME result:

The rod delivered **Something** that can be shared & repels parts of itself

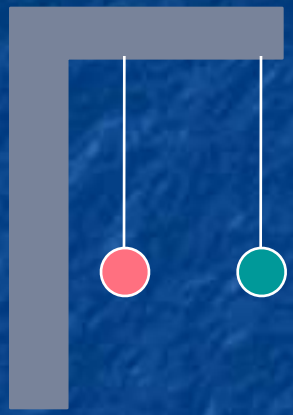
But is it the SAME thing or a NEW thing that acts similarly?

To test, treat each ball differently:

Touch each separated ball, with a DIFFERENT rod, rubbed on a DIFFERENT thing:

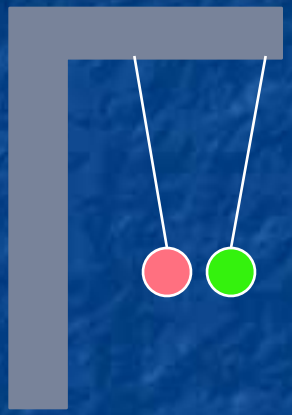
Touch ball 1 with rod 2:

Nothing!

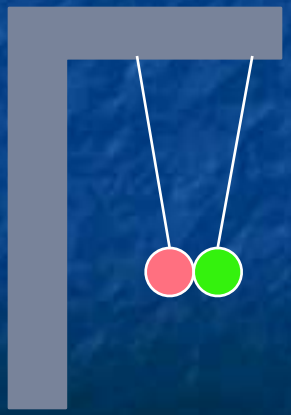


Then touch ball 2 with rod 1:

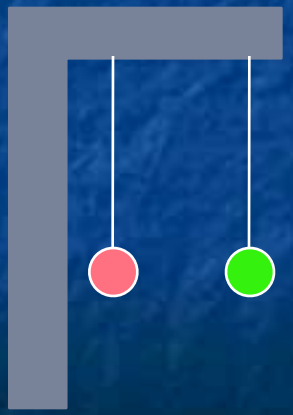
Attraction!



But if they actually touch:



The attraction is lost:



Whoops: We now seem to have TWO THINGS!

1) These two things ATTRACT each other

As opposed to the repulsion exhibited by parts of the same thing!

2) But if allowed to combine, they NEUTRALIZE / CANCEL one another

After considerable analysis and debate, "natural philosophers" concluded:

THING = "ELECTRICAL CHARGE"

TWO VARIETIES = "+" and "-" charge (so labeled because +'s cancel –'s)

"+ Charge" repels itself AND "- Charge" repels itself

BUT "+ Charge" attracts "- Charge"

But what about the observed forces?

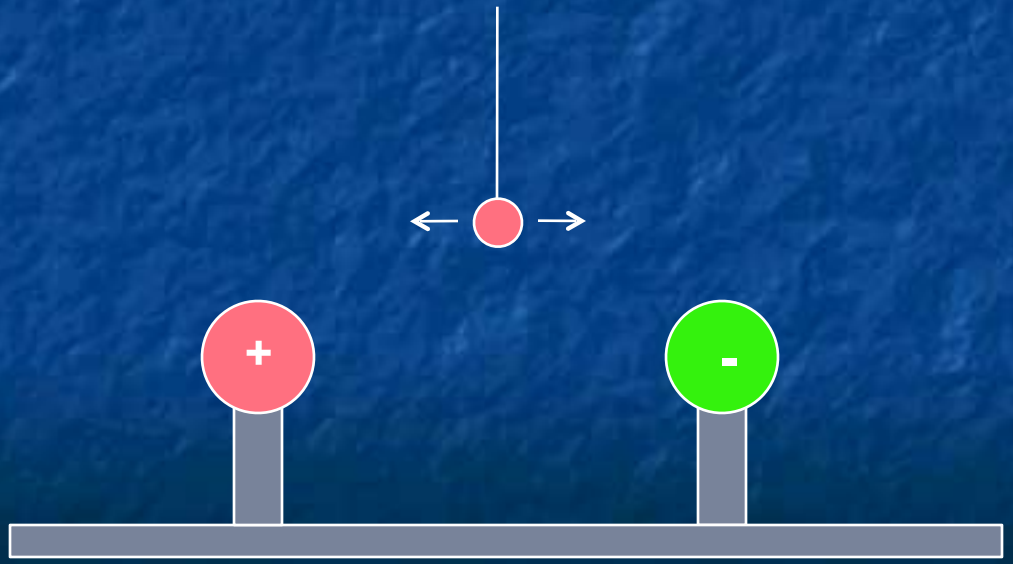
This WAS in same time period when Newton was formulating his Law of Gravity

So scientists of this era would have wanted to quantify/codify this new electric force:

Its direction AND magnitude AND dependence on + / - charges

They could have used two large fixed pith balls + 1 small hanging probe ball

Side view of two large balls mounted above a table PLUS a hanging probe ball:



Then charge up the balls:

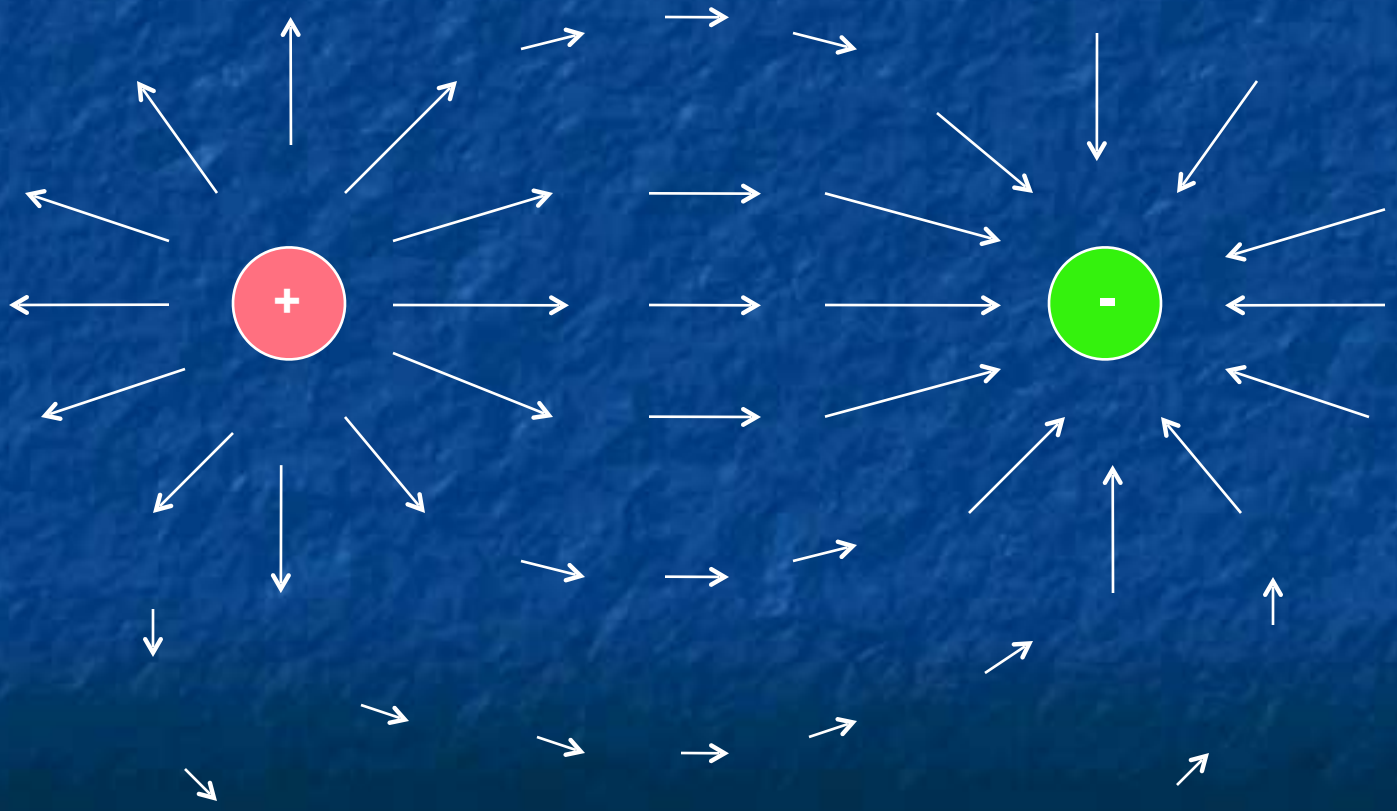
Probe Ball:	+ OR –
Left Large Ball:	+
Right Large Ball:	-

Looking from above, recording the probe ball's deflection:

Here with a probe ball having the same plus charge as the left fixed ball

Length of arrow = Amount of deflection/swing (proportional to force)

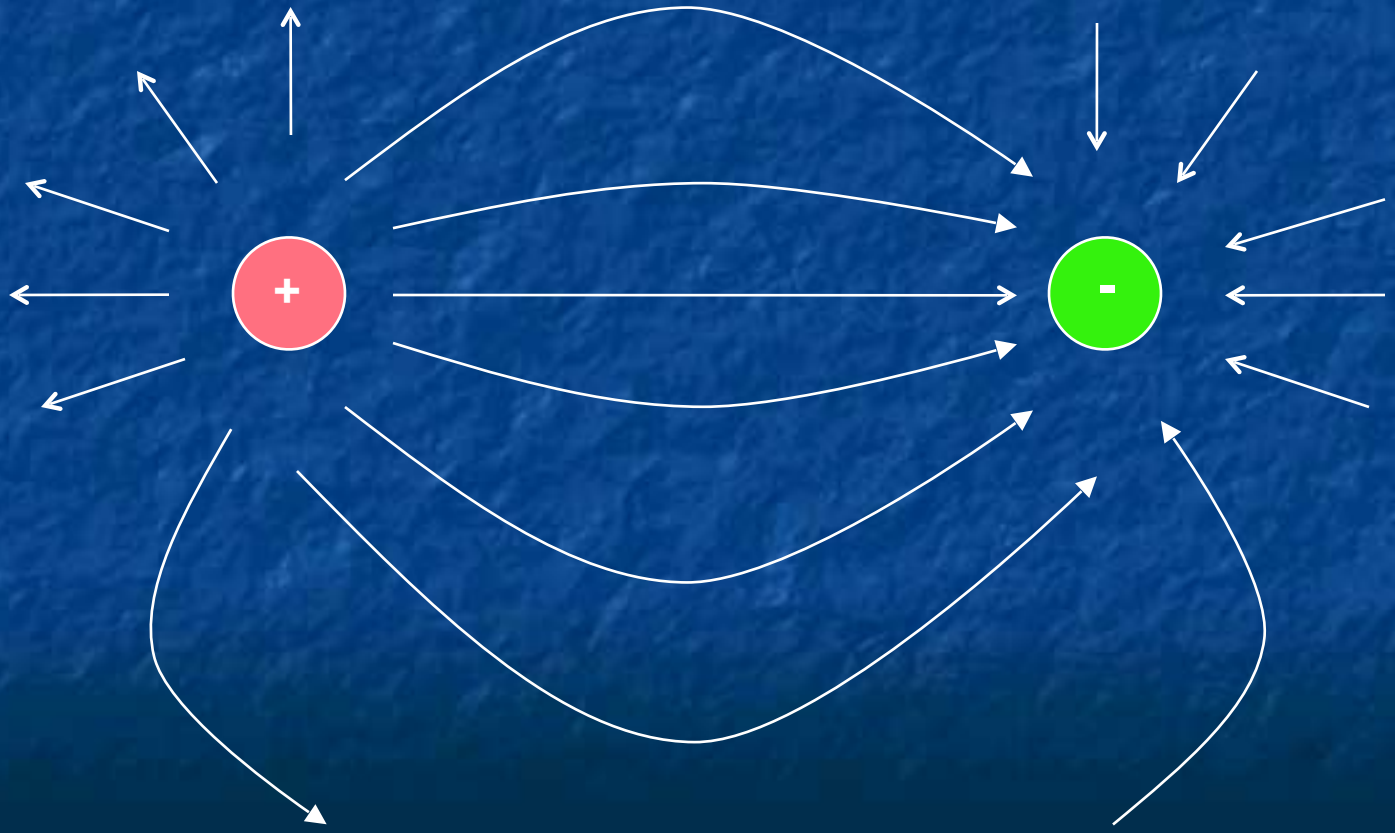
of the hanging probe ball, when it is at that position



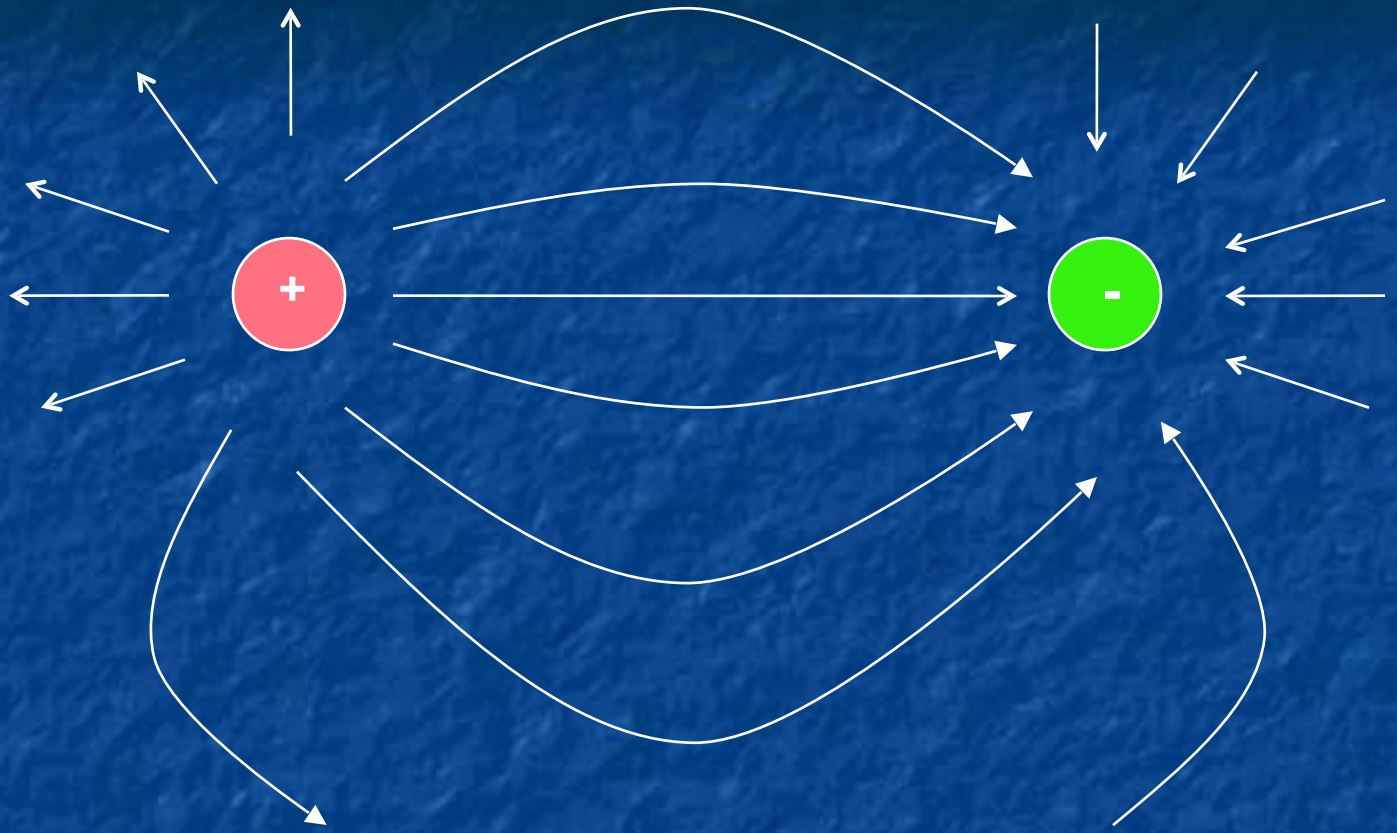
But it's MUCH easier to merge all of those arrows together:

This was as good as I could do with PowerPoint's clumsy built-in graphics:

(Toggle back an forth to preceding slide to see what I've done)



THIS, finally, is recognizable as the common map of an electric field:



The Direction of Force on a + Charge = The Direction of the arrows

But by merging arrows, I have lost information on the STRENGTH of the Force!

I can reclaim it by noticing that now: **Strength of Force** α **Spacing of arrows**

Stepping Back

We have observed that:

There is something called charge

Also now known as "static electricity" or "electrostatic charge"

Which comes in two flavors

Which we've named "plus" and "minus"

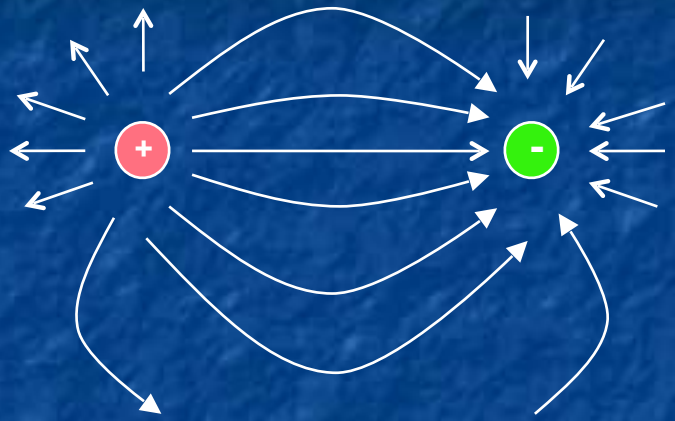
because, if they are allowed to combine, they cancel one another

Each type of charge repels charge of the same type

But attracts charge of the opposite type

Electric Fields = *How forces spread out BETWEEN charges*

For which we now use this shorthand representation:



Arrows give the DIRECTION of that force upon a + charge

Closeness of the lines gives the relative intensity of that force

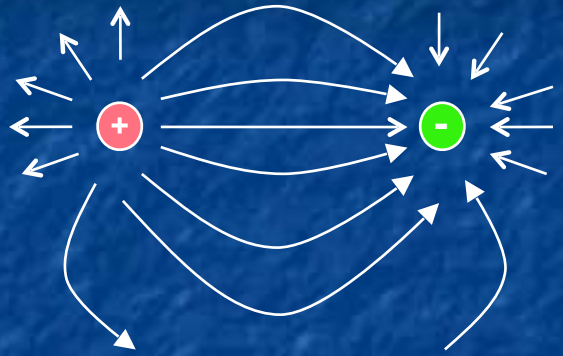
But this is ONLY a way of REPRESENTING that spreading inter-charge force!

That force is not really concentrated into lines

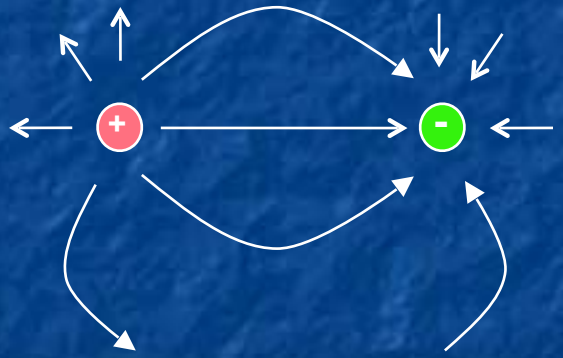
Nor does it fall to zero between those lines

The line spacing does not even (directly) give the strength of the force

In fact, these two diagrams could represent the **exact same situation**:



Or the easier / lazier version:



ONLY the arrow direction,

and the relative spacing of the arrows (across a single diagram) are significant!

Recapping our "basic answers" about Electric Fields:

What ARE Electric Fields?

Spreading force fields

How and when they are created?

By "plus" and "minus" charges

What sort of things do they act upon (and what is that action)?

The force repels charges of the same type

And attracts charges of the opposite type

With the direction of repulsion or attraction parallel to the lines in a field map

And the intensity of repulsion or attraction varying inversely as the line spacing

But to clear up some possible confusion, let's now board a time machine and come forward a century or so:

In 1897 J.J. Thompson discovers the **Electron**

which is identified as the primary source of – charge

In 1911 Ernest Rutherford discovers the **Proton**

which is identified as the primary source of + charge

Over the first third of the 1900's nuclear physics evolves, figuring out that:

Protons are almost always locked up in the nuclei of atoms

While Electrons (as "quantum mechanical" clouds) are outside the nuclei

and (for many atoms) they can be easily separated from those nuclei

=> Electrons are almost always the **only movable** "electric charge"

So it took TWO CENTURIES to fully figure out "simple" electric fields!!

Moving on to:

Magnetic Fields

The BAD NEWS: It's about to get decidedly weirder

The GOOD NEWS: I've created magnetic field demonstrations that DO work

A whole lot of them (nine!)

Which we can now use to FigureThisOut

A necessary logistical digression:

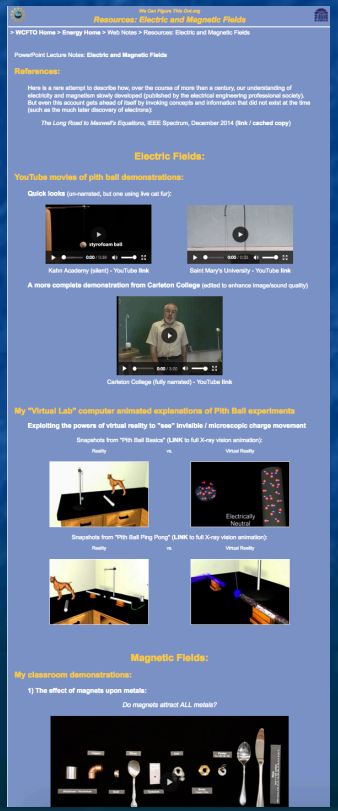
Videos CAN be embedded within PowerPoint files. They can also be called by PowerPoint files if they are at a known/fixed location on the same PC

But in my (painful) experience, both are great ways to lock up a personal computer

And even when things DO work, video files still require long prior downloading

I thus leave videos on my server where they can be streamed from html webpages

The nine video demonstrations we will now use to "figure out" magnetic fields are streamable from this note set's **Resources Webpage:**



That webpage is accessible via this LINK OR this QR code:

OR via this explicit URL:

https://wecanfigurethisout.org/ENERGY/Web_notes/Electricity/Electricity%20and%20Magnetism%20-%20Supporting.htm

Starting at the beginning: What IS a magnet?

A classic magnet consists of:

Iron, or alloys (mixtures) of iron, cobalt, nickel and "rare earth" elements

Which have been exposed to another, intense, already-existing magnet

But then where did our FIRST magnet come from?

Answer: The earth

But that answer only raises other questions, such as:

How did the **earth** become magnetic?

And, as a rather weak magnet, how could the earth
ultimately produce today's much stronger magnets?

The answer to both of those questions lies with the topic of **electro-magnetism**

Which we'll come to a bit later in this note set

For now, a simpler question: "What do magnets do?"

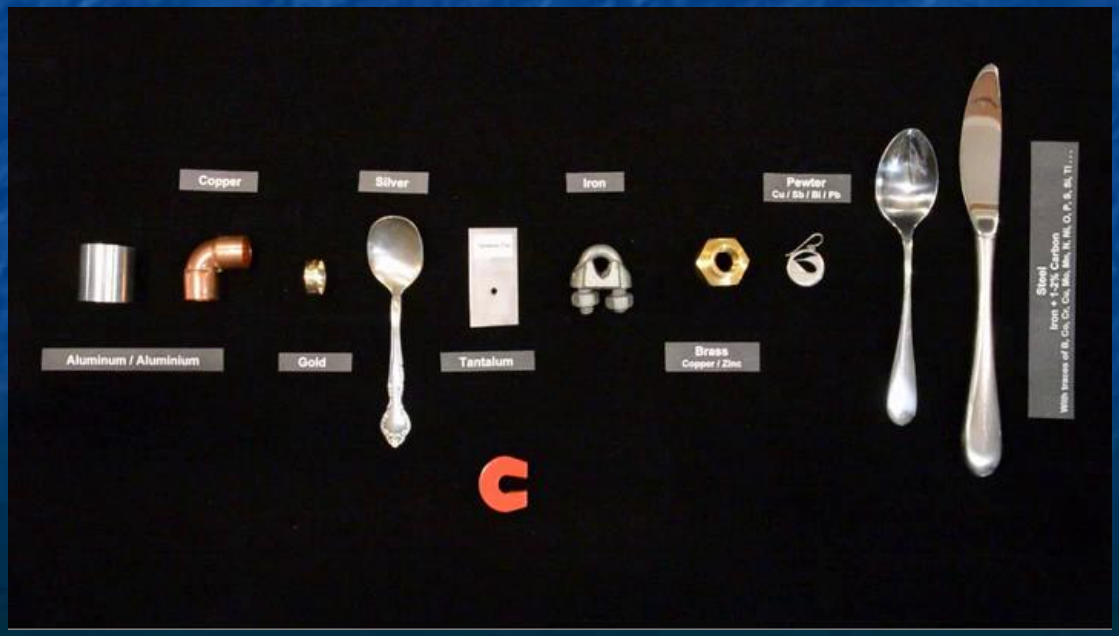
My students' response: **"They attract metals"**

My second question: **"Which metals?"** Typical response: **"Um . . . ALL metals"**

Let's test that via my first video demonstration / experiment

For which I scrounged different types of metals around my home and lab

Please now view demonstration #1 on the Resource Webpage:



Results of that experiment:

MY MAGNET ATTRACTED: Iron

and a piece of ~ 98% Iron + ~ 2% carbon + trace impurities (a "steel")

MY MAGNET DID NOT ATTRACT the elemental metals:

- Copper, aluminum, gold, silver, or tantalum

MY MAGNET DID NOT ATTRACT mixtures (alloys) of:

Copper and zinc (= brass),

Copper + Antimony + Bismuth (= pewter)

~ 98% Iron + ~ 2% carbon + DIFFERENT trace impurities (other "steels")

In fact, MAGNETS ATTRACT VERY FEW METALS, generally only:

- Iron and **some** iron mixtures (which is decidedly weird!)

- Nickel, cobalt, a few "rare earths," along with some mixtures of these

~ The same raw materials used for MAKING magnets!

"Houston, we have a problem!"

You **know** that recyclers use (electro) magnets to pull metal out of garbage:

Photo: http://www.bbc.co.uk/schools/gcsebitesize/science/triple_aqa/keeping_things_moving/the_motor_effect/revision/2/

But, I've just shown you that magnets attract only **iron and some steels**

Plus a few rare combinations of other metals

So how DO we recycle, for instance, aluminum?

Which we DO recycle, and very efficiently: 80-90%

Because recycling takes ~ 1/20 the energy of extracting new aluminum

(I promise to explain how this is done by the end of this note set)

Proceeding to some other "basic questions"

How do magnets act upon one another?

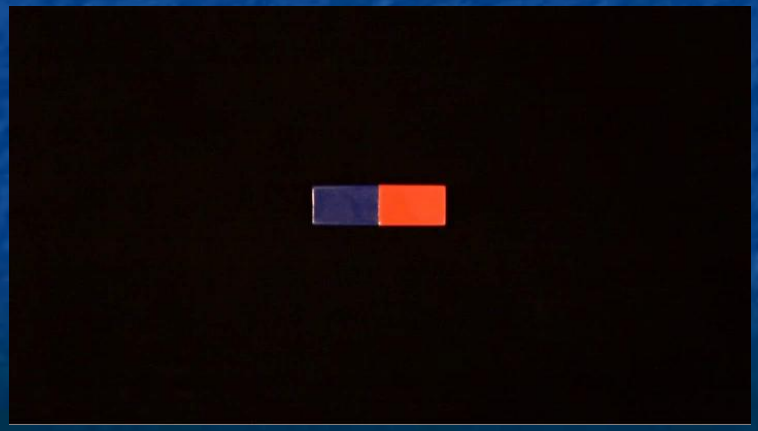
And from either that action

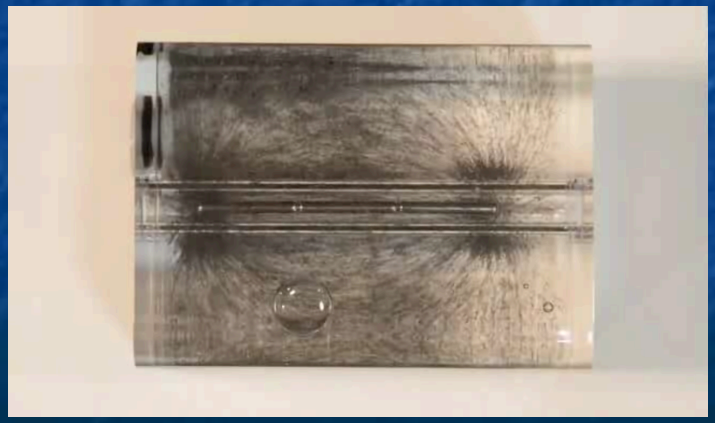
Or our knowledge of how magnets affect the metals they DO affect

Can we figure out:

What are Magnetic Fields?

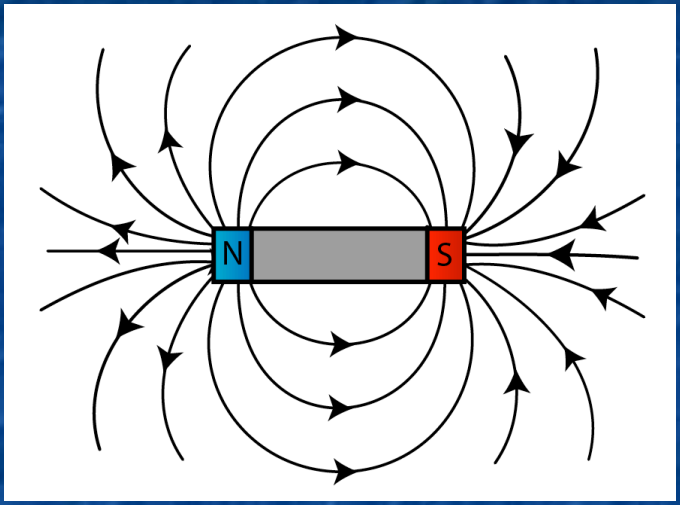
Please now view demonstration #2 on the Resource Webpage:





From experiment / demonstration #2:

The compass arrow and floating iron shavings suggested this pattern:



http://spmphysics.onlinetuition.com.my/2008/06/introduction-to-magnetism-revision.html

Our earlier **Electric Field** pattern mapped out the Electric Force upon charges

So this new pattern might map out the Magnetic Force upon something

But while the iron shavings condensed along such lines

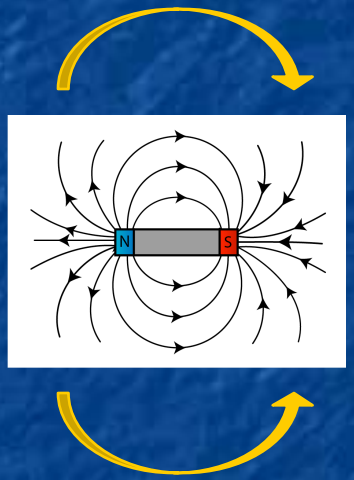
They then flowed **both** directions along the lines!

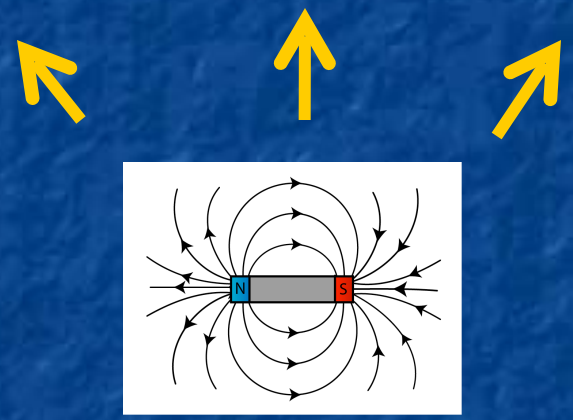
(toward whichever magnet end that was **closest** to them)

*Could the arrows instead map Magnetic Force upon other **magnets?***

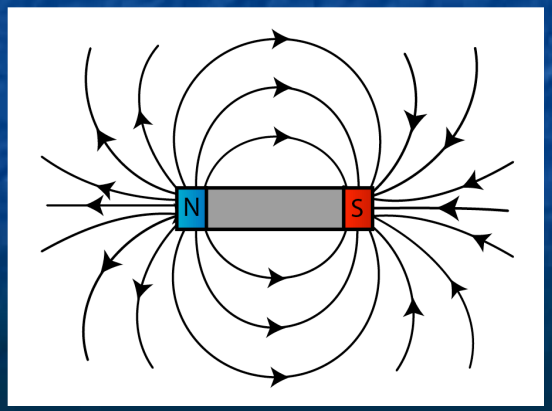
No, that wasn't what we saw when we played with the pair of magnets

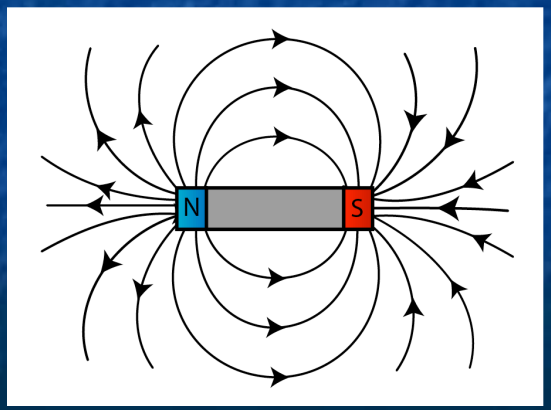
The second magnet instead twirled around and/or danced off to right or left



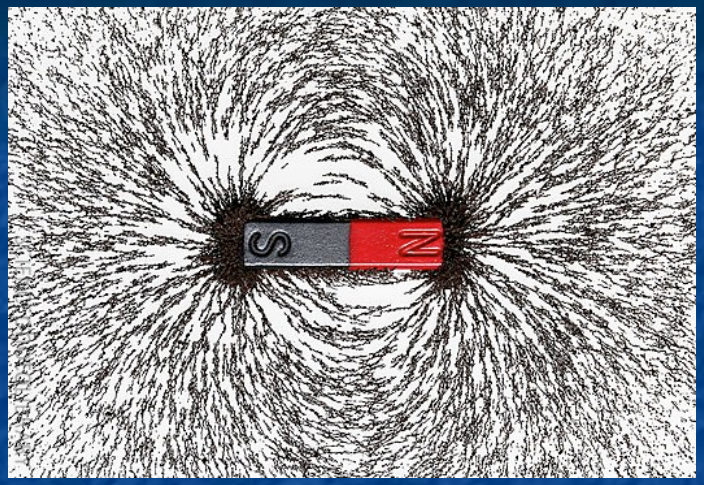


AND / OR:





So whatever this was trying to show us:



http://www.magnetyze.com/page/magnetic-fields.aspx

It was NOT a simple force field map, such as that for Electric Fields

Where arrows gave the force's direction, and spacing gave the force's intensity

But an alternative set of rules CAN account for MAGNET MOVEMENT:

- Parallel "magnetic field lines" repel each other

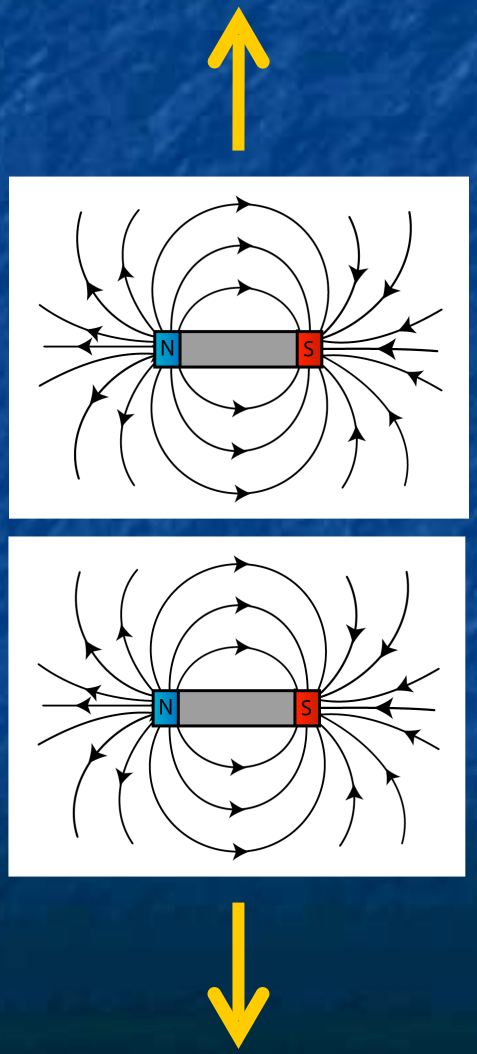
- Anti-Parallel "magnetic field lines" attract each other

- The closer the lines are, the stronger the above effects

Showing how those rules explain the magnets' movements:

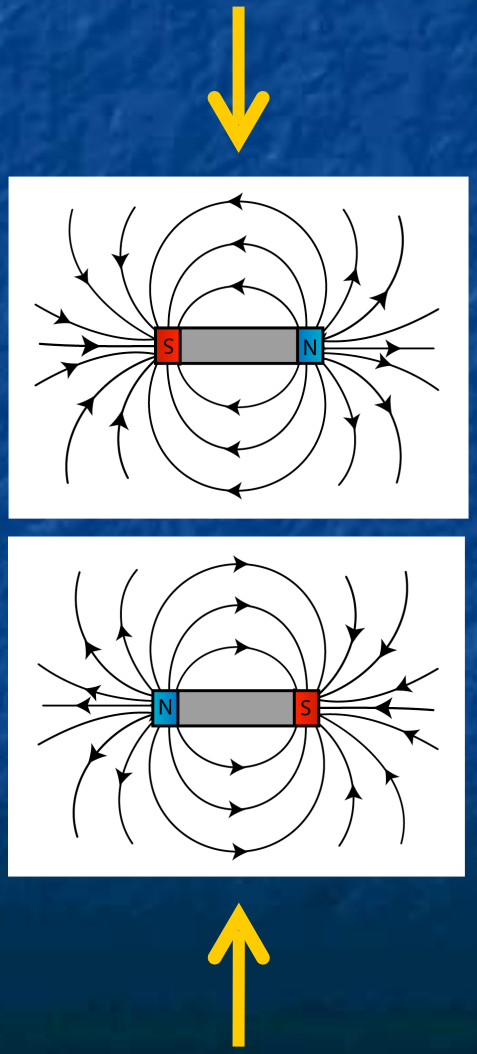
Pushing parallel magnets together:

Parallel lines => Repulsion



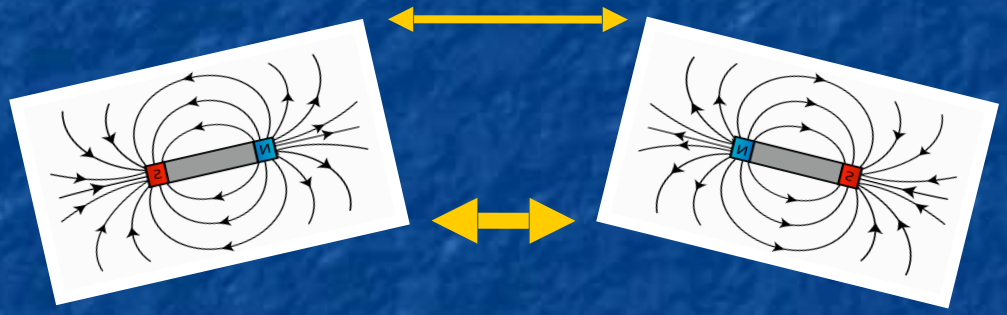
Pushing anti-parallel magnets together:

Anti-parallel lines => Attraction



Or if pushed together while not perfectly aligned

Lower Magnetic Lines are being pushed together more tightly => Stronger repulsion



Producing (if released simultaneously), two magnets spinning away from each other:

But this is a class/website about ***Sustainable Energy Systems***

The **"electricity"** of such Energy Systems

consists of **charge** being pushed along by the **force** of an **Electric Field**

Which makes our earlier observations of electric fields EXTREMELY RELEVANT

But Energy Systems make no comparable use of magnetism

Because we know of no practical way of transporting energy

by pushing **magnets** along under the force of **Magnetic Fields**

Which makes our observation of magnet movement ABSOLUTELY IRRELEVANT!

However, "natural scientists" observed **two more strange phenomena**

That not only restored magnetism's **RELEVANCE** to electrical power systems,

they made magnetism the absolute **BASIS** of electrical power systems!

The first was discovered by Danish professor ***Hans Christian Ørsted***

Who, on 21 April 1820, was preparing a classroom lecture demonstration about

Allessandro Volta's then recent invention of the "galvanic battery"

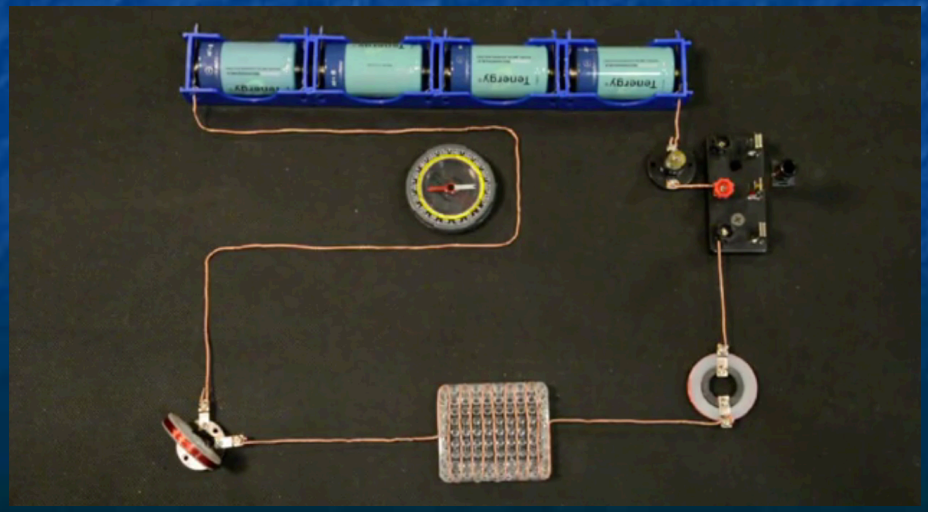
When he connected that battery to a long wire,

by shear chance he happened to notice the deflection a of a nearby compass

His report of this caught the attention of French scientist **André-Marie Ampère**,

who ultimately explained what we now call **electro-magnetism**

Please now view demonstration #3 on the Resource Webpage:



Did some of those names sound a bit familiar?

They should because (ultimately):

The unit of electrical energy, the **Volt**, was named for Allessandro Volta

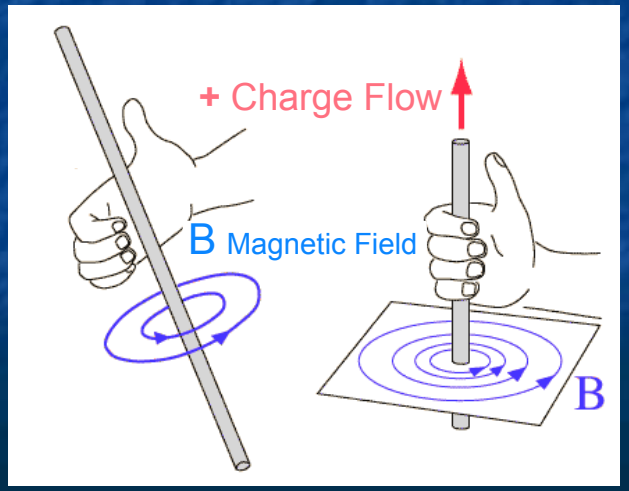
The unit of charge flow, the **Ampere**, was named for André-Marie Ampère

A unit of Magnetic Field, the **Oersted**, was named for Hans Christian Ørsted

Their combined discoveries uncovered the phenomenon of **ELECTRO-MAGNETISM**

= Charge flow in a wire producing magnetic field loops around that wire

Generally now depicted via a **Right Hand Rule**:



Also represented in my membership pin from the international Institute of Electrical and Electronic Engineers (IEEE):

But this was all done in the early/mid 1800's

Well before the discovery of negative movable electrons and positive nuclear protons

Ampere didn't know what the charges were, and assumed both types could move

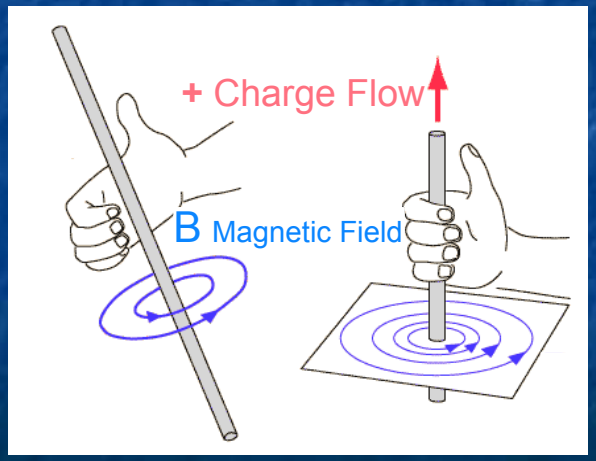
And he thus chose to state his rule in terms of moving **positive** charge

The magnetic field of moving **negative** charge loops in the **opposite** direction

But I find it easier to think of this as two separate rules:

Right Hand Rule for **moving + charge**

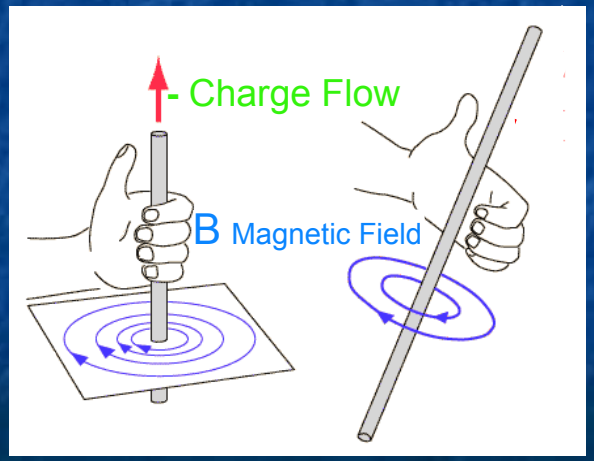
(which, in fact, almost never moves!):



Thumb in direction of **+ charge** flow,
Magnetic field is along curled right fingers

Left Hand Rule for **moving – charge**

(which we now call "electricity"):

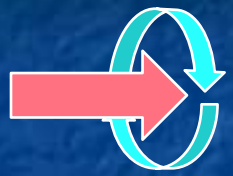


Thumb in direction of **- charge** flow.
Magnetic field is along curled left fingers

In the end, you can often actually ignore the charge's sign:

Because, while + and – moving charges produce reversed magnetic loops:

Moving minus charge: 

Moving positive charge: 

Electric fields push + and – charges in the opposite direction:

Electric field (e.g., along a wire) 

Resulting force on charges: 

Thus in a wire (if both types of charges could move), the net result would be:

Magnetic loops are in the SAME direction + net charge flow is in the SAME direction

=> Continued sloppy discussion of "electrical current" as "positive charge flow"

Electro-magnetism provides a second way of creating magnetic fields

It also provides the source of nearly all of our **permanent magnets** because:

Permanent magnets induced by Earth's magnetic field are ~ uselessly weak

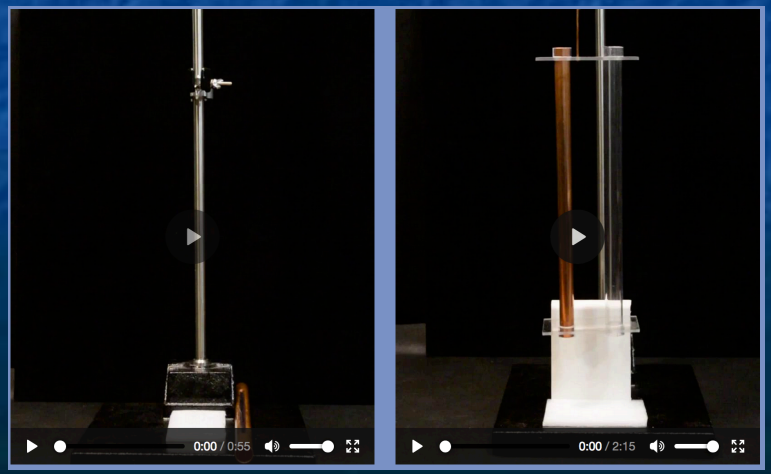
But electro-magnets can be powered up to be immensely stronger

Allowing us to lock much strong magnetic fields into things like iron

But didn't we conclude that magnets (of any type / strength)
were IRRELEVANT to Electrical Power Systems?

Yes. We need one more discovery: **Magnetic Induction**

Please now view demonstrations #3 & #5 on the Resource Webpage:



OK, but how does this defiance of gravity make magnetism relevant?

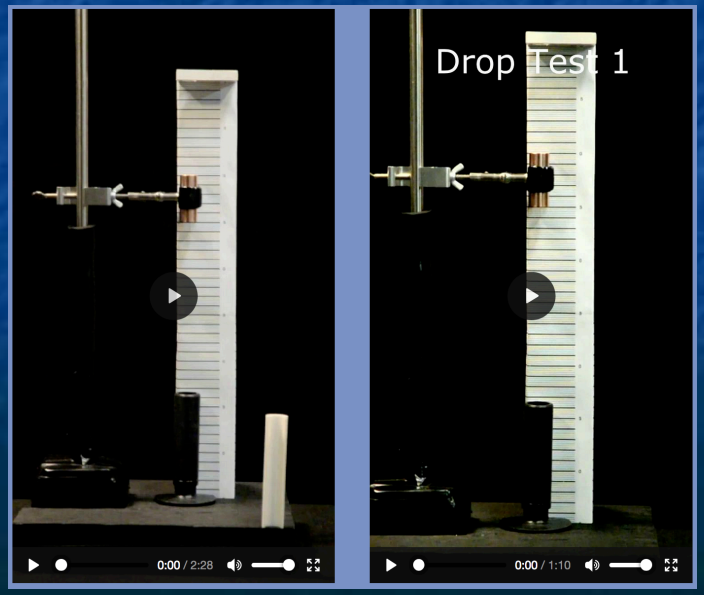
For that, we have to figure out what is CAUSING **magnetic induction**

Which will also explain why it's even called "magnetic induction"

But we have now gotten to the **extreme weirdness** I promised for magnetism

And this explanation is going to require some rather subtle new observations!

Please now view demonstrations #6 & #7 on the Resource Webpage:



Those magnets (partially) resisted the force of gravity

But it now looks like magnet ENDS resist most strongly!

However, the entire fall occurs in a very short (~ 2 second) time span

Could our eyes be fooling with us? To Check:

Those movies were shot in 60 frame (picture) per second QuickTime video format

(The original QT format videos are downloadable from the Resources Webpage)

Right-clicking time in QuickTime player displays the frame number

That frame number, along with the ruler I'd mounted behind the magnet,

allowed me record the magnet's frame-by-frame fall distance

Which converted to distance vs. time using the frame time spacing of 1/60 sec

For each test, I entered fall distance vs. frame and time into an Excel spreadsheet

(Also downloadable from this note set's Resource Webpage)

The "Drop Test #1" part of that spreadsheet:

Drop data | Velocity vs. Time | Acceleration vs. time

DROP TEST 1		V(n+1/2)=[(X(n+1)-Xn]/[T(n+1)-Tn]					A(n+1)=[V(n+3/2)-V(n+1/2)]/[X(n+3/2)-X(n+1/2)]	
Movie Frame Duration =		0.0167	(1/60 sec)					
	FRAMEn	Tn (s)	Xn (cm)	Xn+1/2	Tn+1/2	Vn+1/2 (cm/s)	Tn+1	An+1 (cm/s^2)
	592	0.0000	0.00	0.1	0.01	12	0.02	0
	593	0.0167	0.20	0.3	0.03	12	0.03	1440
	594	0.0333	0.40	0.7	0.04	36	0.05	360
	595	0.0500	1.00	1.4	0.06	42	0.07	720
	596	0.0667	1.70	2.2	0.08	54	0.08	360
	597	0.0833	2.60	3.1	0.09	60	0.10	-720
Lead End In (x=4)	598	0.1000	3.60	4.0	0.11	48	0.12	-720
	599	0.1167	4.40	4.7	0.13	36	0.13	-720
	600	0.1333	5.00	5.2	0.14	24	0.15	0
	601	0.1500	5.40	5.6	0.16	24	0.17	360
	602	0.1667	5.80	6.1	0.18	30	0.18	-360
	603	0.1833	6.30	6.5	0.19	24	0.20	360
	604	0.2000	6.70	7.0	0.21	30	0.22	-720
	605	0.2167	7.20	7.4	0.23	18	0.23	360
	606	0.2333	7.50	7.7	0.24	24	0.25	0
	607	0.2500	7.90	8.1	0.26	24	0.27	0
	608	0.2667	8.30	8.5	0.28	24	0.28	0
	609	0.2833	8.70	8.9	0.29	24	0.30	1080
Lead End Out (x=9)	610	0.3000	9.10	9.5	0.31	42	0.32	1080
	611	0.3167	9.80	10.3	0.33	60	0.33	720
	612	0.3333	10.80	11.4	0.34	72	0.35	720
	613	0.3500	12.00	12.7	0.36	84	0.37	360
Trail End in (x=14)	614	0.3667	13.40	14.2	0.38	90	0.38	-1800
	615	0.3833	14.90	15.4	0.39	60	0.40	-720
	616	0.4000	15.90	16.3	0.41	48	0.42	-720
	617	0.4167	16.70	17.0	0.43	36	0.43	-900
	618	0.4333	17.30	17.5	0.44	21	0.45	360
	619	0.4500	17.65	17.9	0.46	27	0.47	-540
	620	0.4667	18.10	18.3	0.48	18	0.48	1080
	621	0.4833	18.40	18.7	0.49	36	0.50	-720
Trail End Out (x=19)	622	0.5000	19.00	19.2	0.51	24	0.52	1080
	623	0.5167	19.40	19.8	0.53	42	0.53	1440
	624	0.5333	20.10	20.7	0.54	66	0.55	360
	625	0.5500	21.20	21.8	0.56	72	0.57	1080
	626	0.5667	22.40	23.2	0.58	90	0.58	1080
	627	0.5833	23.90	24.8	0.59	108		
	628	0.6000	25.70					

Where **velocity** & **acceleration** came from Newton's: $v = dx/dt$, $a = dv/dt$

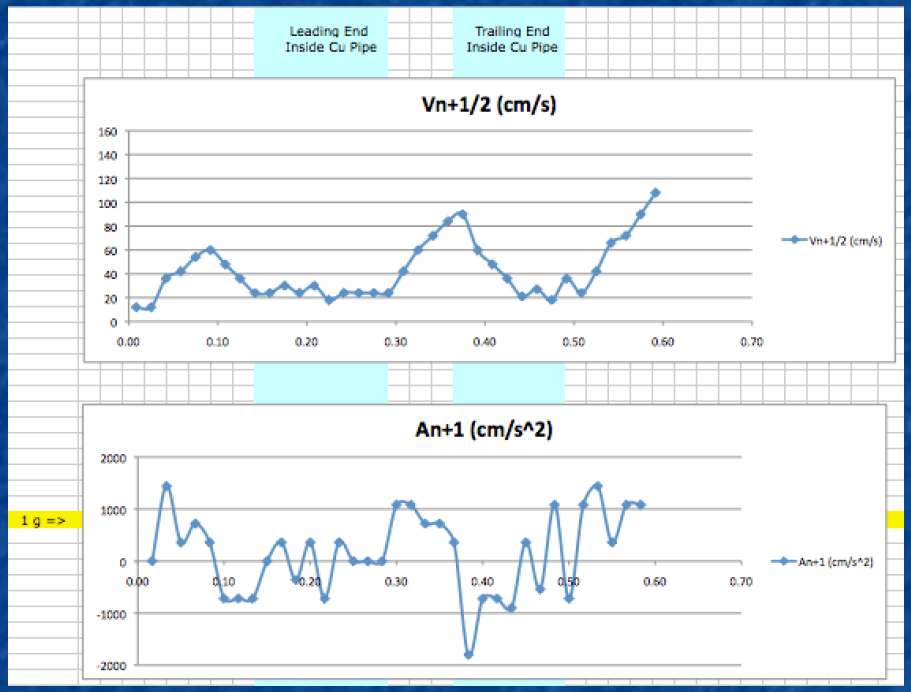
by means of "finite difference" differentiation: $dY/dx \sim \Delta Y/\Delta x$

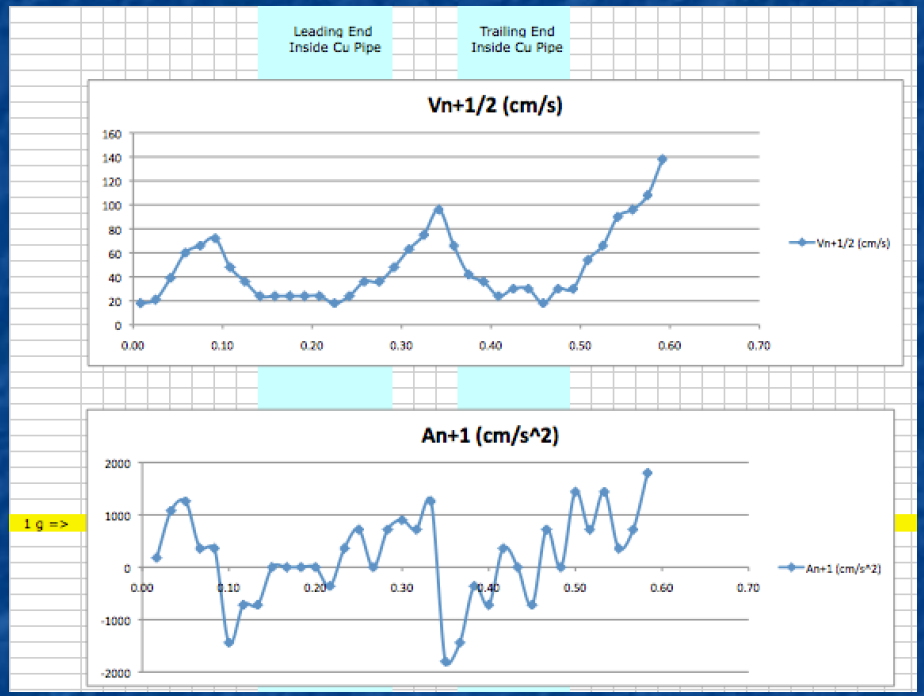
(see the formulae at the top and/or check the cell definitions)

Spreadsheet plots of Drop Test #1 (left) and Drop Test #2 (right):

Left blue band = Only leading edge of the magnet is inside the short copper pipe

Right blue band = Only trailing edge of the magnet is inside the short copper pipe





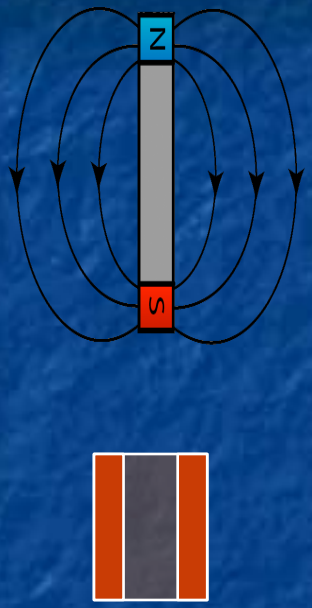
VELOCITY rises steadily UNTIL an end of the magnet enters/approaches the pipe

ACCELERATION rises back to ~ 1000 cm/s^2 (1 g) when NEITHER end is inside pipe

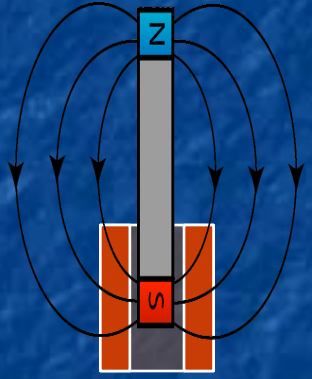
The magnet's fall IS inhibited by its ENDS sweeping through the pipe!

That sequence shown in diagrams:

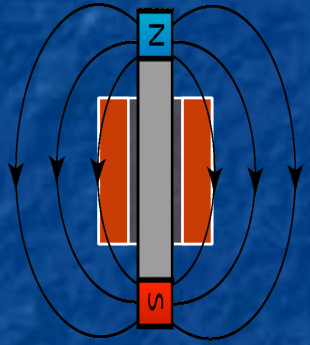
Freefall:



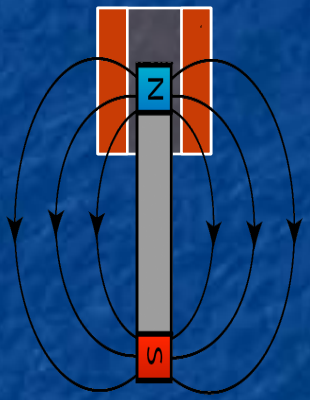
Braking:



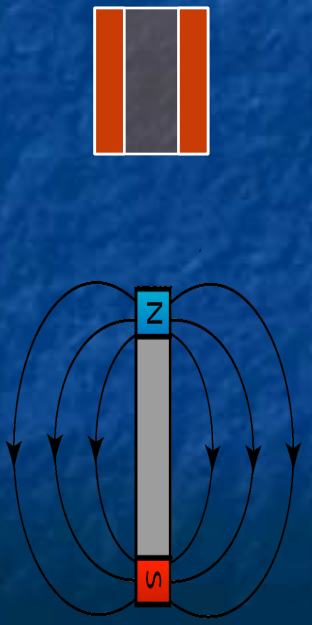
Freefall:



Braking:

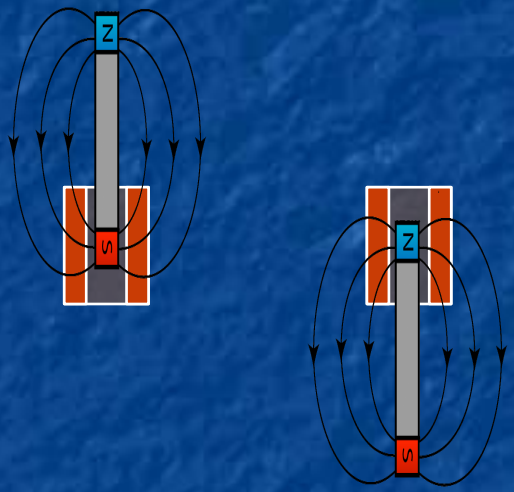


Freefall:

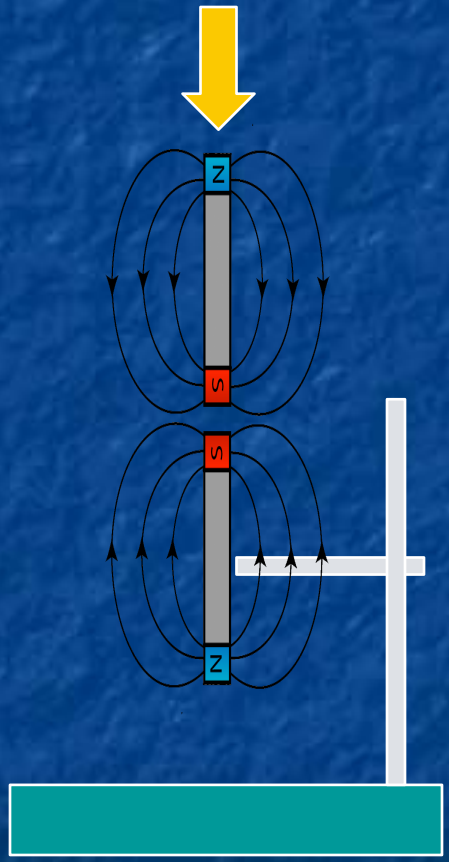


Why do only configurations at left slow the magnet's fall?

With ends inside pipe:



What if the pipe mimicked a flipped magnet?



With parallel Magnetic Lines compressing together

THIS would CERTAINLY slow the top magnet's fall!

But how could a non-magnetic pipe suddenly behave like a magnet?!

If it suddenly became an ELECTRO-MAGNET!

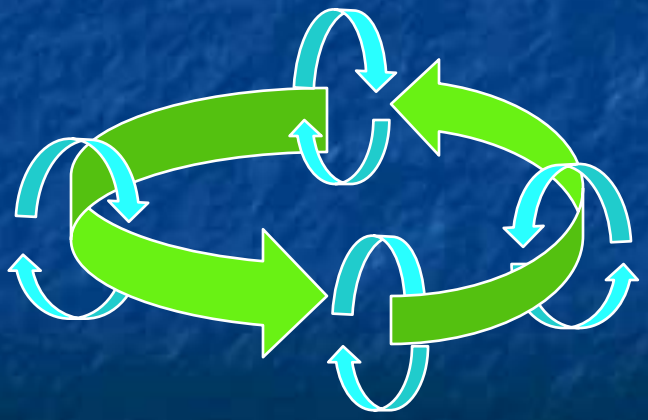
That is, if the metallic copper atoms' movable valence electrons

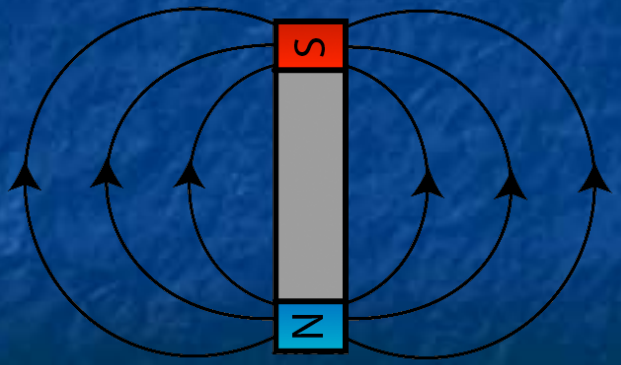
suddenly decided to run around in circles which,

based on my earlier right hand (actually left for electrons) rule,

those circles would be surrounded by loops of magnetic field:

Which would mimic the magnetic field of this:



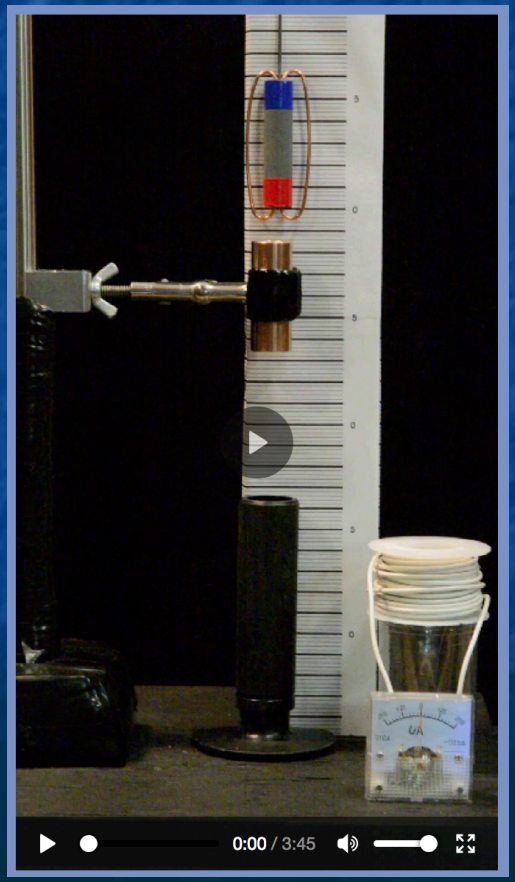


Evidence for such an implausible occurrence?

Replace the copper pipe by a spiral of copper wire

The induced flow of charge within that wire can then be measured

Please now view demonstration #8 on the Resource Webpage:

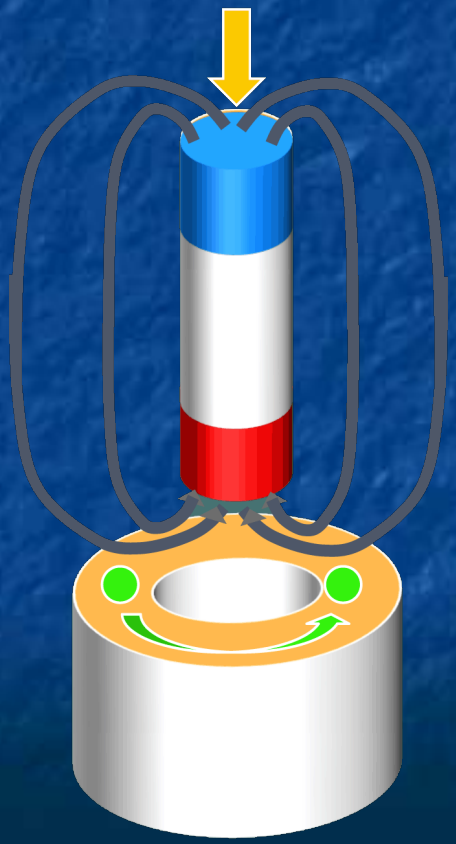


So we really do get dueling magnets! But from our Drop Tests:

This must occur only as the ends of the magnet interact with the pipe

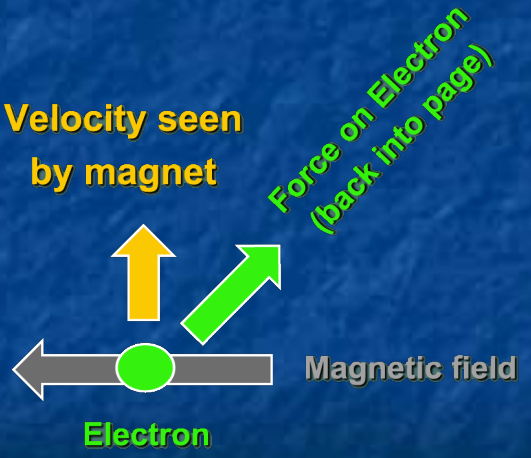
Such as here, as the leading magnetic field enters the pipe:

Big Picture:



Action at right:

Close-up of apparent action:

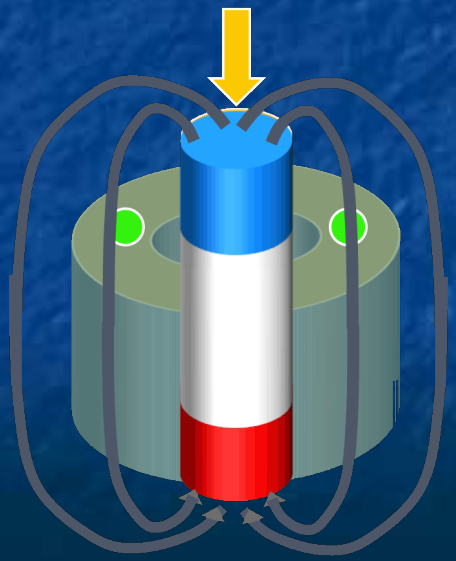


But also from those Drop Tests:

It must cease when the ends of the magnet are well beyond the pipe

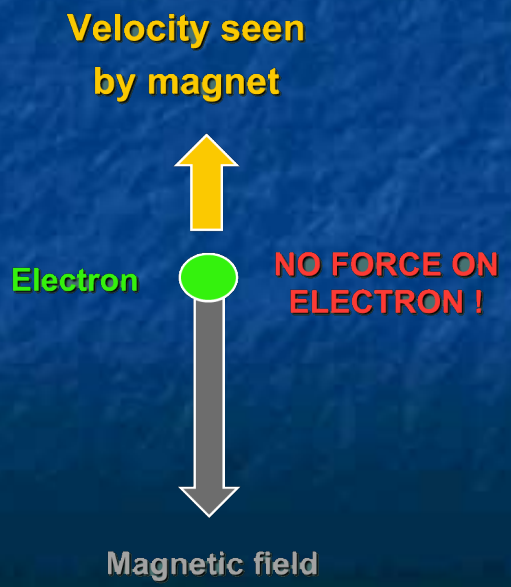
Such as here, a few tenths of a second later:

Big Picture:



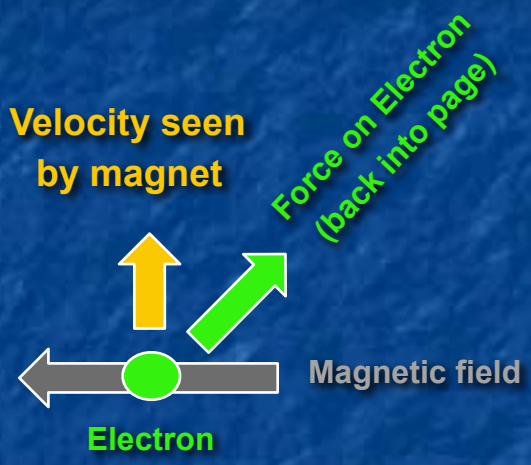
Action at right:

Close-up of apparent action:

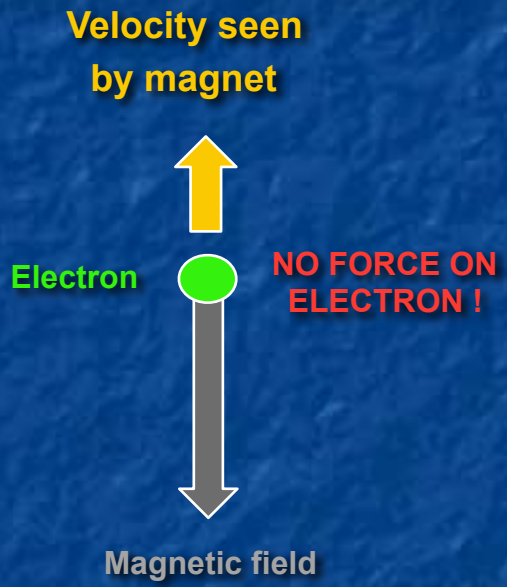


It depends on HOW the magnetic field passes by the electron!

This geometry produces a force:



But this geometry does not:



There IS a force when the magnetic field passes the electron **EDGE ON**

There IS NOT a force when the magnetic field passes the electron **END ON**

= Force scales with electron's velocity PERPENDICULAR to magnetic field!

Putting this together yields what we now call the ***Lorentz Force***

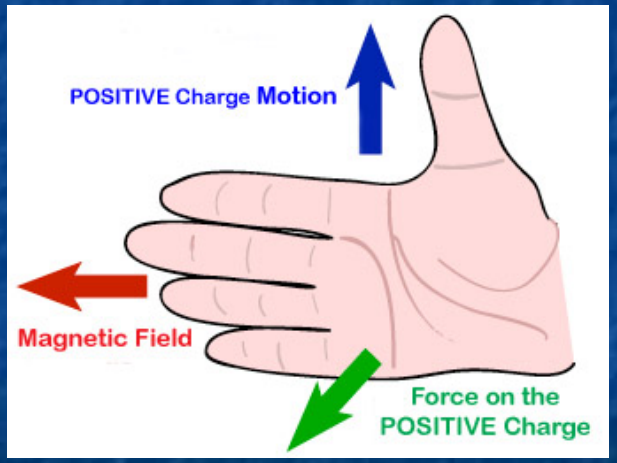
Which is the force INDUCED on a charge by movement through a MAGNETIC field

Giving this phenomenon the name: **MAGNETIC INDUCTION**

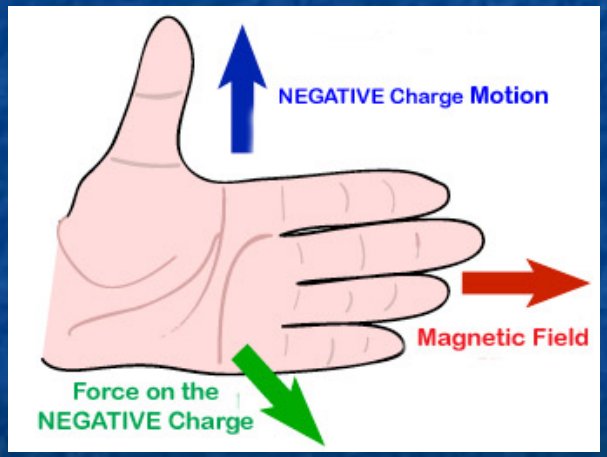
It is described by another **RIGHT HAND RULE** (for moving positive charges)

Which I'll again translate into a left hand rule (for moving negative charges)

Right Hand Rule for positive charges:



Left Hand Rule for negative charges:



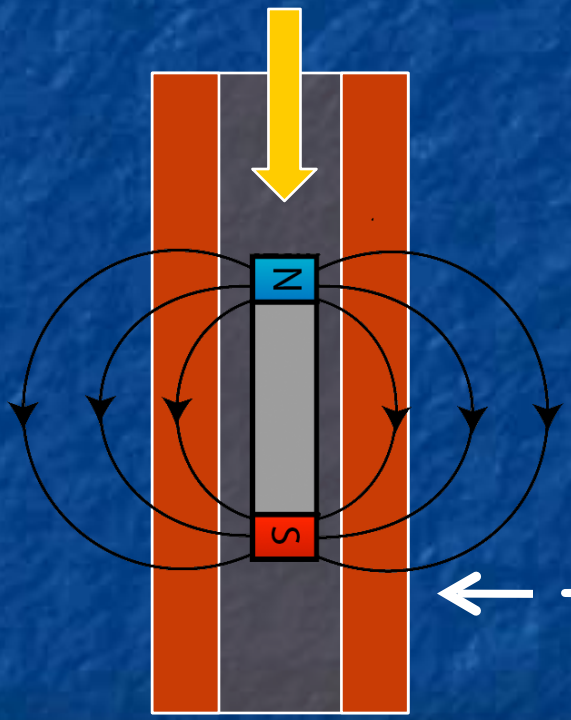
MOTION = Part of electron's velocity that is perpendicular to the magnetic field

(this velocity being evaluated from the magnet's perspective)

*Reviewing this **magnetic induction** + **electro-magnetism** conspiracy:*

A generalized / simplified diagram of all our falling magnet experiments:

Gravity tries to push permanent magnet down through pipe



Copper Pipe = A non-magnetic metal / conductor

Which contains moveable electrons

Thru which a magnetic field is **MOVING** downwards

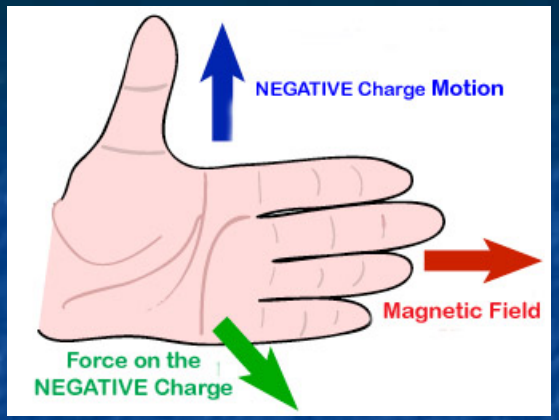
Applying our new Left Hand Rule:

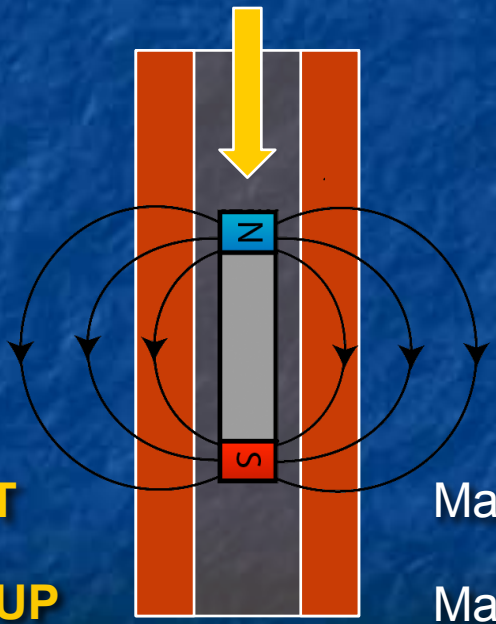
Moving magnetic field applies a force on the pipe's electrons

The magnet is really what is moving DOWN

But IT sees electrons as moving UP towards it

Near the leading (lower) edge of the falling magnet:





Bottom Left Wall of Pipe:

Magnetic field lines point **RIGHT**

Magnet sees electrons moving **UP**

Force on electrons is **out** of page

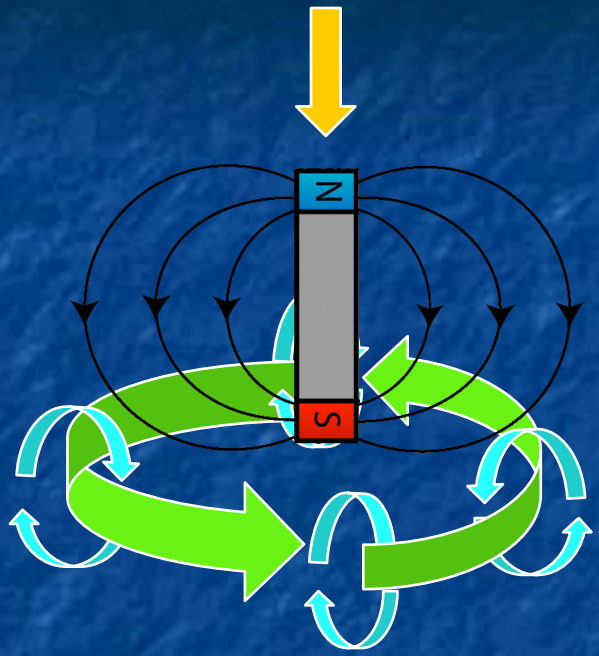
Bottom Right Wall of Pipe:

Magnetic field lines point **LEFT**

Magnet sees electrons moving **UP**

Force on electrons is **into** page

*Those forces of **magnetic induction** drive an electron loop*



Electro-magnetism causes electron loop to produce its own magnetic field

With this electro-magnet's field lines parallel to those of falling magnet (black)

The two magnets (permanent and electro) thus push **against** one another

Transferring momentum from permanent magnet to electrons of the pipe

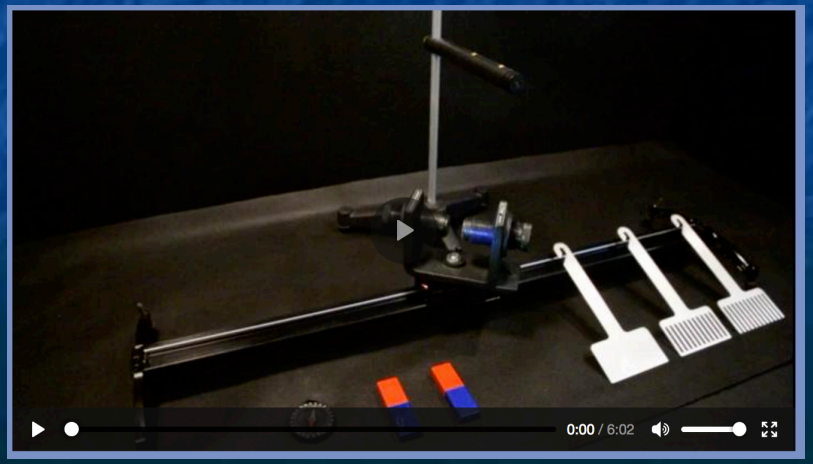
I'm going to guess "brain-freeze" may be now be setting in!

But many slides ago I promised that by the end of this note set

I'd explain how we recycle **non-magnetic** metals (e.g., Al & Cu)

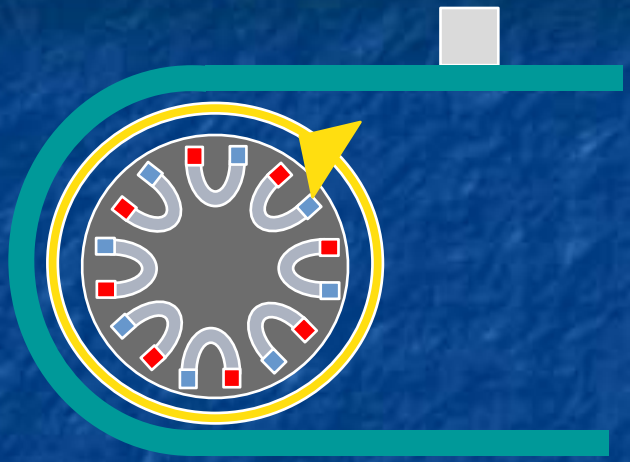
To do that, we need one FINAL demonstration:

Please now view demonstration #9 on the Resource Webpage:



Based on that demonstration:

Just embed magnets in the roller at the end of a trash conveyer belt!!



As that roller rapidly rotates, magnets are whipping up toward the top of belt

Slinging their magnetic fields upward and to the left

When that **block of metal** approaches the end of the belt

Its **electrons** are going to be pummeled by those moving magnetic fields

=> **Forces** that will push those electrons (and the block) up off the belt!

*So while the **trash falls** off the end of the belt:*

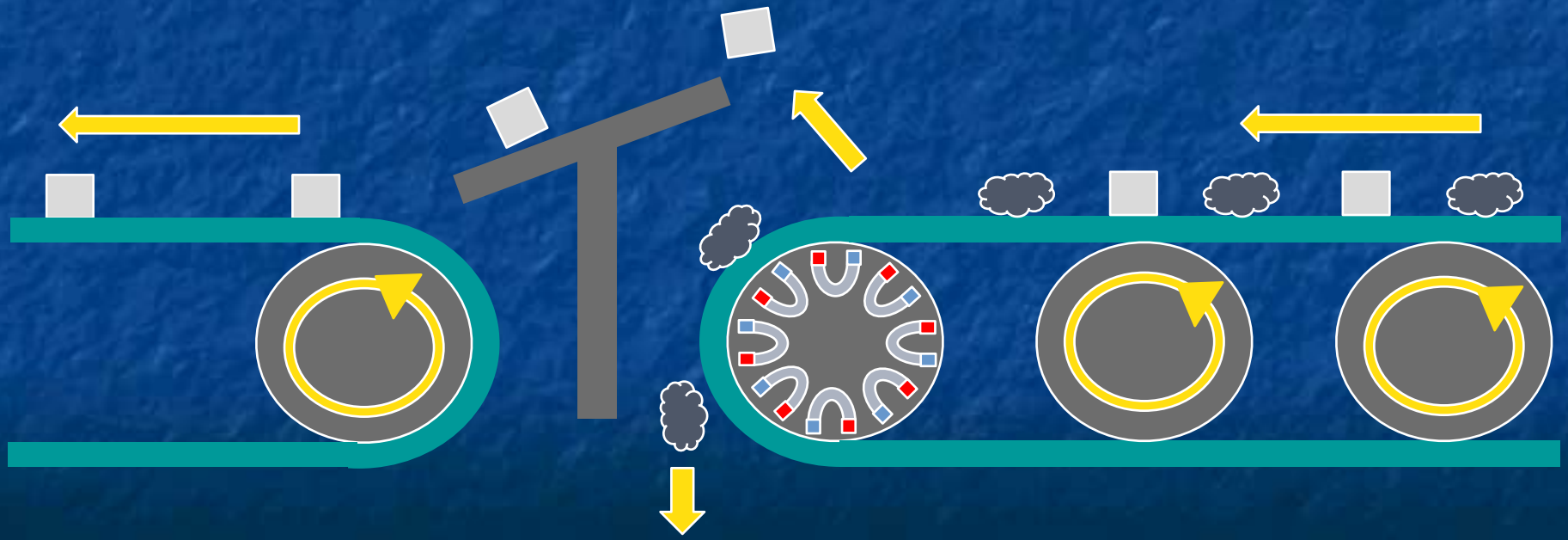
Nonmagnetic metals (such as Al & Cu) missed by the earlier electromagnet

Are now going to be **slung upward**

Allowing them to jump over a barrier

Onto a second conveyor now carrying away ONLY metals

Or flicking them into a separate "metals only" bin:



From the bottom of this note set's Resources Webpage:

A video from the "American Recycling Center" of such an operating conveyor

Using **magnetic induction** to sort out **non-magnetic** aluminum & copper:

https://www.youtube.com/channel/UCurq7PjCvPBx4zZ6v0i0wGw

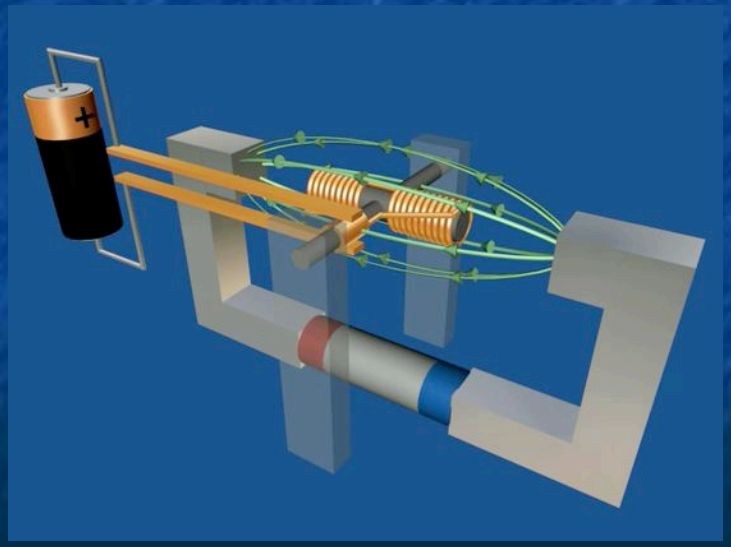
The energy savings of recycling make magnetism MILDLY relevant

But in the note set **Magnetic Induction** (pptx / pdf / key) I'll show you how:

Magnetic Induction + Electro-Magnetism

yield electric motors, electric generators & transformers

= THE KEY ELEMENTS OF ALL ENERGY SYSTEMS



Credits / Acknowledgements

Some materials used in this class were developed under a National Science Foundation "Research Initiation Grant in Engineering Education" (RIGEE).

Other materials, including the WeCanFigureThisOut.org "Virtual Lab" science education website, were developed under even earlier NSF "Course, Curriculum and Laboratory Improvement" (CCLI) and "Nanoscience Undergraduate Education" (NUE) awards.

This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.