Magnetic Induction: Motors, Generators & Transformers

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Outline

A review of electric & magnetic fields (drawn from preceding note set)

Magnetic-field-sucking "ferromagnetic materials" => Magnetic field directing "Pole Pieces"

The surprisingly straight-forward inner working of electric motors

- DC motors that switch "rotor" magnetization via "split ring" electrical contacts
- Even simpler AC motors

Increasing and smoothing out a motor's torque by adding multiple electro-magnet pairs

Nikola Tesla's clever "brushless" induction motor alternative

- Which, flattened out, now provides the basis for ultrahigh speed "maglev" trains

How the two adjacent coils of "transformers" allow one to transform AC power

- Optimizing Voltage x Current choices for either long distance power transmission
- Or for the myriad voltages now required for the most efficient & safe use of power

(Written / Revised: January 2018)

Magnetic Induction: Motors, Generators & Transformers

In the preceding note set about **Electric & Magnetic Fields** (pptx / pdf / key),

we figured out what they are and how they work

We now want to apply that knowledge to electrical power systems

Specifically, to learning how:

Magnetic induction + **electro-magnetism** provide the basis of

electrical motors and **electrical generators**

And how they are used in **transformers**

Which make electricity immensely more versatile

And facilitate transmission of electrical power over long distances

To get started, let's refresh our memories a bit:

For **ELECTRIC FIELDS**, we figured out that:

Electric fields are created between charges, which come in two types: **+** and **-**

- So named because they can act to cancel one another out

- Each type of charge repels it own kind while being attracted to the other kind

- We now know that most **+ charge** is due to **protons** locked in atomic nuclei

- While most **- charge** is due to **electrons**

Which either surround those nuclei OR flow through many materials

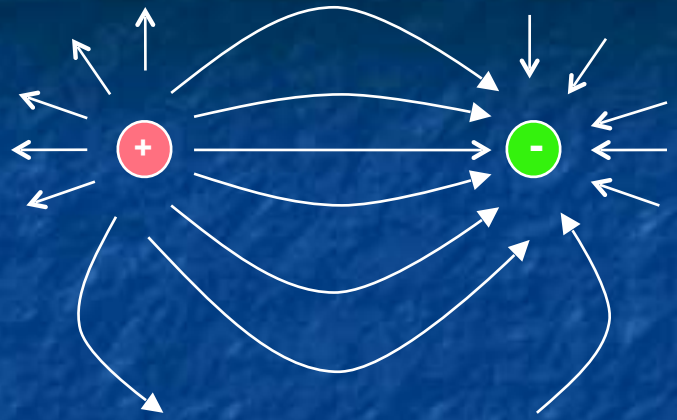
(which are then called "conductors" or "metals")

The repulsive or attractive forces between those **+** and **-** charges

extend well beyond the charges themselves, out into space

We call the resulting force field an **Electric Field**

*We represent **Electric Fields** using diagrams such as this:*



Where:

The arrows give the DIRECTION of electric force upon a + charge

(which is reversed for - charge)

The closeness of the arrows / lines gives the relative intensity of that force

But this is ONLY A SHORTHAND REPRESENTION of that spreading inter-charge force

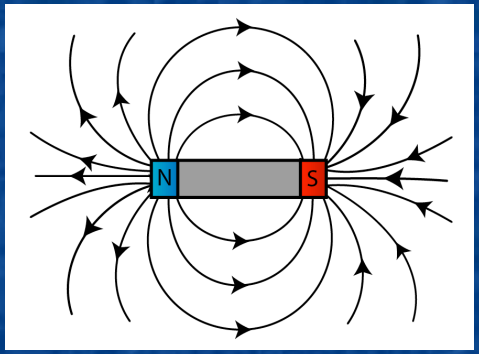
The force really NOT just along those lines

It is instead distributed throughout the inter-charge space

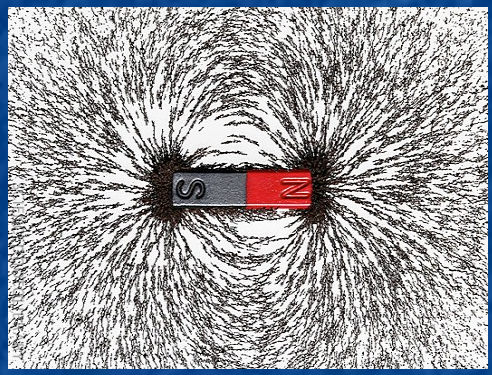
For **MAGNETIC FIELDS** we instead found that:

They are NOT mere abstractions, they can apparently be seen!

But what we see is NOT a simple map of magnetic force!!



The only thing these maps directly represent is how iron filings move when they're near a magnet:



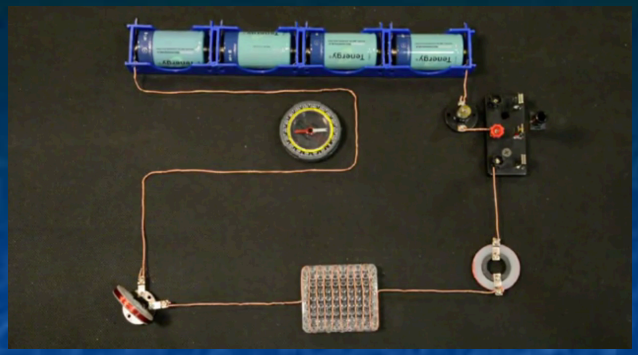
But FROM such maps we CAN figure out how another magnet will move,

by making use of this alternative set of rules:

- **Parallel "magnetic field lines" repel each other**
- **Anti-Parallel "magnetic field lines" attract each other**
- **The closer the lines are, the stronger these effects**

Left figure: http://spmphysics.onlinetuition.com.my/2008/06/introduction-to-magnetism-revision.html
Right figure: http://www.magnetyze.com/page/magnetic-fields.aspx

Then, based on experiments such as this:

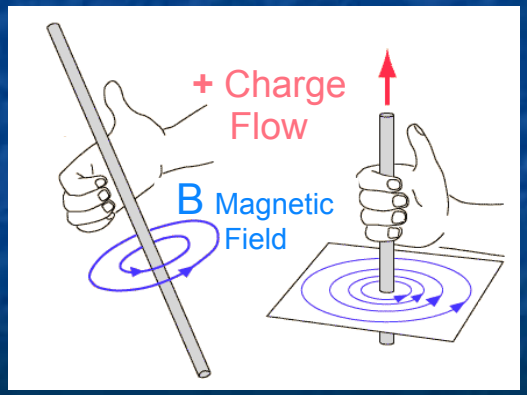


We figured out that, in addition to permanent magnets,

Flowing Electric Charge produces Magnetism = ELECTRO-MAGNETISM

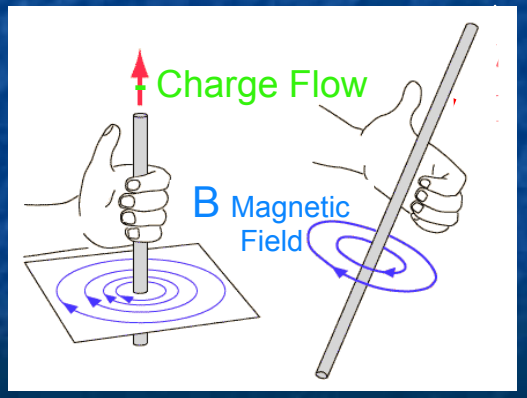
Which is described by "hand rules" (this set is known as **Lenz's Law**):

Right Hand Rule for **moving + charge**



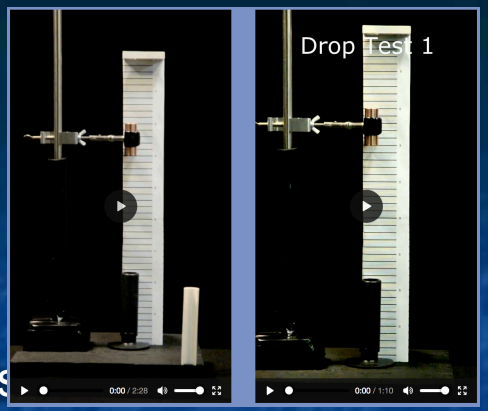
Thumb in direction of **+ charge** flow,
Magnetic field is along curled right fingers

Left Hand Rule for **moving – charge**



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

Further experiments taught us that:

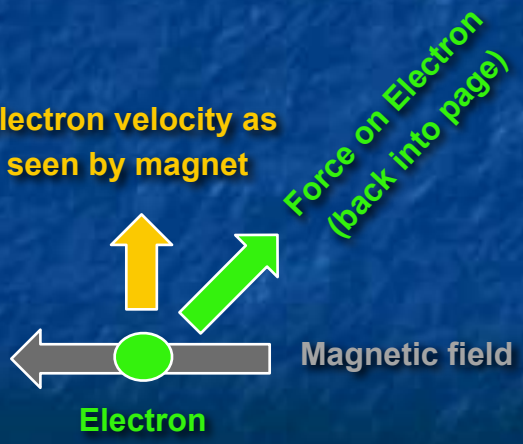


MOVING Magnetic Fields apply a force upon charges

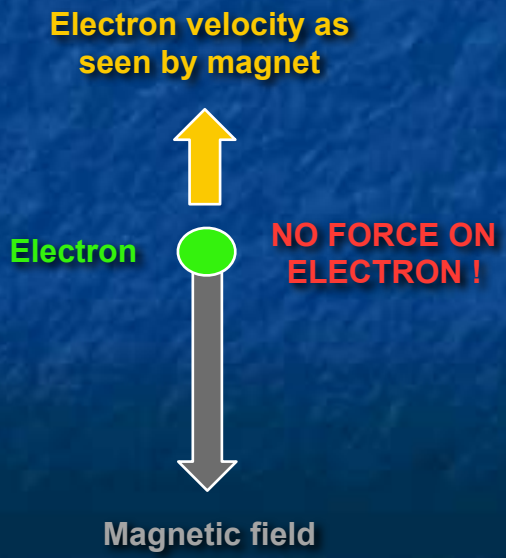
This also occurs when charges MOVE THROUGH Magnetic Fields

But this force depends subtly on the directions of the Magnetic Field and the motion

This geometry produces a force:

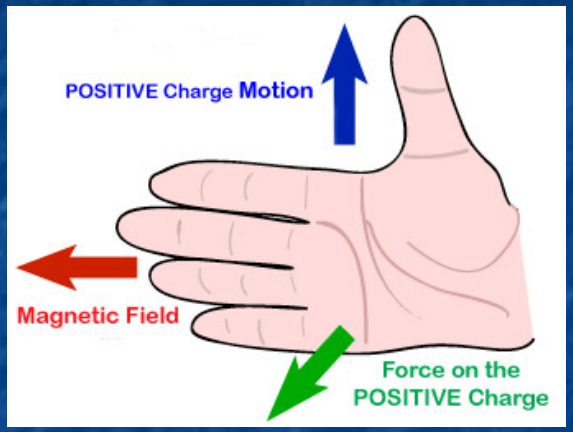


But this geometry does not:

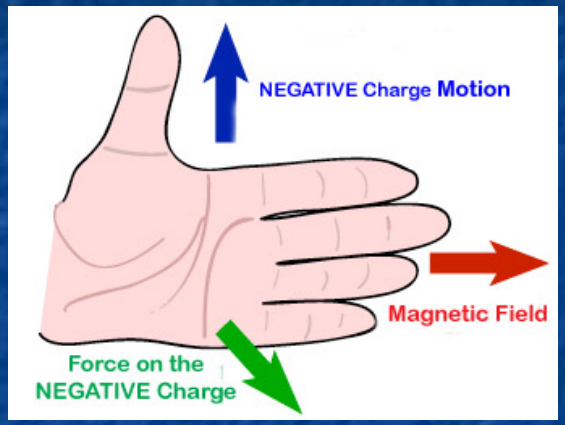


Which can be described by a another set of "hand rules"

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

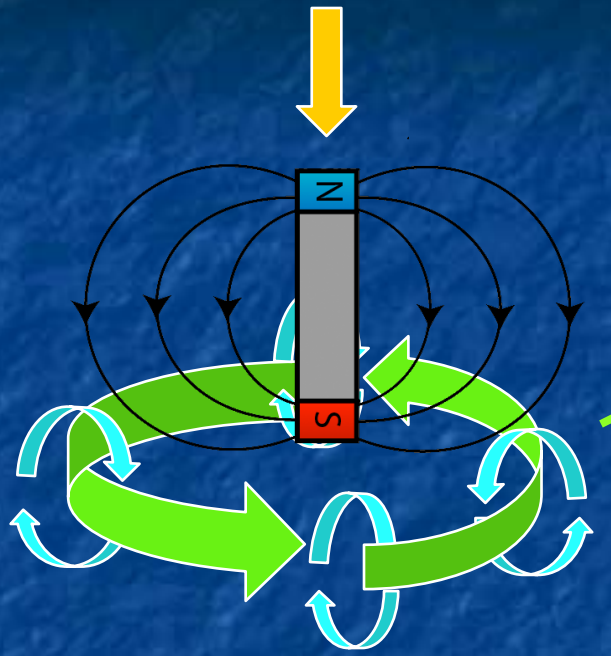
(this velocity being evaluated from the magnet's perspective)

Because this force is **INDUCED** by **MAGNETIC** Field motion relative to charges

This phenomenon is called **MAGNETIC INDUCTION**

(it is also referred to as the "magnetic part of the **Lorentz Force**")

Magnetic Induction *drives the formation of electron loops in conductors*



These induced electron loops are often called EDDY CURRENTS

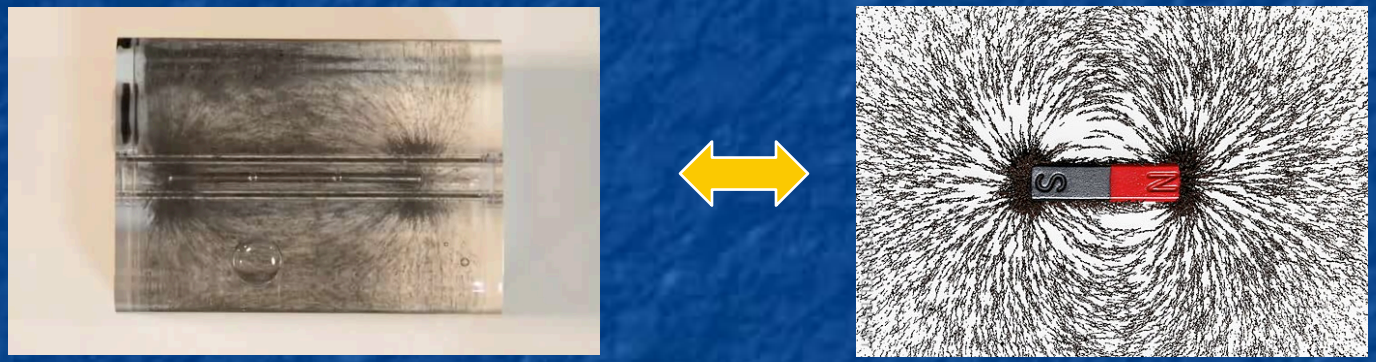
Electro-Magnetism then causes the electron loop to produce its own magnetic field

Its electro-magnetic field lines **parallel** those of moving magnet (in black)

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

*I am now **almost** ready to explain electric motors & generators!*

But we first need to **explain one more observation** from the last note set:



In the demonstration shown on the left (= Demonstration #2 at this LINK)

We saw iron filings form and then flow along these looping lines

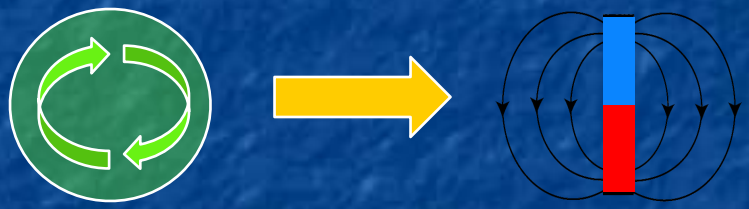
WHY do they to do this?

The somewhat complex explanation:

Electro-magnetism causes looping charge to produce a magnetic field

Well, individual electrons ARE just blobs of charge, what if THEY can spin?

Spinning electron clouds => Tiny loops of current => Tiny magnetic fields



Physicists discovered that electrons DO indeed generate tiny magnetic fields

Which they first attributed to "electron spin"

Later, more sophisticated (and vastly more obscure) Quantum Mechanics

concluded that it wasn't as simple as just spinning clouds of charge

But QM still concluded that individual electrons DO have tiny magnetic fields,

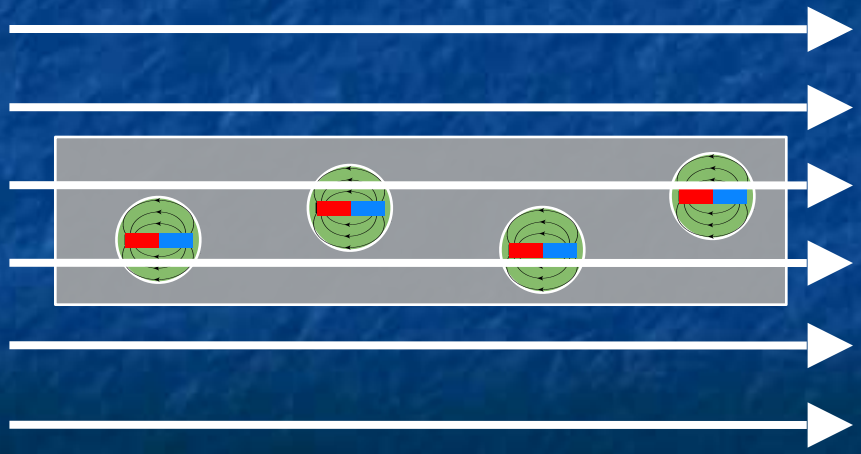
which it still refers to as "electron spin"

What if a material's "spinning electrons" meet an applied magnetic field?

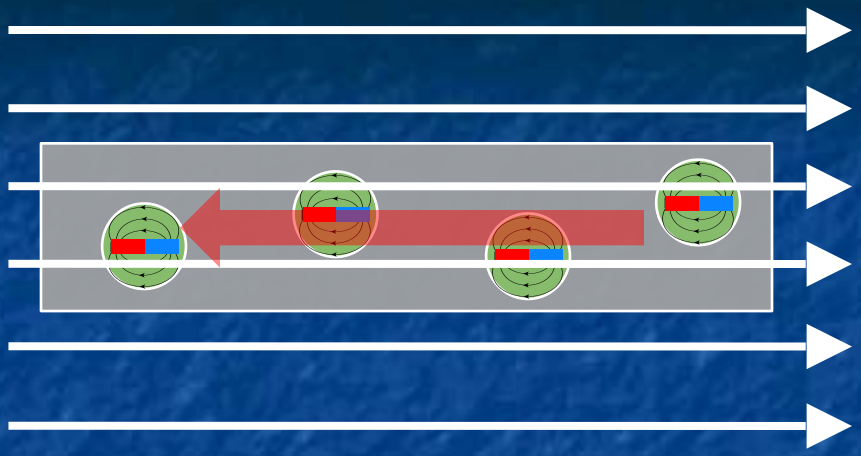
Heat tries to randomize the orientation of the electrons, along with their "spins"

But when a magnetic field is it IS applied, the parts of it penetrating the material

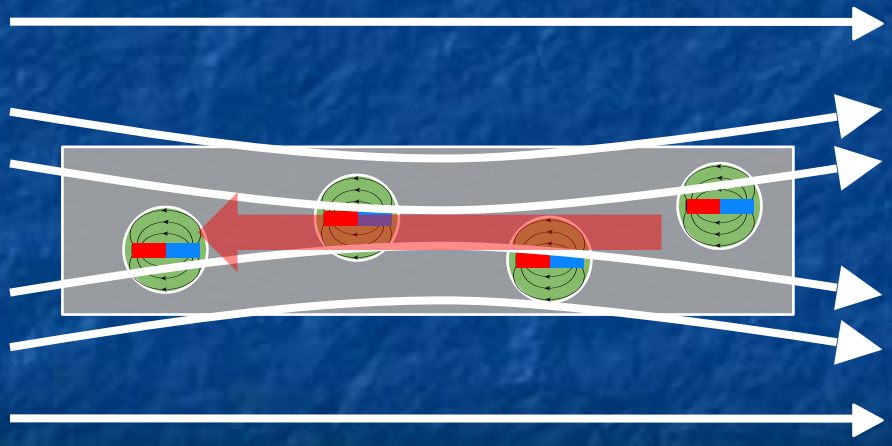
will drive the spins to rotate their magnetic fields in the **opposite direction**



The spin magnetic fields will then blend into a counter magnetic field:



Which will ATTRACT the external magnetic field, drawing more of it inside

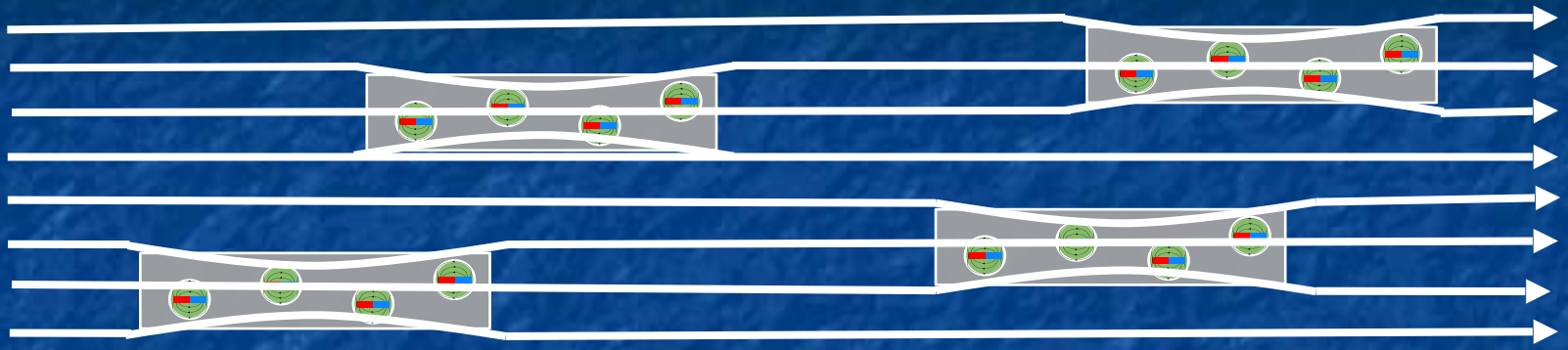


This REDUCES the intensity of the MAGNETIC FIELD REMAINING OUTSIDE

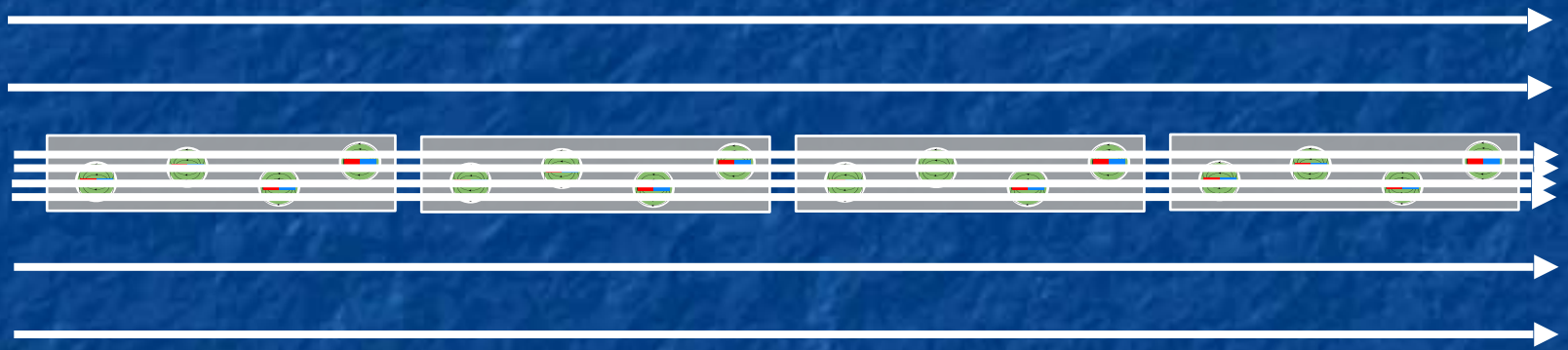
Increased spacing of the remaining external field lines => **Lowered energy!**

If our iron filings are those bits of of material:

They can better suck in field (lowering its energy) by rotating along the field lines:



But they can suck in MUCH MORE field if they also assemble into nose-to-tail chains:



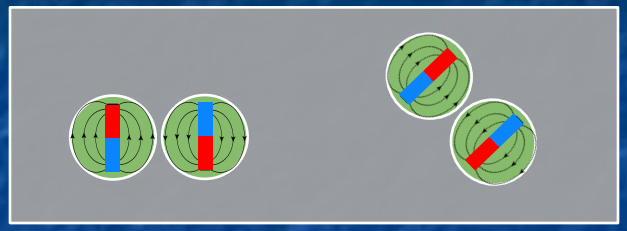
A majority of "external" magnetic field lines can then be sucked in,

leaving a vastly weaker, and thus lower energy, magnetic field outside,

=> Our iron filing patterns of "magnetic field lines"

But this does NOT occur for ALL materials

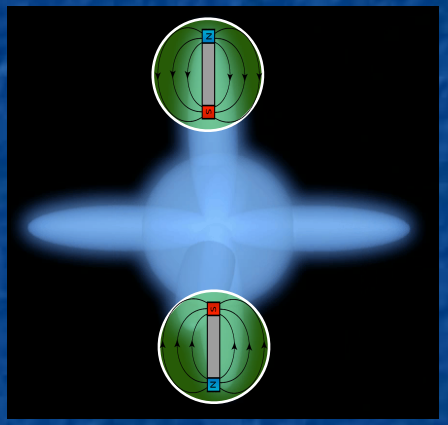
In many materials, spins themselves pair up oppositely (countering charge repulsion)



Magnetic fields of paired electrons cancel

=> External magnetic fields then have no effect

In some atoms, spin directions are locked by electrons in other atomic orbitals



And in some atomic mixtures (such as steels),

minute quantities of certain impurities can lock up spins

For a material to suck in magnetic fields

(which ALSO means that it will be ATTRACTED BY MAGNETS)

IT MUST HAVE SOME UNPAIRED, UNLOCKED, ELECTRON SPINS

But if spins ARE free to align opposite to an applied magnetic field:

Then that material is called a **ferromagnetic** (= it behaves like iron)

Ferromagnetic materials are attracted to magnets

Ferromagnetic shapes trap & redirect external magnetic fields

And because ferromagnetic materials DO "suck in" magnetic fields:

They can be made into special shapes, called **POLE PIECES**, which

concentrate and direct magnetic fields where we need them,

as required in both **electric motors** and **electric generators**

Which I am NOW FINALLY ready to explain!

Motors and generators depend upon the motion of magnetic fields

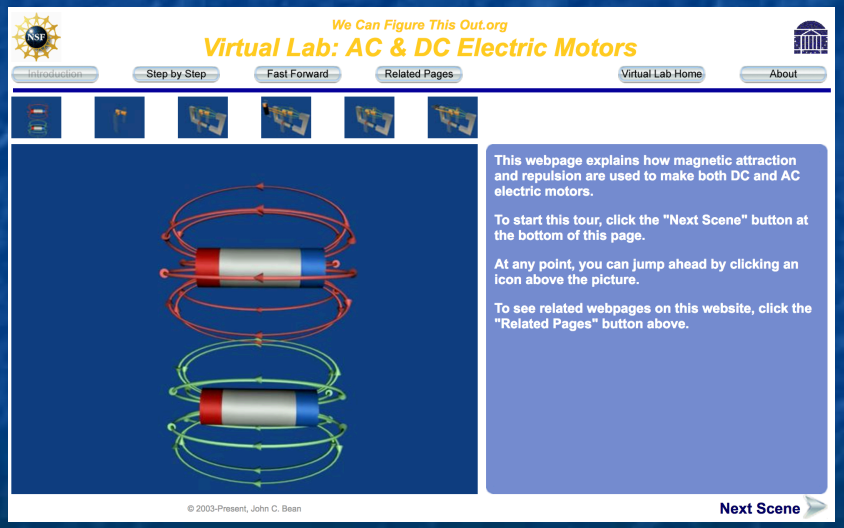
Static images & figures cannot show motion. Nor can Magnetic Fields be videotaped

Hence the computer-animated "Virtual Lab" section of WeCanFigureThisOut.org

Where I've posted my fully animated explanation of motors and generators

Please now view that complete presentation:

(For each scene: View the animation, read the text explanation, then repeat the animation)



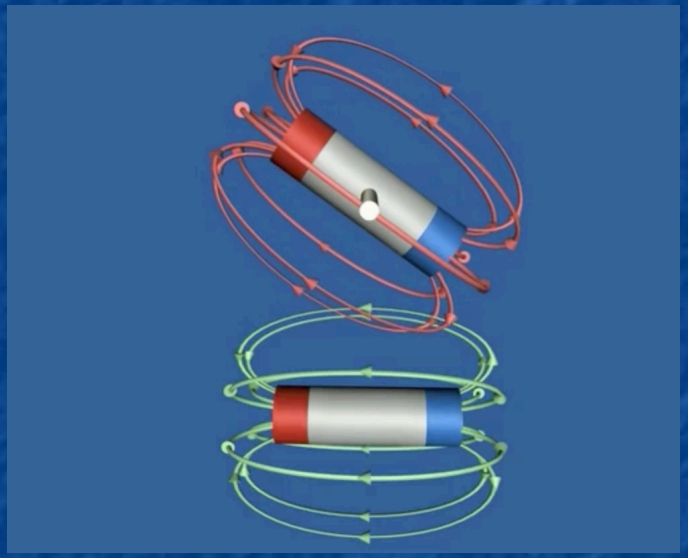
Its Link: AC and DC Electric Motors Its explicit URL: https://www.wecanfigurethisout.org/VL/Motors.htm

Review of preceding "AC & DC Electric Motor" presentation:

Scenes 1 & 2:

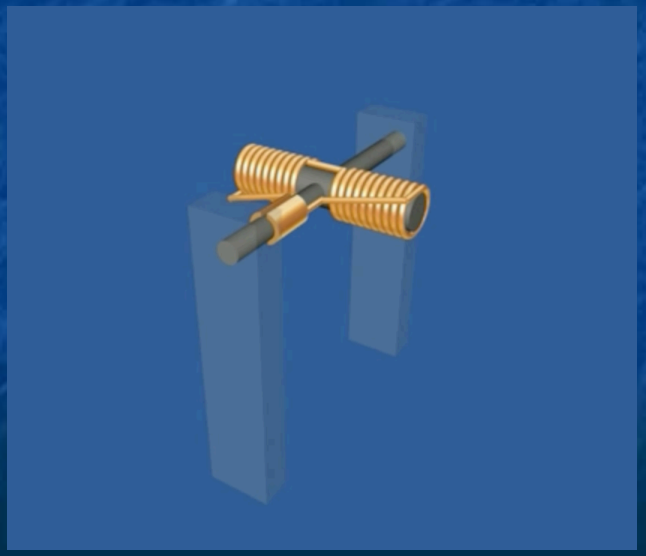
How one magnet can cause another to rotate.

How magical pole switching could sustain rotation.



Scenes 3 & 4:

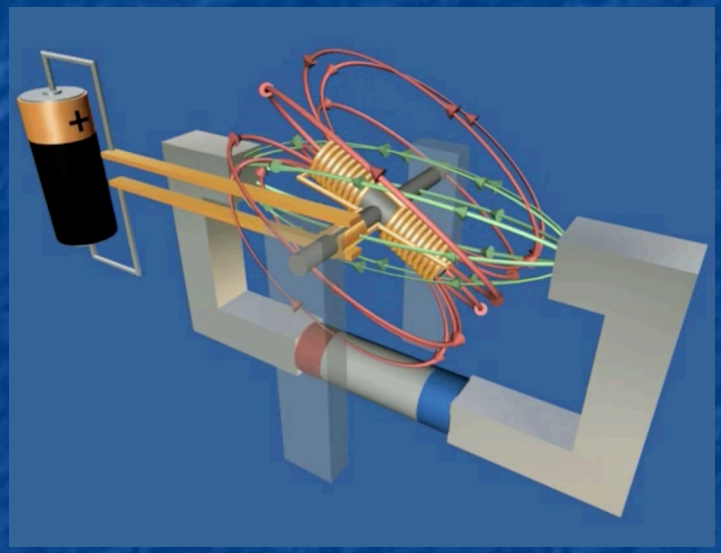
How the top permanent magnet can be replaced with a non-magic electro-magnet.



Review of preceding "AC & DC Electric Motor" presentation (continued):

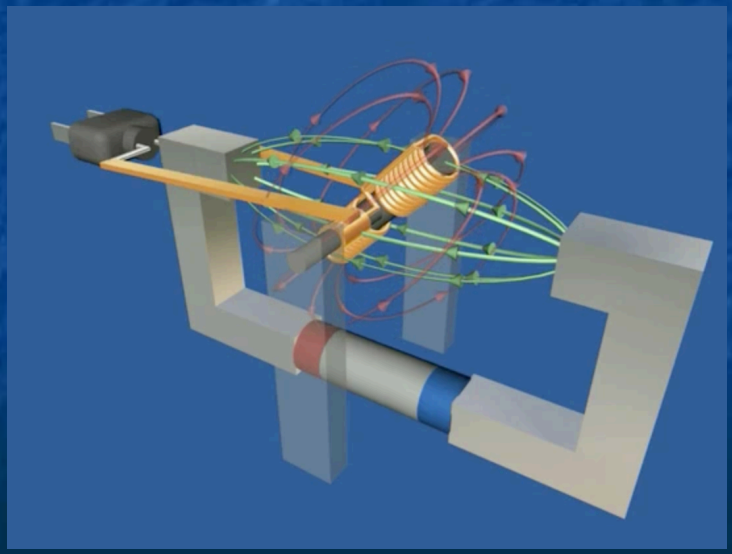
Scenes 5 - 8:

How "split-ring" battery contacts can then switch the electro-magnet's direction of current flow every half turn



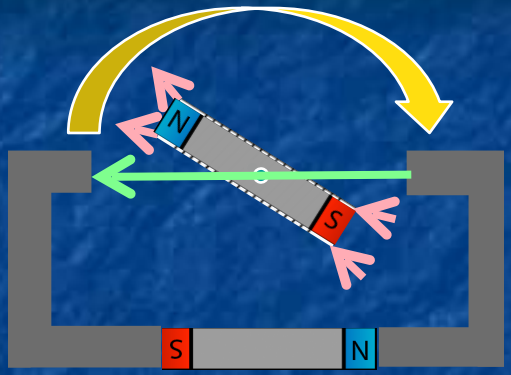
Scenes 8 - 11:

How a different (simpler) set of contacts can send naturally switching AC current to the electro-magnet

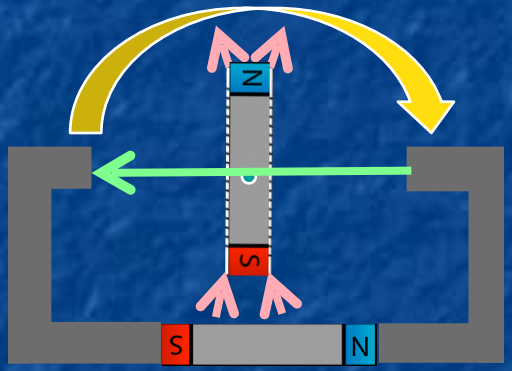


A subtle problem: The Motor's torque is not constant during rotation

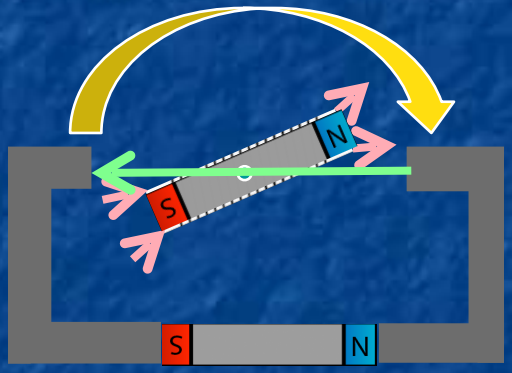
Using all permanent magnets, let's run through a half turn of motor rotation:



Start of turn:
Nearly parallel magnetism
LOTS of repulsion
LOTS of torque



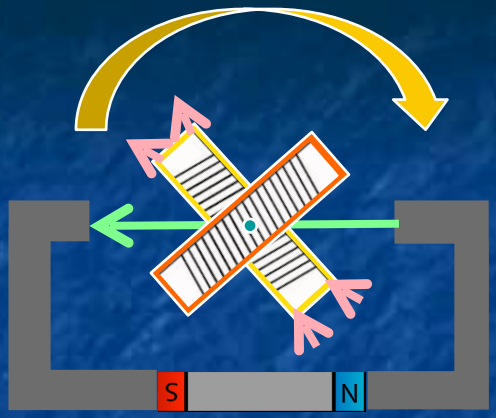
¼ turn:
Perpendicular magnetism
MINIMUM repulsion
MINIMUM torque



Nearly ½ turn:
Nearly anti-parallel magnetism
LOTS of attraction
LOTS of torque

Thickness of yellow PowerPoint arrow ends up representing torque vs. rotation!

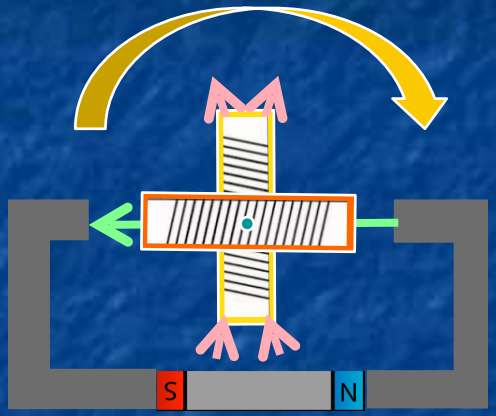
A solution: Multiple rotor electromagnets



During first 1/4 turn:

YELLOW electromagnet ON
~ Parallel magnetism
Maximum torque

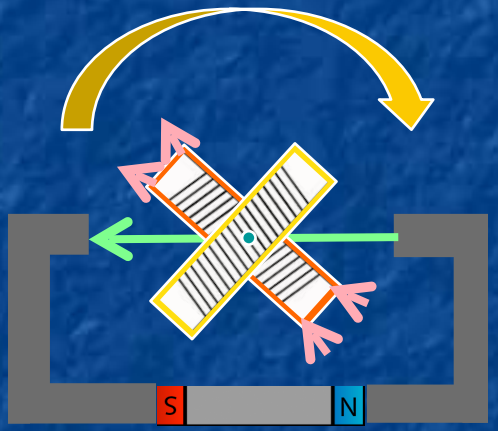
ORANGE electromagnet OFF
No magnetism, NO torque



At ¼ turn:

Turn YELLOW electromagnet OFF
=> No torque

Turn ORANGE electromagnet ON
=> Torque



During second 1/4 turn:

YELLOW electromagnet OFF
No magnetism, NO torque

ORANGE electromagnet ON
~ Parallel magnetism
Maximum torque

Keep turning NEW electromagnets on
WHEN they are oriented to push most strongly!

Taking that to an extreme:

Photographs I took of the motor from an old woodworking router tool:

Assembly minus the tool's outer shell (which took with it part of contact assembly):

LEFT: "Stator" pair of electromagnet

RIGHT: Rotor with MANY electromagnets

Close-up of rotor:

The electromagnets are wrapped around green-tinted rectangular **pole pieces**:

Their wires then run down to the sections of split ring near the bottom

But THIS ring has not been split in half

It has been divided in to **28 contacts!**

At two contacts per electromagnet

28 contacts => 14 electromagnets

(confirmed by count of the green rectangles)

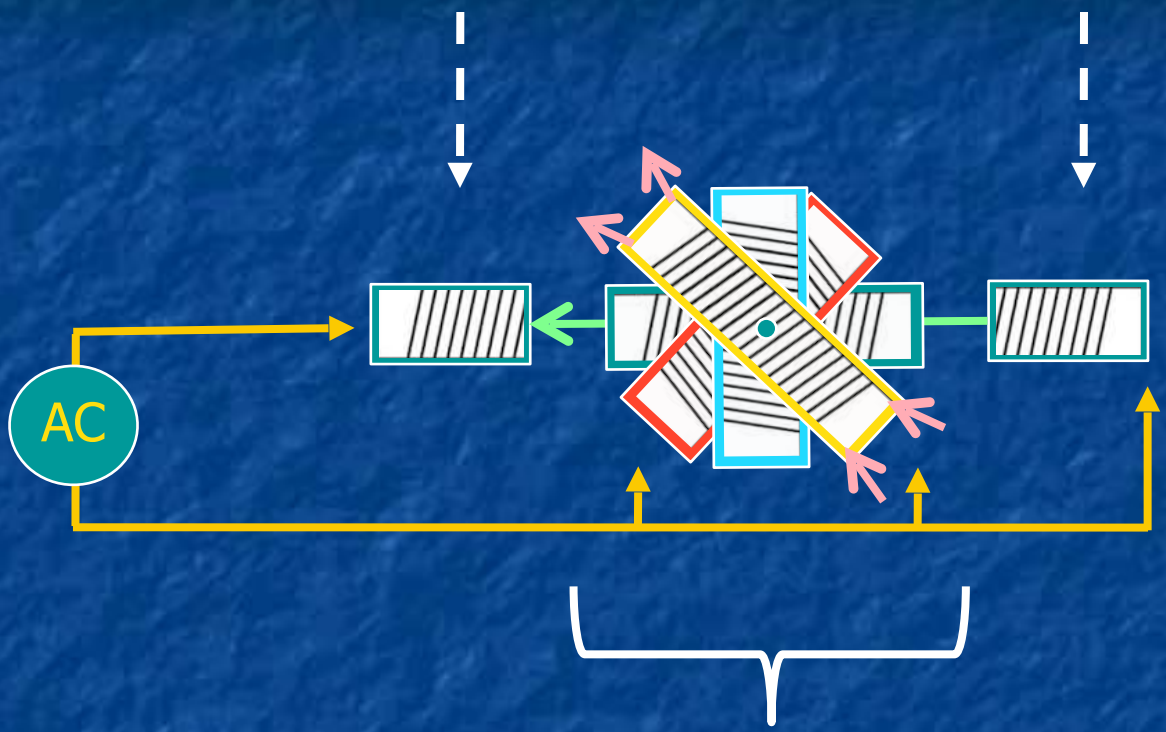
The manufacturer did this because wood routers

drive HUGE cutting bits into wood

and they thus require LOTS of continuous torque!

So my router motor was actually more like this:

OUTER ("stator") AC electromagnet pair, switching polarity 120 times a second



INNER ("rotor") AC electromagnets (14 rather than the 4 that I fit into drawing)

Only ONE of which receives AC power at any time

That ONE "selected" by its contacts rotating under the fixed "brushes"

BIG ENERGY SYSTEM TAKEAWAY MESSAGE #1:

In ALL of the above: **CAUSE & EFFECT ARE INTERCHANGEABLE**

Moving currents **create** magnetic fields (via Lenz's Law)

Switching currents => Switching Magnetic Fields = **The basis of Motors**

Moving magnetic fields **induce** currents (via the Lorentz Force)

Rotation of charge-containing wires in a magnetic field =>

Induced current flow in those wires = **The basis of Generators**

Electric Motors and Electric Generators thus have the SAME structure

One is just the other "being run backwards"

Turn a DC motor => You get DC POWER OUT = DC generator

Turn an AC motor => You get AC POWER OUT = AC generator

*But there are complications in **really Good or Big** motor/generators*

Strong **permanent** magnets are really large and heavy

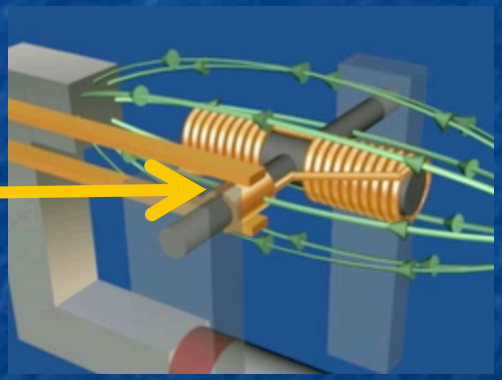
Not something you really want to spin at thousands of RPM!

Thus, where possible, spinning **electro-**magnets are substituted

But spinning electromagnets have their own problem:

Those rubbing contacts ("brushes"), either DC split ring or dual AC ring:

They wear away!



Especially split rings (which can also spark when the contacts slide over gaps)!

*And there is an additional (embarrassing) problem in **Big Generators**:*

If you build a big generator using ONLY electromagnets

You will NEED SOME INPUT POWER TO PRODUCE OUTPUT POWER

Why? because you have got to **START** with a magnetic field

Which can then be rotated to induce electrical current in a wire

This magnetic field can be in the rotating "rotor" part of the generator

DC current applied to rotating electromagnet => Rotating B field

OR the rotating magnetic field can be created by stationary "stator" electromagnets

AC current applied/switched between electromagnets => Rotating B field

Either way you need power INTO electromagnets to get power OUT of the generator

THUS: A Hydroelectric Dam w/o Grid or local auxiliary power

may not be able to produce power even when water is spinning its generators!

Reflecting on those motor / generator challenges:

There's no easy solution for the preceding generator complication

That of needing a little incoming power to generate a lot more output power

But there IS a solution to the problem of massive rotating permanent magnets

And there IS a solution to the problem of contact wear in rotating electromagnets

What if you could completely do away with the rotating magnet

And just make the "rotor" out of a dumb unpowered chunk of metal?

HUH?

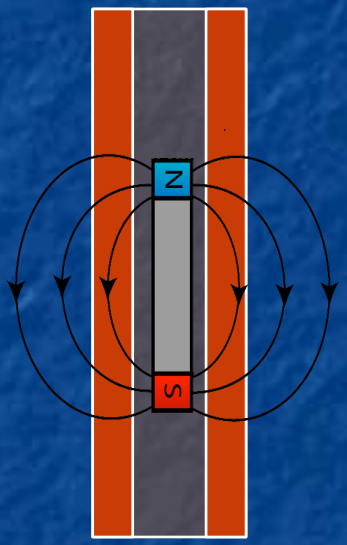
What would the magnets of the "stator" push against ? (!@$!)

Nikola Tesla figured out the solution!

You saw it in the video demonstrations & explanations of the preceding note set!!

LINK to those video demonstrations / LINK to that note set's explanations

When a magnet fell through a (non-magnetic) copper pipe, its fall was slowed



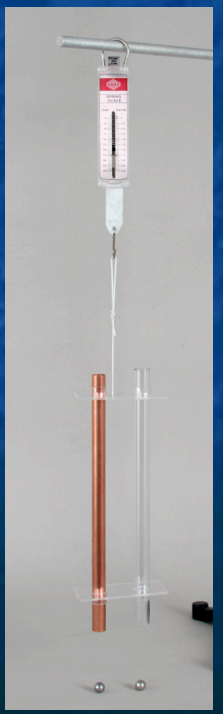
BECUASE its movement induced loops of current in the pipe

Those loops of current generated their own magnetic field

Which pushed back upon the falling magnet

But via Newton's: "Action = reaction"

The pipe was also pushed downward



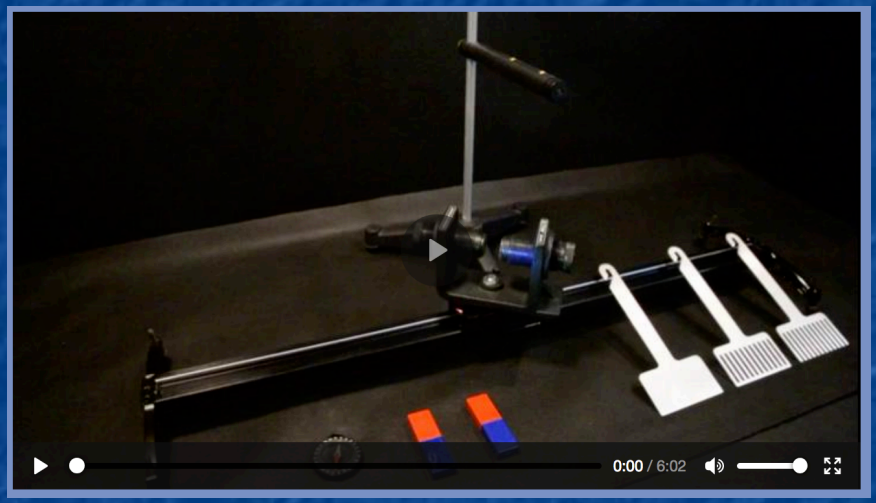
And we actually measured the force on the pipe using this apparatus:

"Lenz's Law Apparatus" (#32520) from The Science Source (www.thesciencesource.com)

But how would falling magnets + pipes be made into an electric motor?

OK, Nikola Tesla's new motor idea actually followed more naturally from

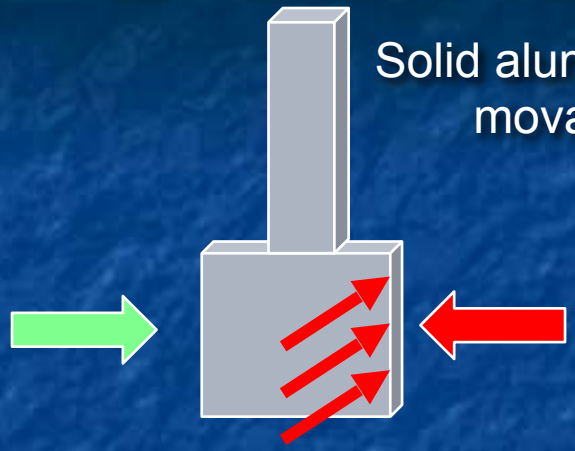
this OTHER apparatus I demonstrated for that note set

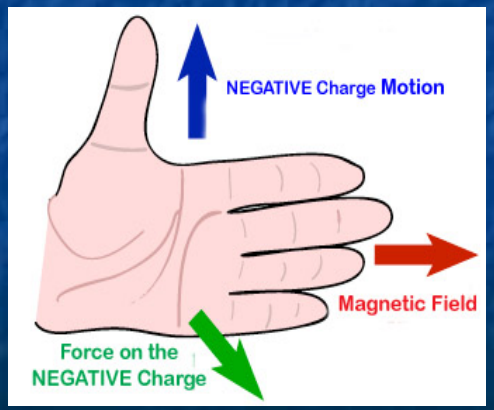


If you have not recently viewed that demonstration, please do so now

It is demonstration #9, near the bottom of this webpage: LINK or QR code:

Exactly HOW the moving magnet pushed upon the aluminum shapes:





As magnet enters from right (it's field pointing **into** page):

its field first encounters right (leading) edge of paddle

Magnet perceives electrons in paddle as **moving rightward**

Lenz's LH Rule: **Thumb right**, **fingers into page**

Electrons at right of paddle pushed out of left palm = **DOWN**

Electrons at right/far edge of paddle scurry back upward

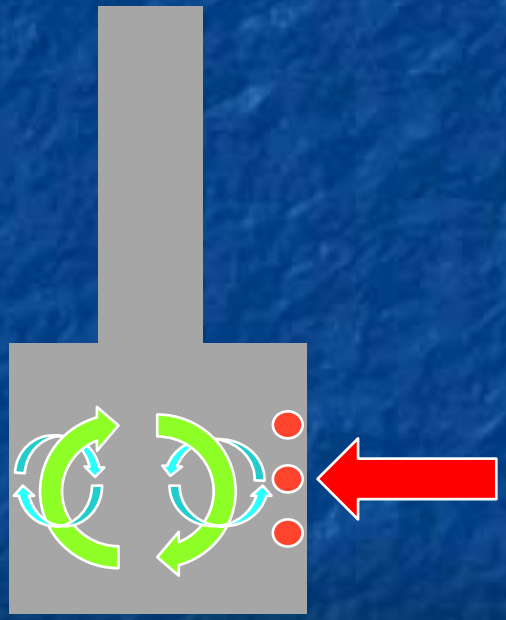
The arriving magnet thus "induces" loops of electron flow:

Then, via electro-magnetism's LH Rule (curled fingers):

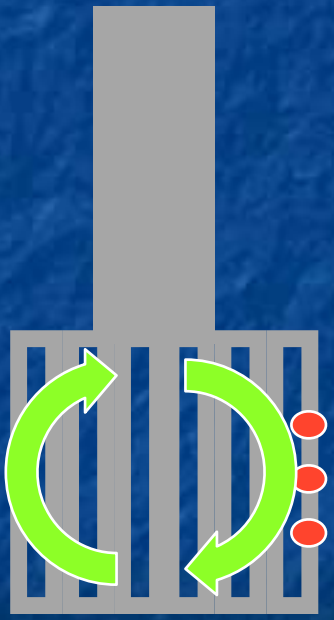
Green loop of electrons generates **blue** magnetic field loops

Which, where they meet the **red** incoming magnetic field, are PARALLEL

So magnet & induced fields repel one another



Magnetic
field movement



Which works the same way, almost as well, with this second aluminum shape

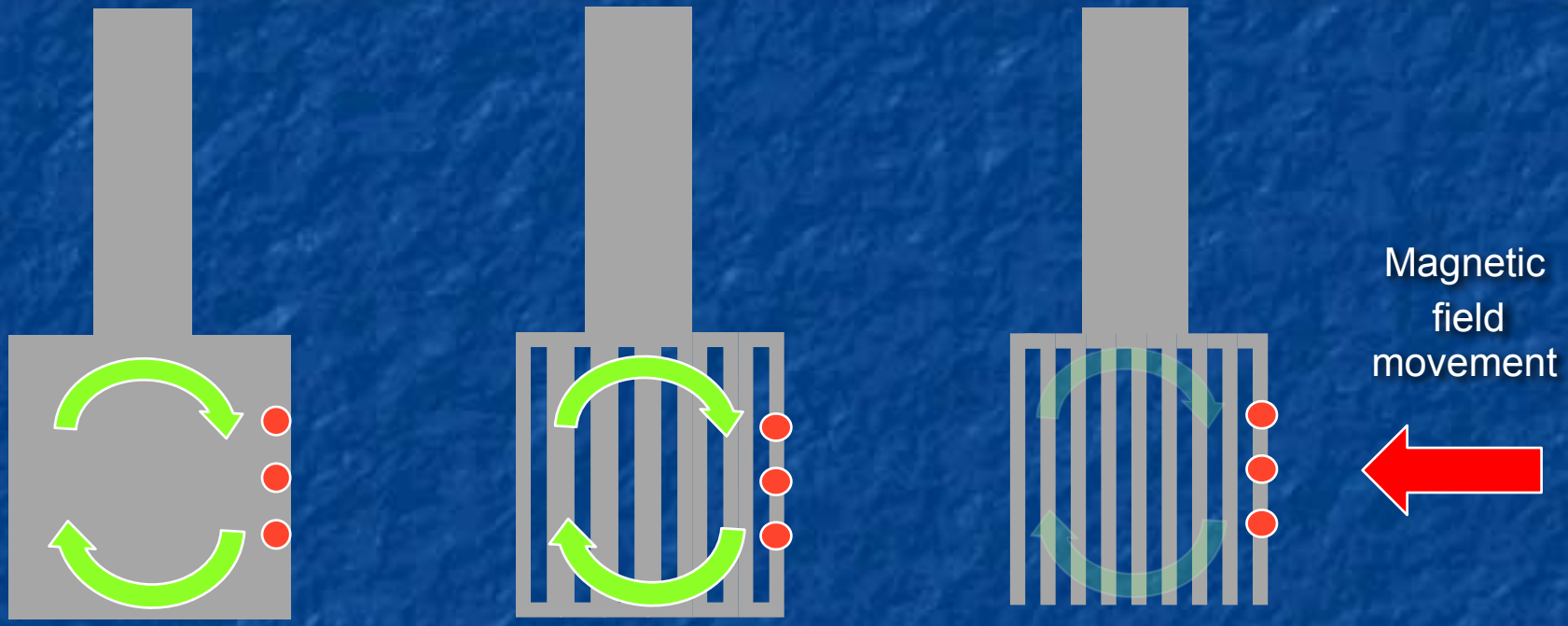
But in the "comb" shape

an induced electron loop cannot form:

Shape #1

Shape #2

Shape #3



By blocking the induced electron current loops in the final comb shape

a parallel magnetic field is NOT set up in the COMB

and there is NO resistance to passing a magnet field through it!

*From this, **Nikola Tesla** proposed the "induction motor"*

Which as its rotating core ("rotor") did NOT use ANY magnets

It was instead a simple metal shape, with absolutely no electrical connections

(Mimicking our aluminum shapes above)

It was propelled by electro-magnets effectively rotating in a circle around it

"Effectively rotating" because there was actually a circle of electro-magnets

That were all, in fact, stationary

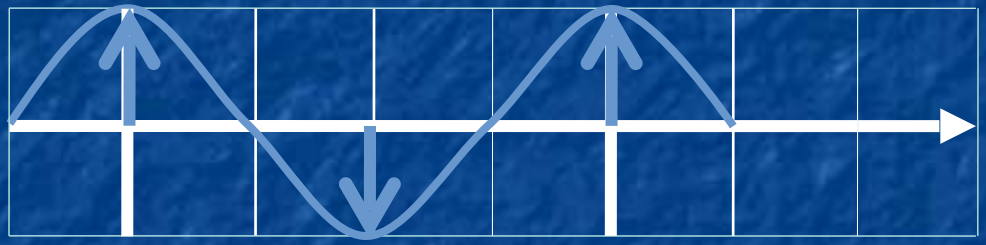
The trick? Energizing pairs of electro-magnets in a rotating sequence

How? By connecting them up to three "out-of-phase" AC power lines

Diagrams of the required three AC power line voltages:

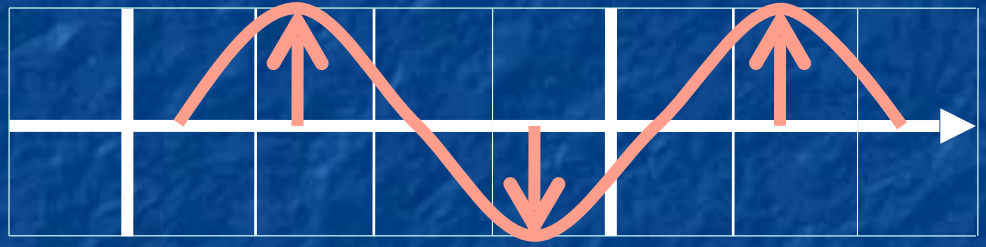
Three "out of phase" AC (alternating current / voltage) signals:

Signal 1)



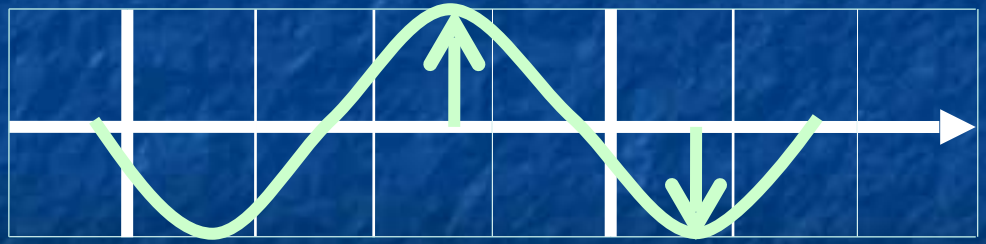
Time / Degrees

Signal 2)



Time / Degrees

Signal 3)

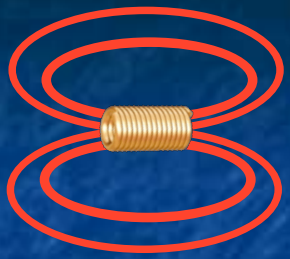


Time / Degrees

Arrows mark when each reaches a positive or negative peak

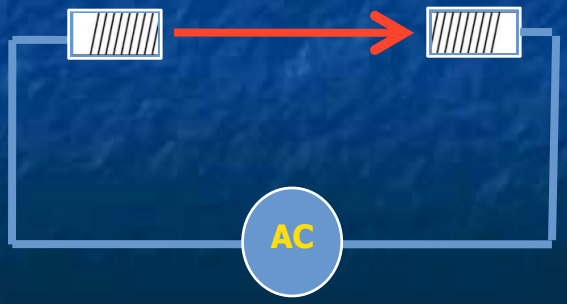
Apply each of those signals to a PAIR of stator electromagnets:

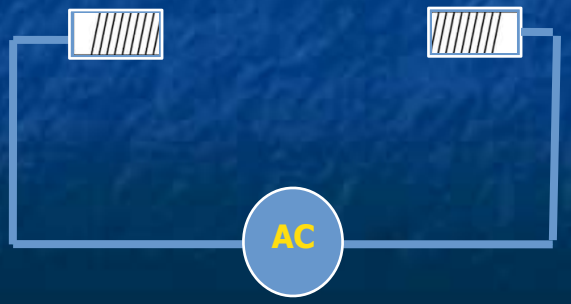
One electromagnet:



Pair of electromagnets, wired together "in series:"

Which (including AC power source), I will represent this, OR just this:





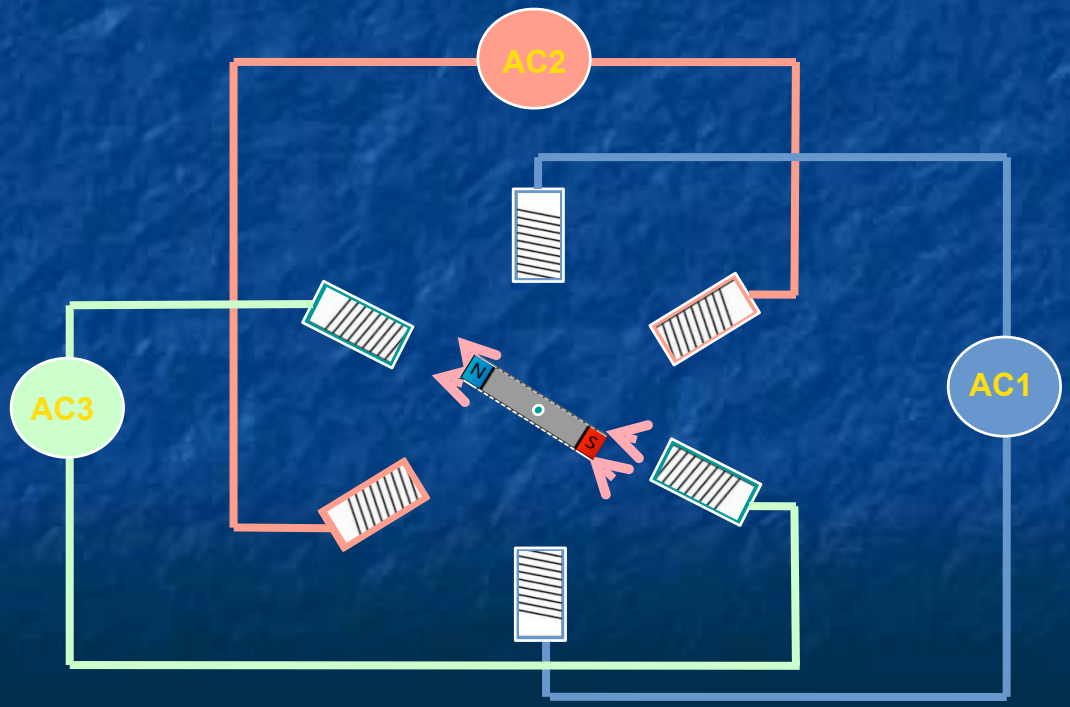
Three such electromagnet pairs, each powered by its own AC:

Each of those pairs rotated 1/3 of a circle from each other:

AC current/voltage #1 to blue electromagnets

AC current/voltage #2 to pink electromagnets

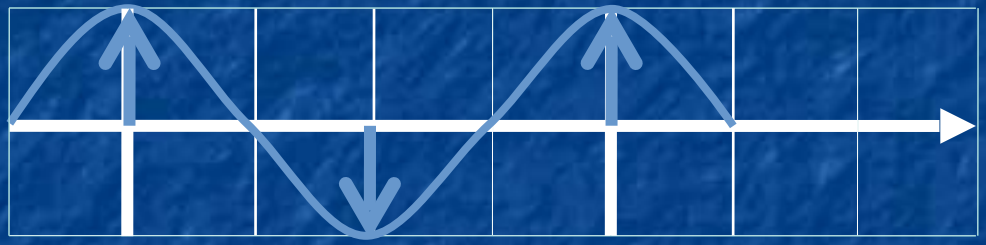
AC current/voltage #3 to green electromagnets



Looking more closely at the timing of the three AC power signals:

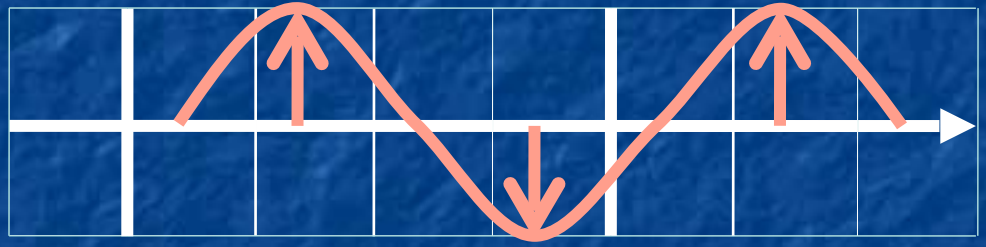
Noting exactly **when** each AC signal reaches its highest and lowest point:

Signal 1)



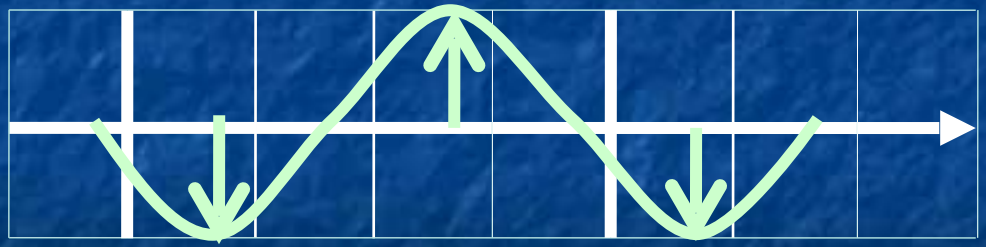
Time / Degrees

Signal 2)



Time / Degrees

Signal 3)



Time / Degrees

0 90 180 270 360

Arrows mark when each AC power signal reached an up or down peak

AC peaks => Max fields from the connected electromagnet

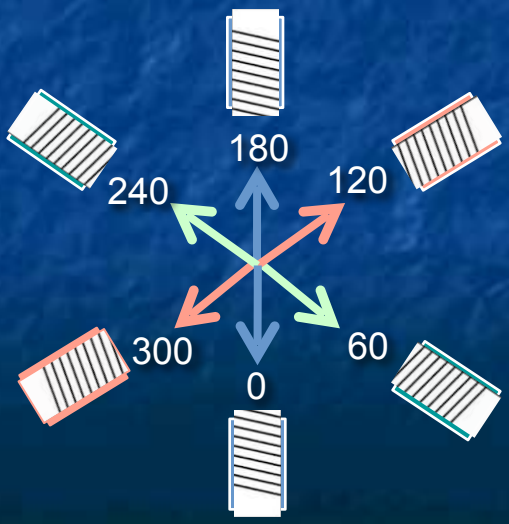
Combining the timing of AC "up" and "down" peaks

with the orientations of the three connected electro-magnets:

Timing & orientation of "up" peaks

Timing and orientation of "down" peaks

Resulting, at those times, in these magnetic field directions within the motor:

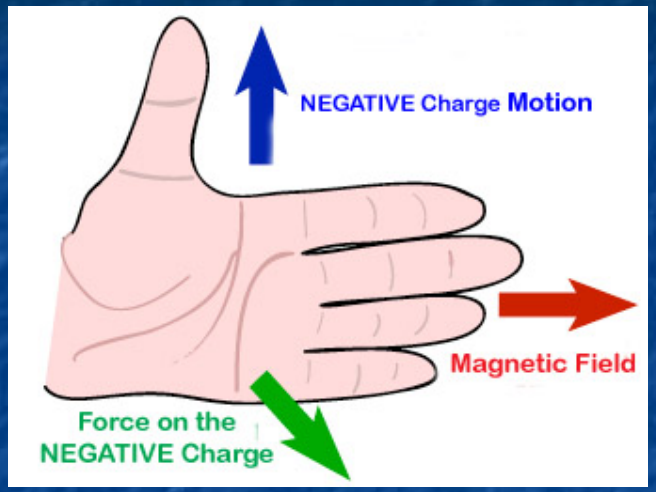


Net Result:

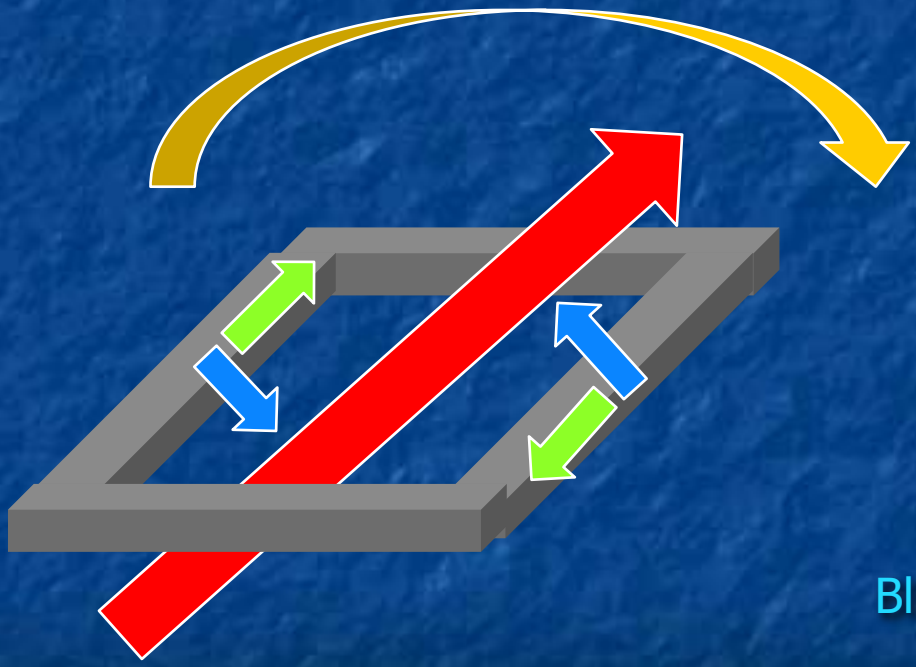
Magnetic Field, rotating in circles!

*Now, between those electromagnet pairs, put a **plain** metal ring*

Then apply the **LH Rule of Magnetic Induction**:



Using this to figure out electron flow in metal ring:



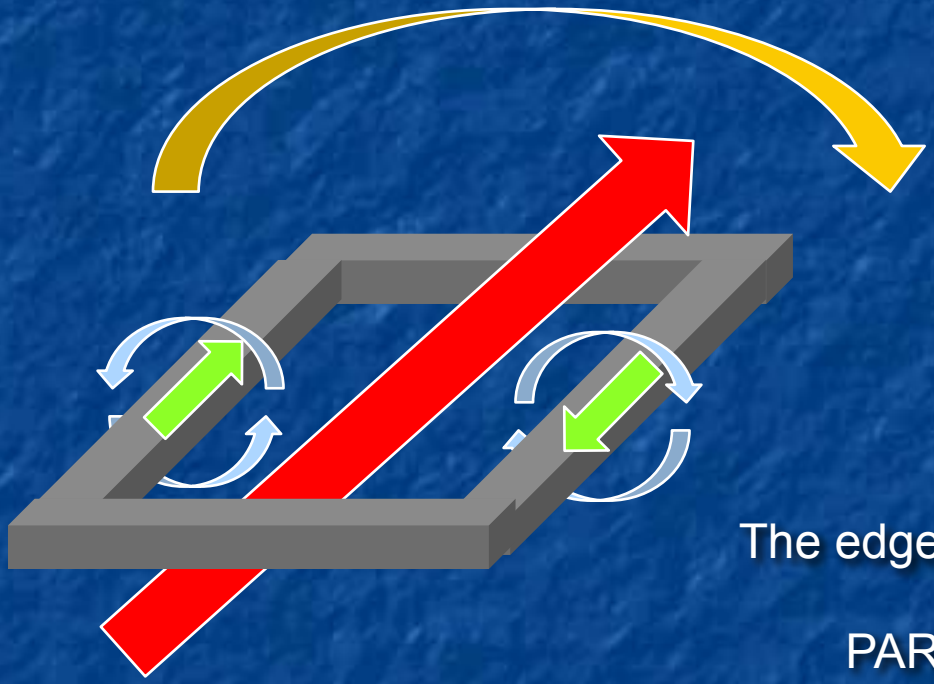
Red: Rotating magnetic field

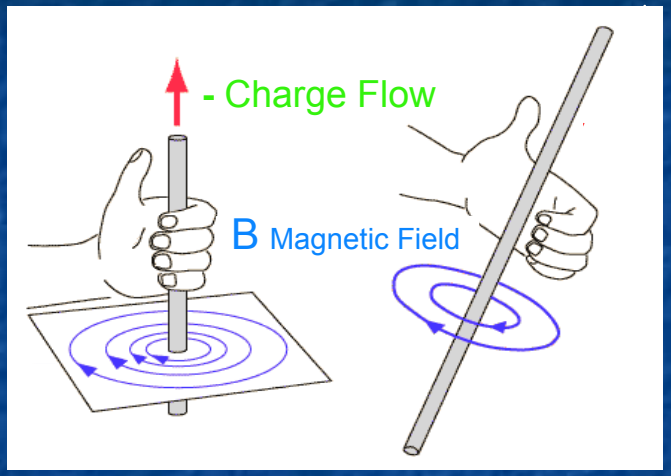
Blue: Motion of charge, relative to field

Green: Force on electrons => movement

Next apply Lenz's LH Rule of Electro-Magnetism:

To figure out the magnetic field created by those now moving electrons





The edges of the ring's **induced magnetic field**

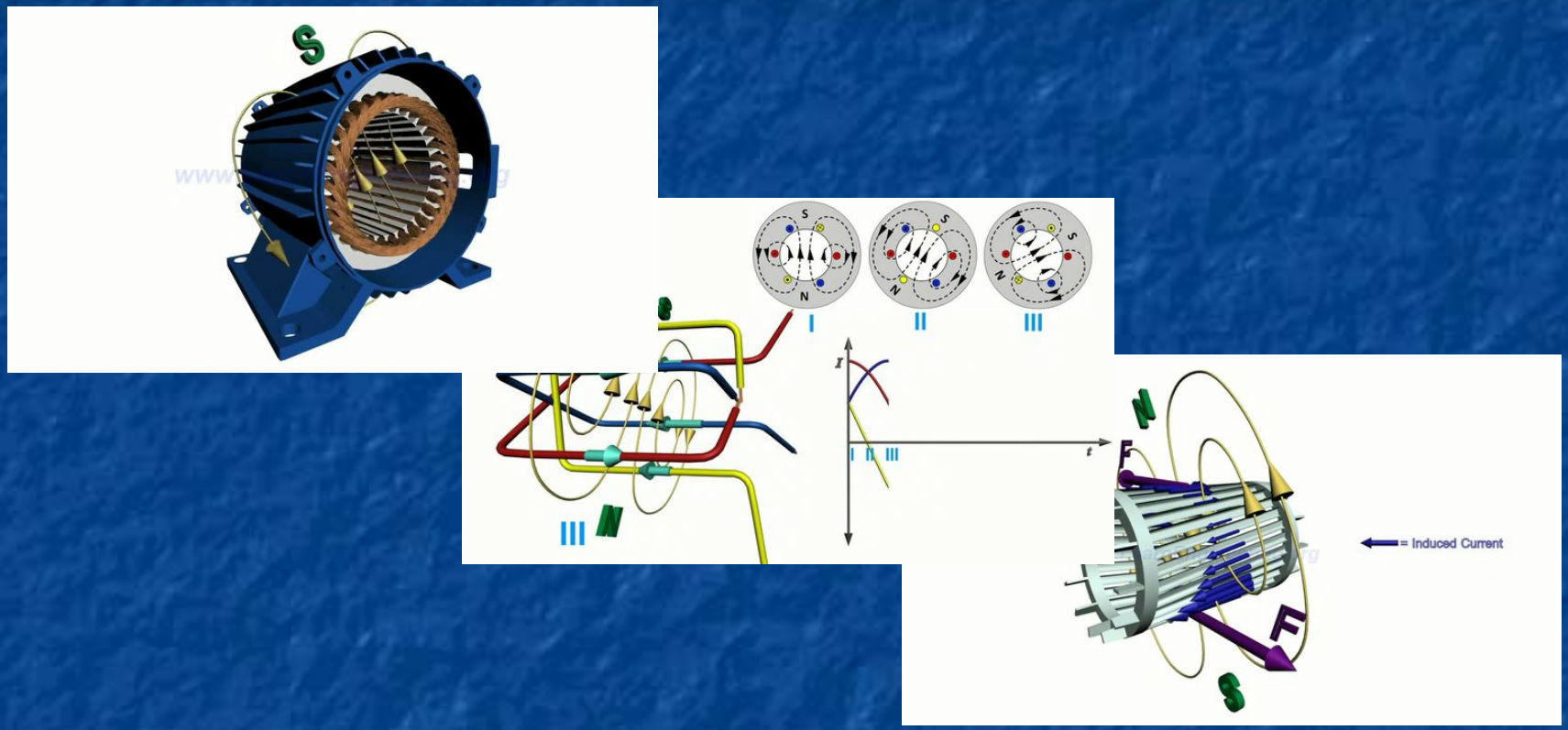
PARALLEL those of the **rotating field**

So these two fields REPEL one another

Rotating field will thus drive rotation of ring

As depicted in this "www.LearnEngineering.org" animation

Screenshots from the almost five minute long animated tutorial:



One of MANY excellent teaching animations on this website

Link to original: www.learnengineering.org/2013/08/three-phase-induction-motor-working-squirrel-cage.html

YouTube posting: www.youtube.com/watch?v=LtJoJBUSe28&feature=kp

"Slip?"

Did you catch that animation's reference to slip?

The idea that rotor had to rotate more slowly than rotating magnetic field?

Slip did NOT OCCUR in our earlier permanent magnet or electro-magnet motors

But it MUST OCCUR in **induction** motors because

to have an effect on charges (rather than on other magnets)

the applied magnetic field must be **MOVING** relative to those charges

If the rotor kept pace with rotating field, there would be no relative motion!

Instead, the rotor HAS to rotate more slowly than the magnetic field

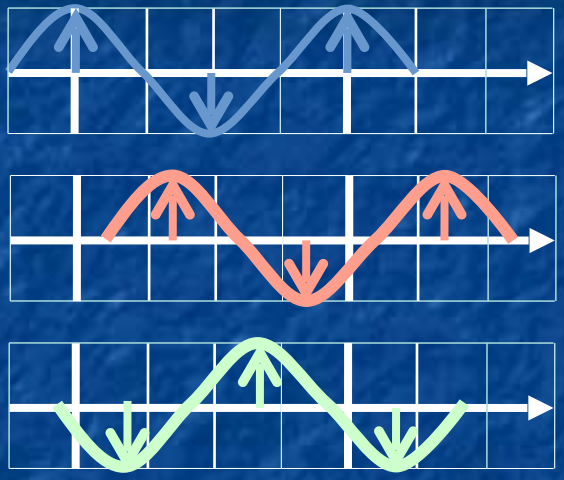
so that the rotating magnetic field is always **moving towards** it,

which THEN induces current in rings => Induced magnetic field,

which **pushes back** against rotating applied field

Time Out!

But this **induction/brushless motor** requires **THREE DIFFERENT AC INPUTS**!



Is it really worth all of that trouble?!

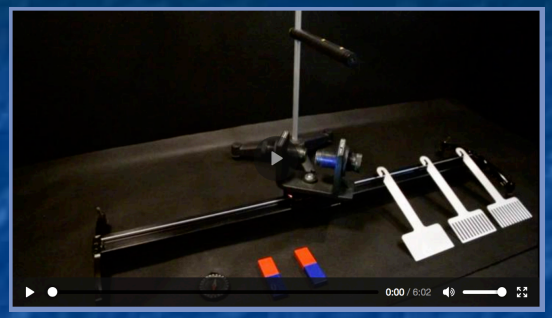
It's actually no trouble because the most efficient power station generators

naturally incorporate multiple pairs of stator coils

which naturally send three different phases of AC power into the Grid!

Flattening out this motor yields a ***Linear Induction Motor***

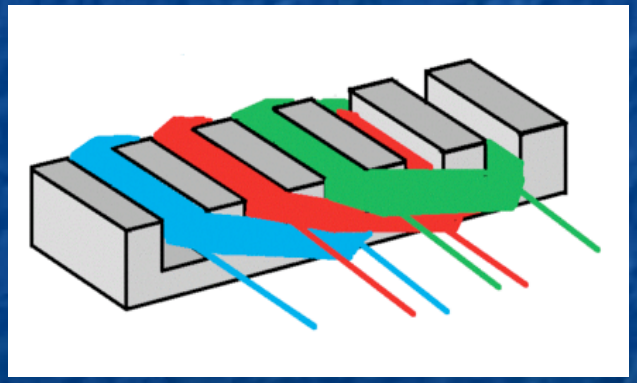
Which can propel metal shapes in a line by passing moving magnets below them:



As evident in this demonstration

But in lieu of moving permanent magnets, a linear induction motor makes use of

long rows of electromagnets, which are turned on and off in sequence



=> Levitation & propulsion of **MAGLEV TRAINS**

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

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

On to this note set's final topic: ***TRANSFORMERS***

What exactly IS electrical power? It involves flowing electrical charge

Which delivers power in a way that is analogous to water power

Imagine two pipes supplying water:

A **Fat Pipe** supplies lots of water flow, but at miniscule pressure

A **Skinny Pipe** supplies miniscule flow, but at at high pressure

NEITHER could supply very much water power, because to do much work:

You need BOTH flow AND pressure

In fact: Water Power = Flow x Pressure

The Electrical Power equivalent = Current x Voltage

But what are the best choices of current and voltage?

Shortcomings of LARGE CURRENT:

Current = electron flow through a material

But flowing electrons bump into atoms, loosing kinetic energy

(=> vibration of those atoms = "heat")

So current flow => LOSS of electrical energy / power

Shortcomings of LARGE VOLTAGE:

Voltage is the analog to water pressure:

High pressure water requires **thicker** pipes

High voltage electricity requires thicker/better insulation

Insulation adds cost / takes up more volume

But too little insulation => chance of failure => electrocution!

The optimum choice thus depends upon the application:

When **TRANSMITTING** electrical power, we want to minimize losses

So there is a strong incentive to REDUCE CURRENT

But power is then maintained by using INCREASED VOLTAGE

When **USING** electrical power (especially in homes and/or appliances):

We often want to minimize bulk by minimizing the thickness of insulation

But to keep the chance of insulation failure to a minimum

We then need to DECREASE VOLTAGE

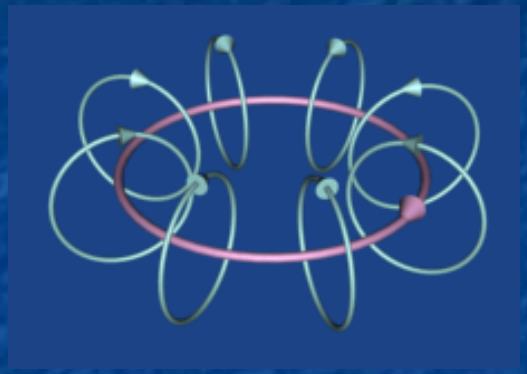
Maintaining power by by then using INCREASED CURRENT

And modern **IC-based electronics** insists on ESPECIALLY LOW VOLTAGES

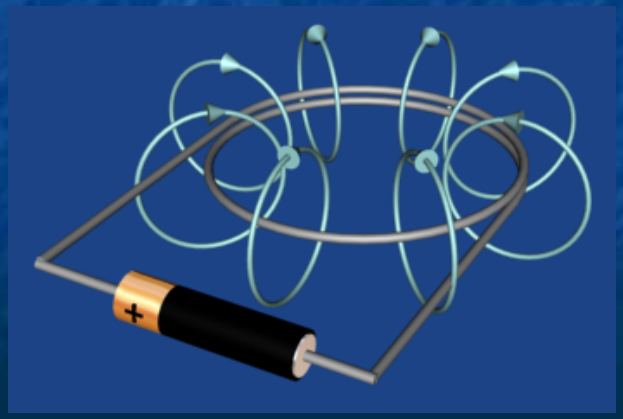
But how can you move from one VOLTAGE to another?

*You need a **transformer***

We've seen how current loops produce magnetic fields (via electro-magnetism):

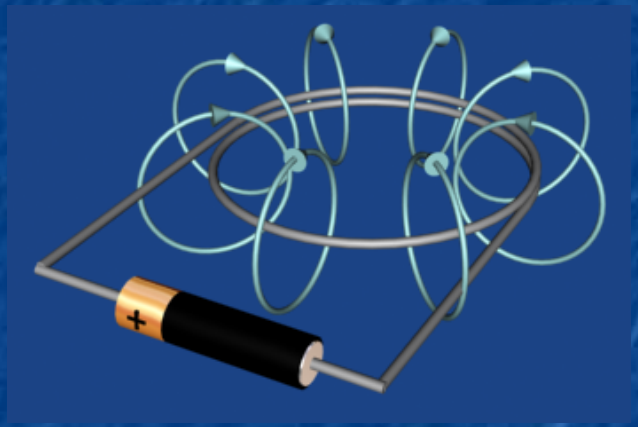


You can drive a (steady) loop of current by connecting a coil of wire to a battery

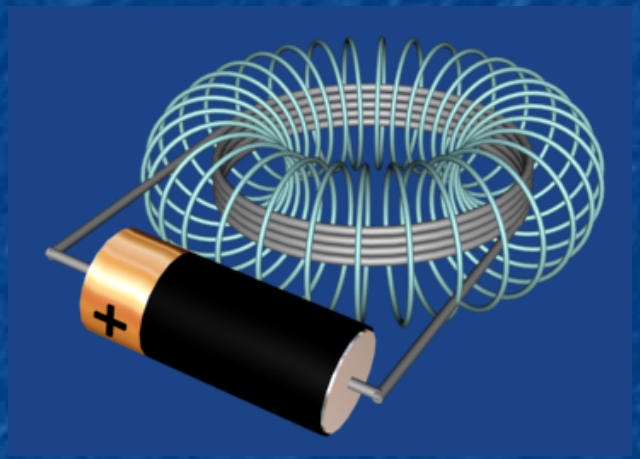


More turns of wire => More intense magnetic field:

One full circle:



Versus four full circles:



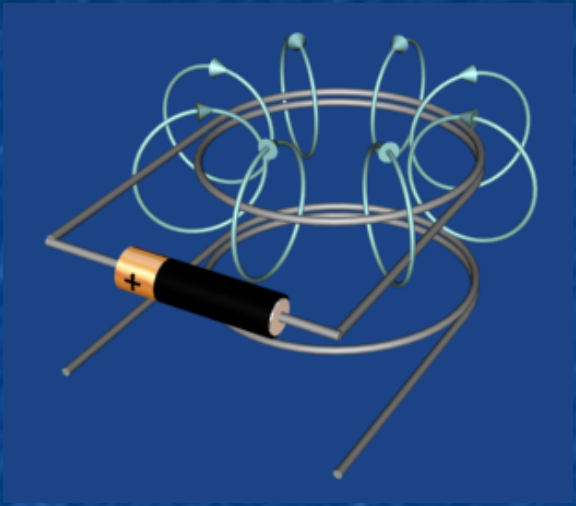
But more loops => More resistance to current flow ("a longer pipe")

So you'll also need higher applied voltage ("pressure") to get the same flow

Which will require a larger (higher voltage) battery

Place two such wire coils side by side

Close enough that the magnetic field from the 1st coil can impinge upon the 2nd coil



There is **CHARGE** in the lower 2nd wire coil

Constant current through upper 1st coil is making a constant **MAGNETIC FIELD**

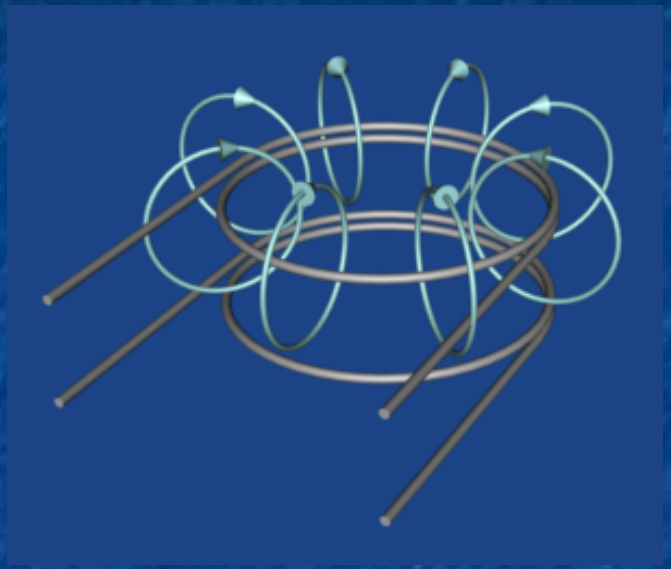
That magnetic field impinges upon the charge in the 2nd coil

But it does not grow or contract, and thus does not **MOVE** by that charge

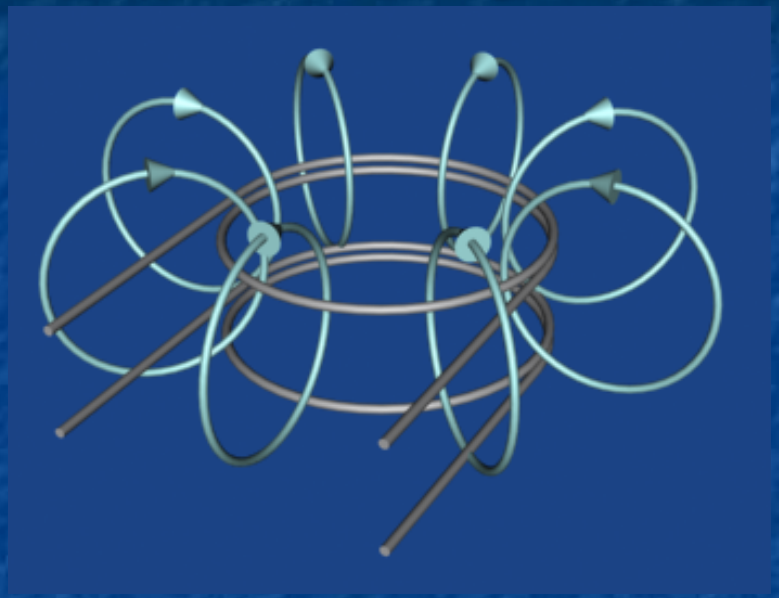
So NOTHING will happen in that 2nd coil!

Instead, apply a CHANGING (AC) voltage/current to the top coil:

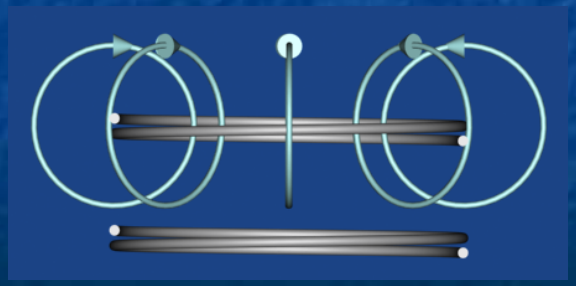
Time 1:

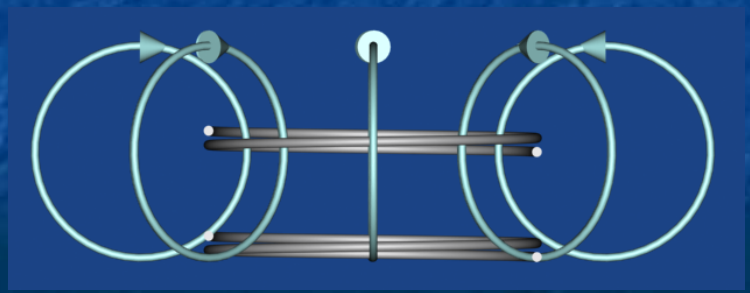


Time 2 (increased voltage/current):



Side view: **See how growing field from top coil sweeps thru the lower coil!**

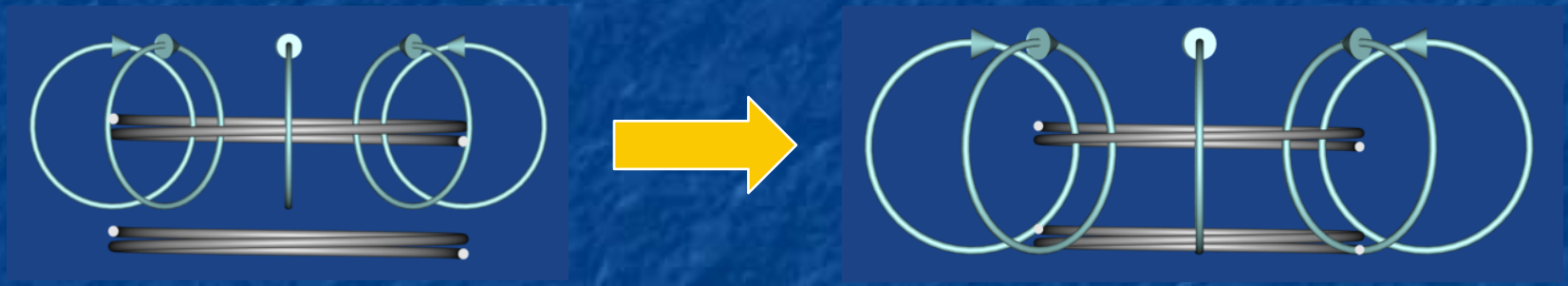




But due to magnetic induction:

The sweep of top coil's growing magnetic thru the bottom coil

will try to induce a current flow out of that bottom coil



So AC electrical power can actually be transmitted between the coils!

Is this the current/voltage transformer that we are looking for?

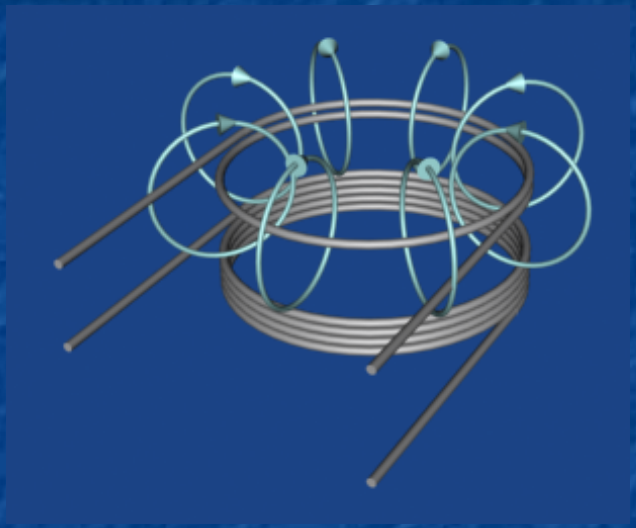
Not yet, at least not with these ~ identical coils

We instead need mismatched coils:

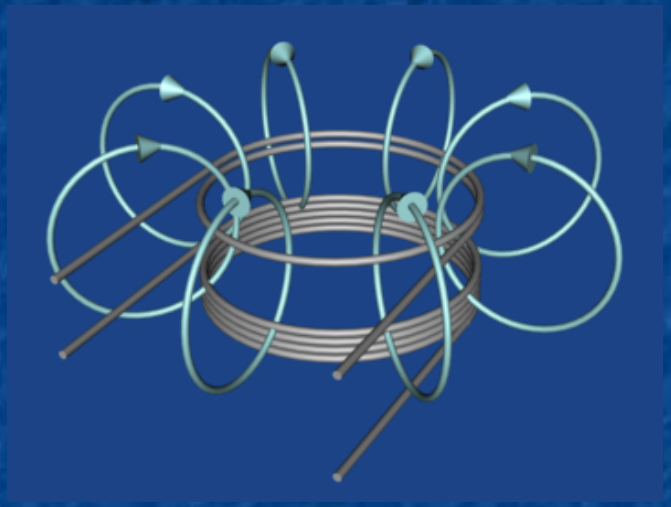
Coils with different numbers of turns:

Again apply AC (changing) voltage/current to the top coil:

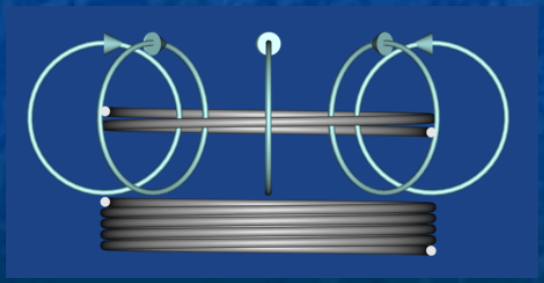
Time 1:

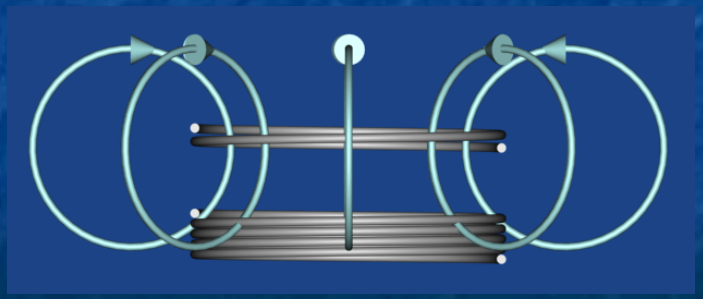


Time 2 (greater voltage/current):



Side views:





More turns intercepted at bottom => We expect MORE (something) coming out!

But more WHAT coming out?

We can't get more POWER out of the bottom coil than was put into the top coil

That would be creating power (and thus not conserving energy)!

But we CAN change the **form** of that constant power = **Current** x **Voltage**

But which goes up, which goes down?

Hint: The longer wire in the 2nd coil more strongly resists flow of current

With coils above we'd get higher voltage but lower current out of the bottom coil

More generally:

For a **TRANSFORMER** (which IS two such closely spaced coils), with

N_{in} = number of input turns N_{out} = number of output turns

Apply an AC SIGNAL to the "input" coil

Because unchanging DC signals produce no magnetic induction!

Between the coils, voltages and currents will then be "transformed" as:

$$\text{Voltage}_{out} / \text{Voltage}_{in} = N_{out} / N_{in}$$

Which, for $\text{Power}_{in} = \text{Power}_{out}$ (i.e., $V_{in} \times I_{in} = V_{out} \times I_{out}$) requires that:

$$\text{Current}_{out} / \text{Current}_{in} = N_{in} / N_{out}$$

But that is for IDEALLY EFFICIENT magnetic induction!

It's the part of the magnetic field sweeping through the 2nd coil that does the work

But in our simple "transformers" above, most magnetic field is way out in space

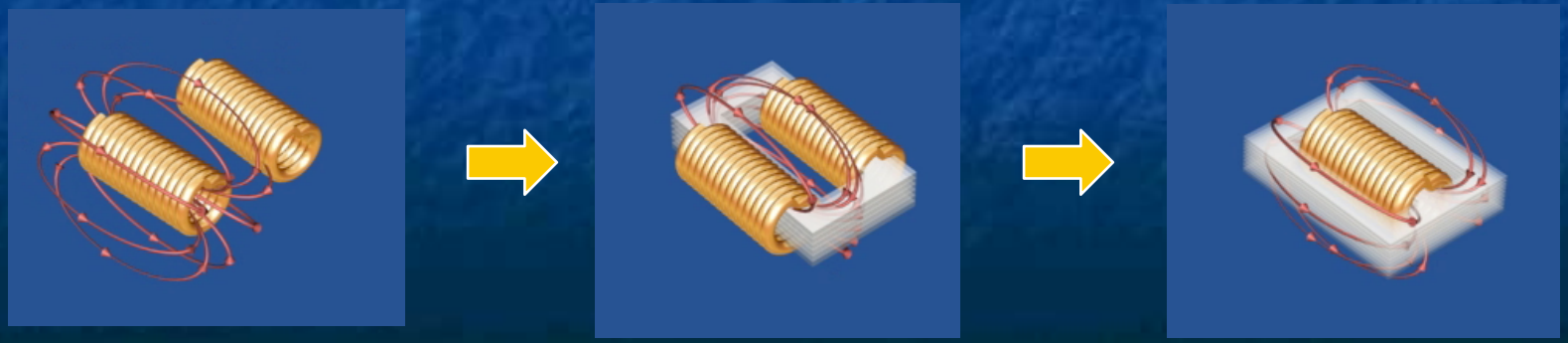
Doing very little to couple the input and output coils together!

So an efficient **transformer** must redirect/concentrate magnetic fields

Which (as we did with motors) can be done by adding "pole pieces"

Consisting of materials that, like iron, tend to "suck in magnetic fields"

(Remember? Due to reorientation of "electron spins")



For anyone interested in the details:

Those **more efficient transformer designs** are fully explained in my **virtual reality animations** on this note set's **Resources Webpage (link)**

But rather than further risk **brain freeze**, I think it's more important that I now wrap up with a summary of this note set's most important points:

Magnetic Induction provides the basis of:

DC electric motors which, if we **drive** their rotation, become **DC generators**

AC electric motors which, if we **drive** their rotation, become **AC generators**

Including Nikola Tesla's clever **AC induction / "brushless" motor**

Which requires nothing other than a piece of metal for the rotor

(for which there is a similar - but not identical - generator design)

MOTORS (along with heaters) are our #1 consumers of electrical power

GENERATORS now provide 99% of that U.S. electrical power

(With the remaining 1% is instead provided by photovoltaic solar cells)

Magnetic Induction also provides the basis for:

AC transformers which allow us to alter AC voltages and currents

And to do this cheaply, compactly, and very efficiently

For motors, AC power is more versatile & more controllable:

DC motors change speed any time the voltage wanders or the load changes

But AC motor speed is pretty much locked into the AC power frequency

And ONLY AC power can be "transformed" via **transformers**

Allowing for separately optimized power transmission AND power consumption

Thus, while some early power systems were built with DC and others with AC,

for instance in the US: Thomas Edison's ruthlessly promoted DC systems

versus Nikola Tesla & George Westinghouse's AC systems

By more effectively exploiting Magnetic Induction
AC power systems won out . . . EVERYWHERE!

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