

FieldForge: Electricity, Magnetism & Microelectronics

Name	Integral equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\epsilon_0} \iiint_{\Omega} \rho dV$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \left(\iint_{\Sigma} \mathbf{J} \cdot d\mathbf{S} + \epsilon_0 \frac{d}{dt} \iint_{\Sigma} \mathbf{E} \cdot d\mathbf{S} \right)$

About Me



Mike.Ranjram@asu.edu

Mike Ranjram

Assistant Professor

School of Electrical, Computer, and Energy Engineering

Ph.D., Massachusetts Institute of Technology, Cambridge, MA (2021)

M.A.Sc., University of Toronto, Toronto, ON, Canada (2015)

B.A.Sc., University of Toronto, Toronto, ON, Canada (2013)

Dr. Ranjram's main research interest is in making power electronics smaller, more efficient, and more capable, and in leveraging these improvements to enable the next generation of sustainable systems and devices. A current focus is on high-frequency power conversion, and on system- and component-level techniques for reducing the cost, volume, weight, and loss of power magnetic components, which today present a dominant bottleneck toward improved power conversion.

He has developed high performance power electronics in a wide range of applications, including 45W mobile phone chargers, 1kW data center supplies, 30kW battery energy storage systems, and MW-level high-voltage dc systems.

Dr. Ranjram is a recipient of the IEEE Transactions on Power Electronics Prize Paper Award, the 2025 IEEE Region 6 Outstanding Educator Award, and is a multiple-time winner of the ASU Top 5% Teaching Award. He authored the solutions manual for the 2nd edition of *Principles of Power Electronics*.

Miniaturized and Advanced Power Electronics Lab

“MAPEL” (🇨🇦)



Roderick



Vibhas

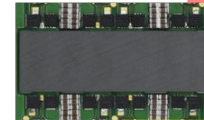


Diego

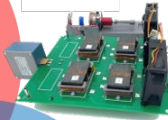


Brandon

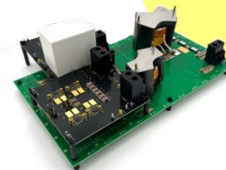
Our research group seeks to dramatically improve the **size, efficiency, operating range, and performance** of power electronics and leverage these improvements to move energy systems forward.



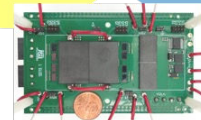
Components



Converters



Systems



NSTXL
NATIONAL SECURITY TECHNOLOGY ACCURATOR

Our Broadest Objective as Engineers



The world is this big,
complicated, seemingly
unknowable thing

Our Broadest Objective as Engineers



[wikipedia.org/Maxwell's equations](https://wikipedia.org/Maxwell's%20equations)

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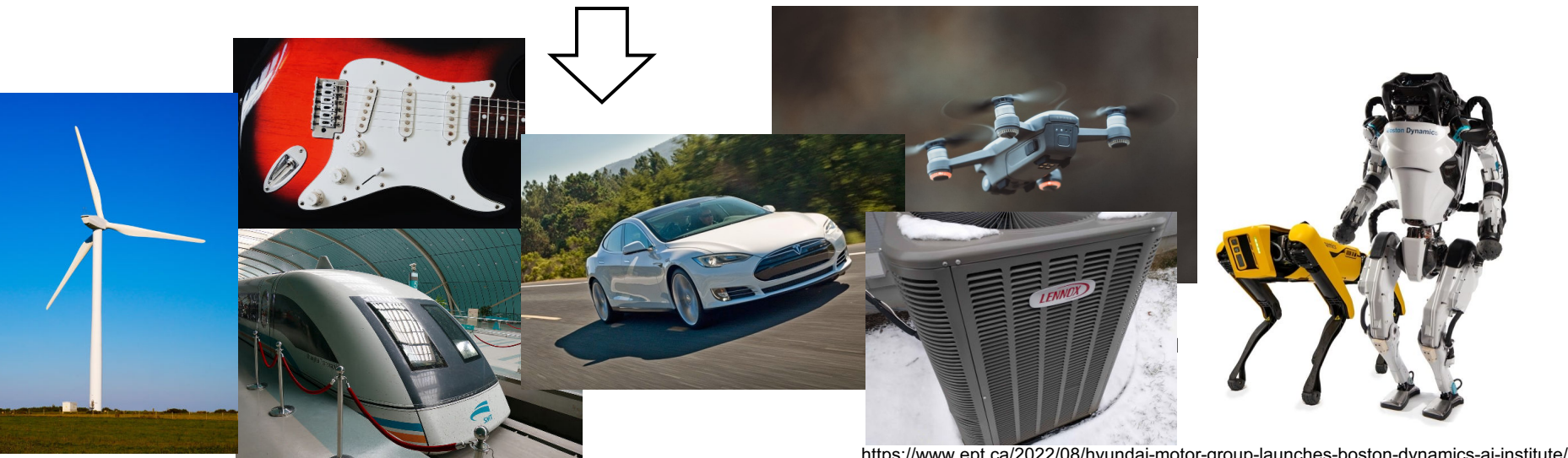
Over time and with hard
work, we've worked out
useful patterns and
structures

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\epsilon_0} \iiint_{\Omega} \rho \, dV$	$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$
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Our Broadest Objective as Engineers

Name	Integral equations	Differential equations
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Our job is to get comfortable with these **tools**, so that we can help build the next great, important things that will make the world a better place.



Maxwell's Equations are the Foundation

- All of electrical engineering is built on the physics of electricity and magnetism
- These physics are captured by four beautiful equations called

“Maxwell's Equations”

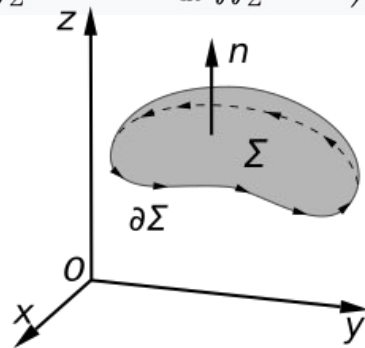
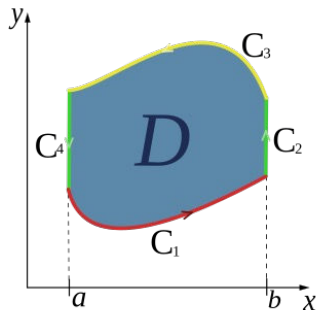
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- But my junior and senior students ***routinely*** communicate a feeling of discomfort with these equations – **that was my feeling too**

These Equations are Confounded by Vector Calculus

- The most common way we encounter these physics is tied to learning 3D vector calculus.
- A barrage of squiggles and three-dimensional unit spaces formalizations and transformation (cartesian, cylindrical, spherical)
- It is easy to become inundated with the *mathematics*

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$$\oint_C (L dx + M dy) = \iint_D \left(\frac{\partial M}{\partial x} - \frac{\partial L}{\partial y} \right) dA \quad \oint_{\partial\Sigma} \mathbf{F} \cdot d\mathbf{r} = \iint_{\Sigma} (\nabla \times \mathbf{F}) \cdot \mathbf{n} dS.$$

Problems and Proposed Solutions

Problem 1: Electricity and Magnetism are invisible; we have limited opportunities to gain intuition for them.

Solution: Give students more hands-on experiments to build intuition.

Problem 2: Maxwell's Equations are intimidating owing to their reliance on 3D vector calculus

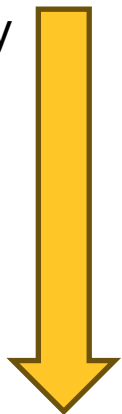
Solution: Show students these equations early, acknowledge they are intimidating, but walk through how they match the intuition built from hands-on experimentation.

Our Track: Gain Intuition on Electricity and Magnetism

- Piloted five-day program for Grade 10 Students at Wego High School in Taipei, Taiwan

“Maxwell’s Equations”

Monday



Friday

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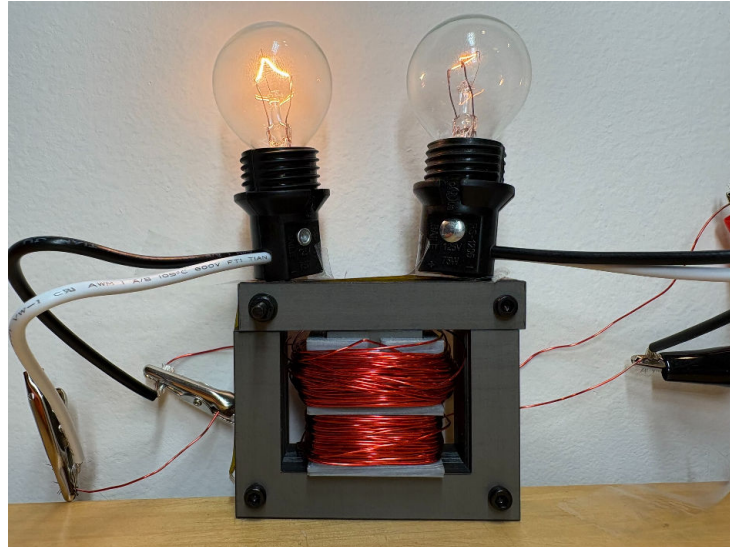
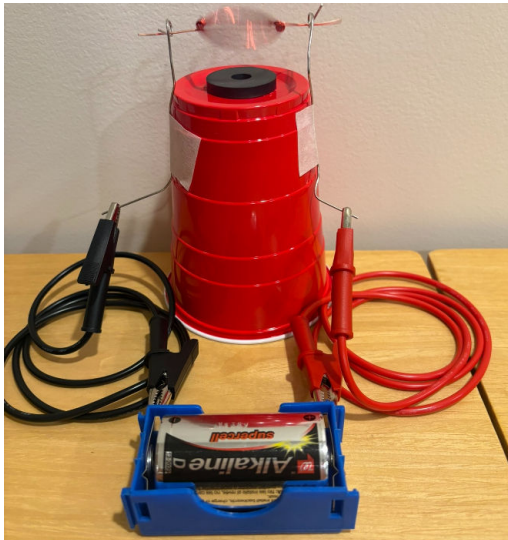


James Clerk Maxwell

We explored these physics and built an understanding and intuition for what these equations tell us, and how they were discovered

Our Goal Today: A Crash Course of This Track

Monday	Tuesday	Wednesday	Thursday	Friday
Electrostatics	Magnetostatics	Electricity → Magnetism	Magnetism → Electricity	Waves and Conclusion



Gauss's Law of Electricity

$$\oiint E \cdot dA = \frac{Q_{enc}}{\epsilon}$$

“Add up everything on the surface of a volume of interest”

“Specifically, the electric field through the surface”

“That equals”

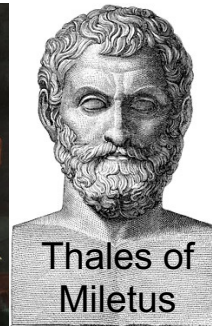
“The total electric charge inside that volume”

The *permittivity of the material*



Gauss

Coulomb

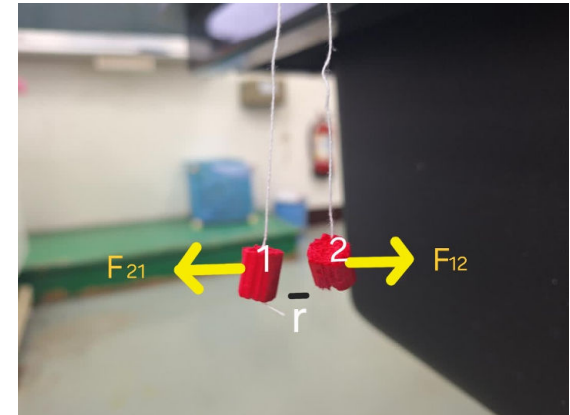
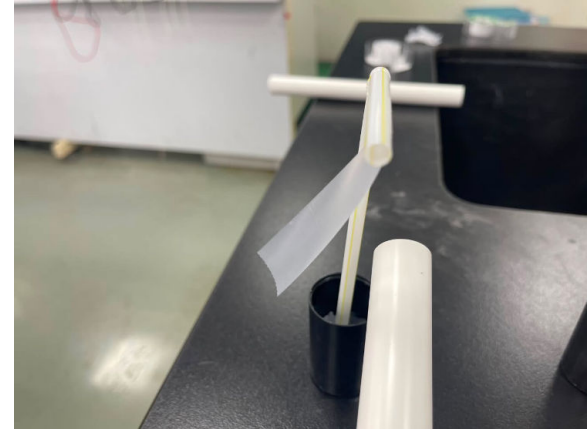


Thales of
Miletus

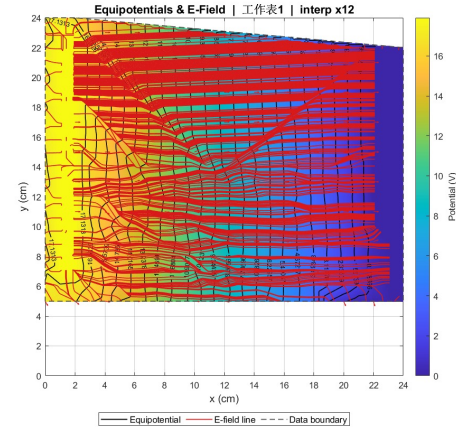
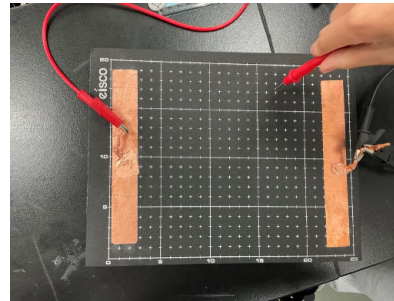
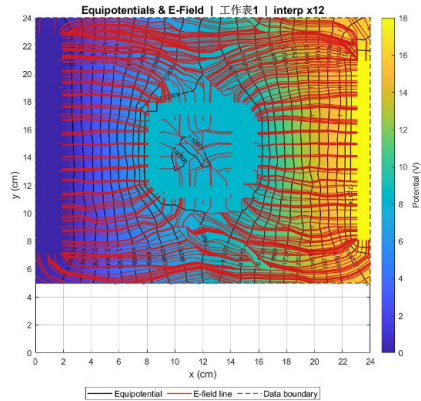
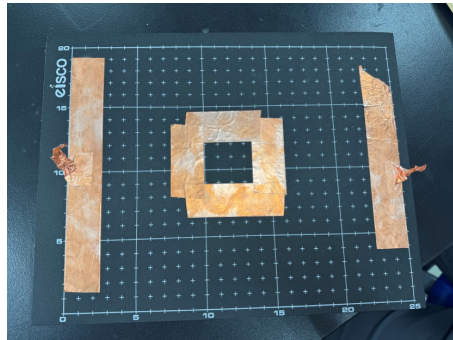
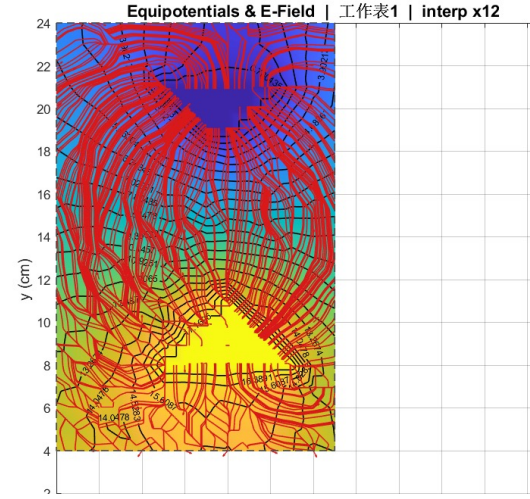
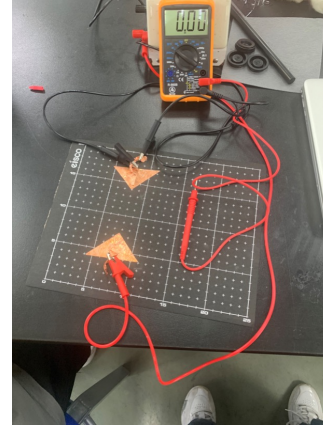
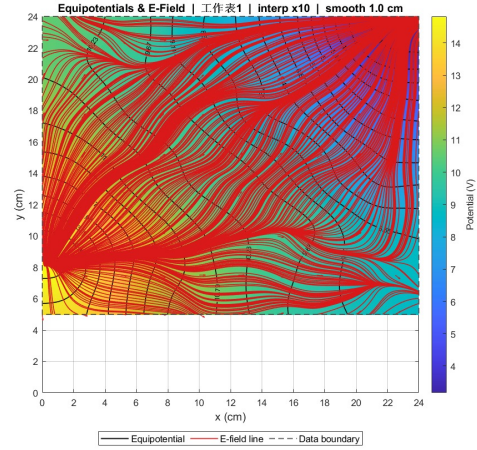
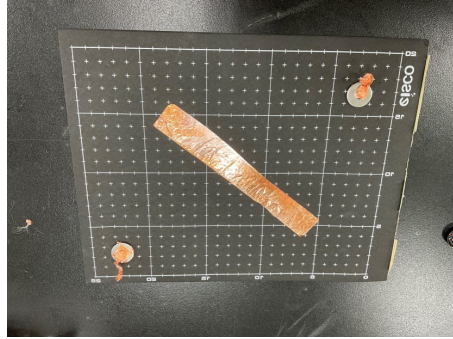
“Charges create electric fields that radiate outwards”

Key Properties of Electricity

- Everything has charge
- Charges can be transferred between dissimilar materials; insulators hold charge, conductors move them
- *Electroscopes* can measure electrical forces
- Simple experiments can be used to prove quantitative predictions



Electric Fields Can be Shaped By Geometry



The Electrostatic Repulsor Experiment

<https://www.exploratorium.edu/snacks/flying-tinsel>

Uses common hardware:

- Foam insulation block
- Aluminum pie pan
- Plastic cup
- Tape
- Something to generate charge (e.g., lamb's wool)
- Tinsel

Connection to Gauss's Law

The diagram shows the mathematical expression of Gauss's Law: $\oiint E \cdot dA = \frac{Q_{enc}}{\epsilon}$. Four yellow arrows point from descriptive text to parts of the equation: one from the surface integral symbol to the text "Add up everything on the surface of a volume of interest", one from the dot product $E \cdot dA$ to "Specifically, the electric field through the surface", one from the equals sign to "That equals", and one from the denominator ϵ to "The permittivity of the material". A fifth arrow points from the numerator Q_{enc} to the text "The total electric charge inside that volume".

$$\oiint E \cdot dA = \frac{Q_{enc}}{\epsilon}$$

“Add up everything on the surface of a volume of interest”

“Specifically, the electric field through the surface”

“That equals”

“The total electric charge inside that volume”

The *permittivity of the material*

Gauss's Law Says that Charges Radiate An Electric Field

$$\oiint E \cdot dA = \frac{Q_{enc}}{\epsilon}$$

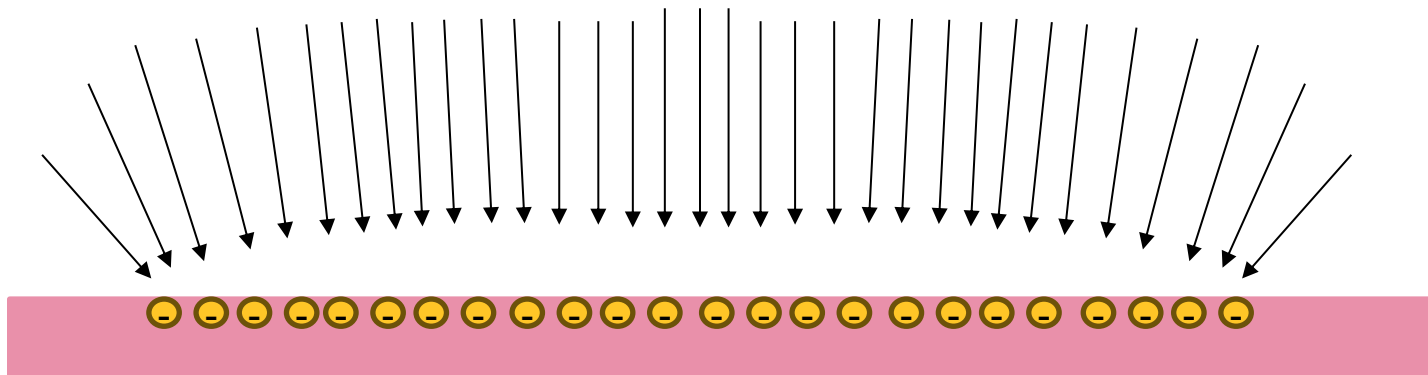
“Add up everything on the surface of a volume of interest”

“Specifically, the electric field through the surface”

“That equals”

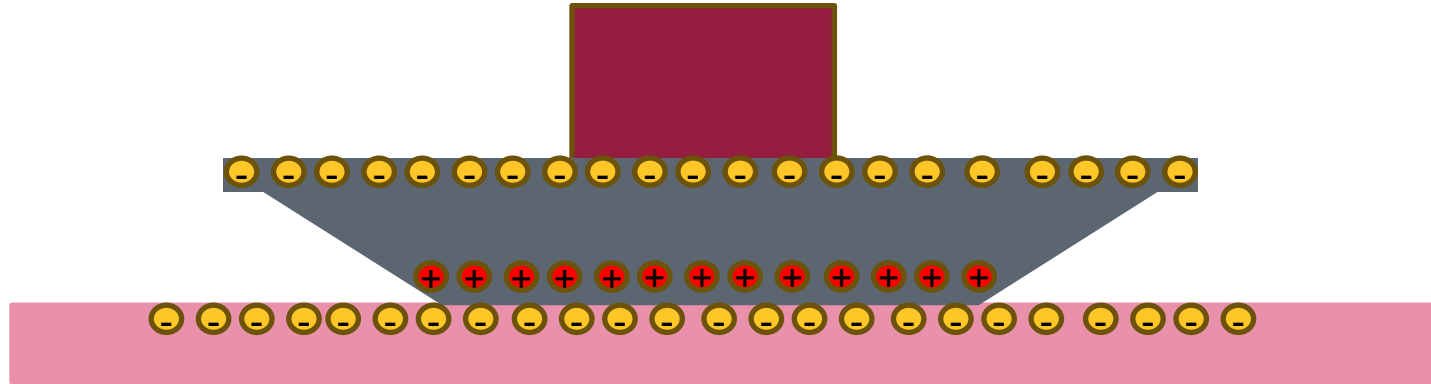
“The total electric charge inside that volume”

The *permittivity of the material*



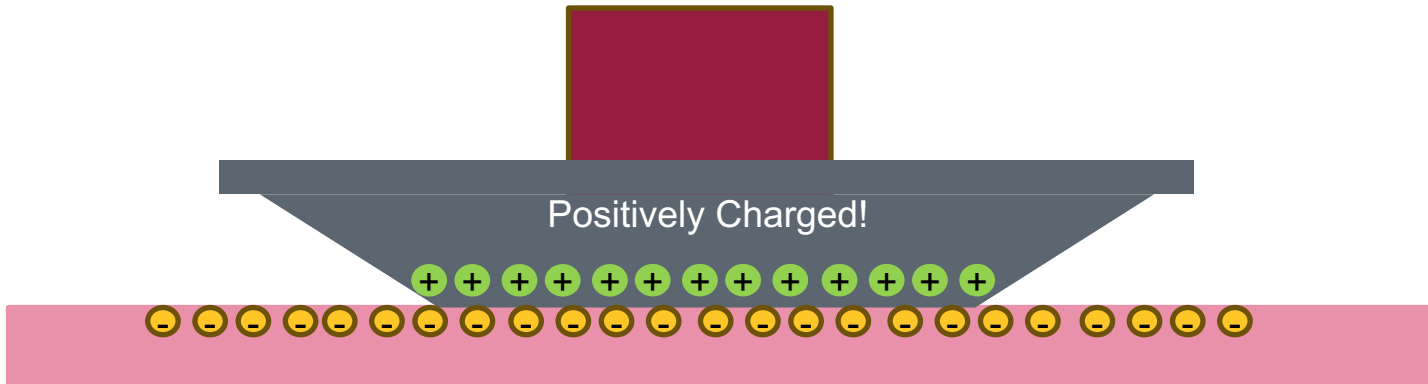
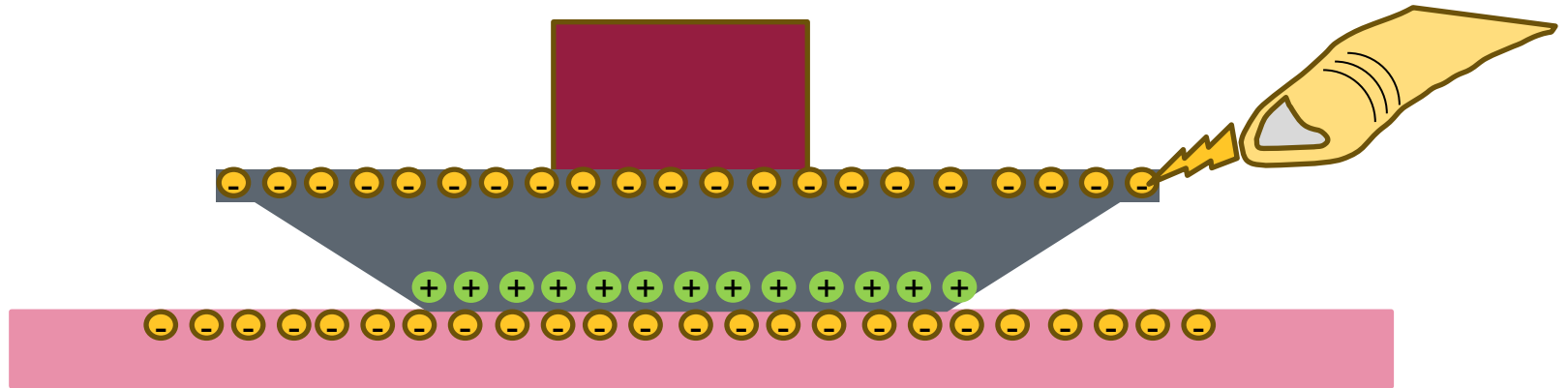
- We can move charges onto our foam block by rubbing lamb's wool on it.
- The charges we deposit radiate an electric field according to Gauss's law
- This field radiates away from the charges, so it is strongest when I am close, and gets weaker as we move away
- We can see this on the block by playing with tinsel

Charges Interact With Other Charges via Electric Fields



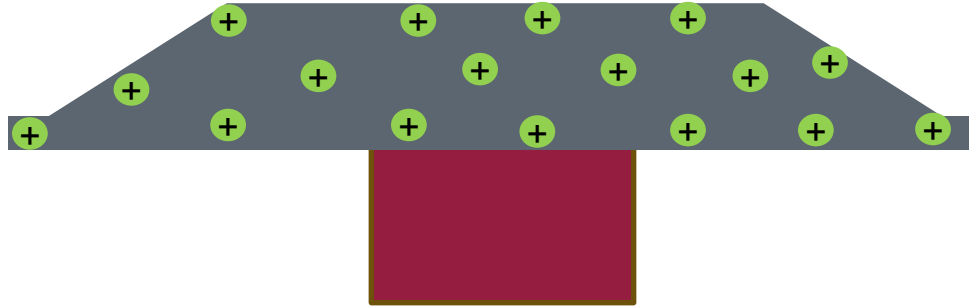
- When we put something metallic, like a pie pan, on the block, it pushes the electrons inside the metal pan away, to the rim of the pie pan
- They want to move as far as possible from the charges on our block
- If I bring my finger to the rim, I give those electrons an escape to move as far as possible away!

Dramatic Illustration



The Charges on the Pan Behave Like the Charges on the Block – They Follow Gauss's Law

- This pan now has a net positive charge, so it also now radiates electric fields just like the block did, just like Gauss's law says it should (e.g., it attracts tinsel)
- (the charges don't like being near each other, so they distribute themselves evenly)



$$\oiint E \cdot dA = \frac{Q_{enc}}{\epsilon}$$

“Add up everything on the surface of a volume of interest”

“Specifically, the electric field through the surface”

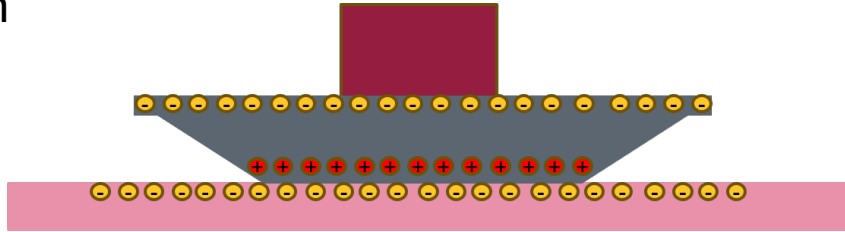
“That equals”

“The total electric charge inside that volume”

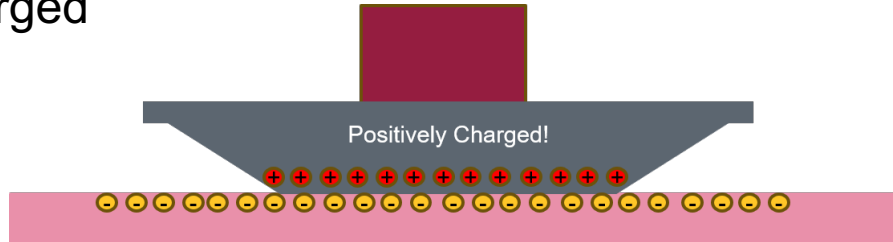
The *permittivity of the material*

Engineering: Can We Do Something Useful With This?

- When we brought the metal pan to the foam block, it pushed charges to the edge of the pan

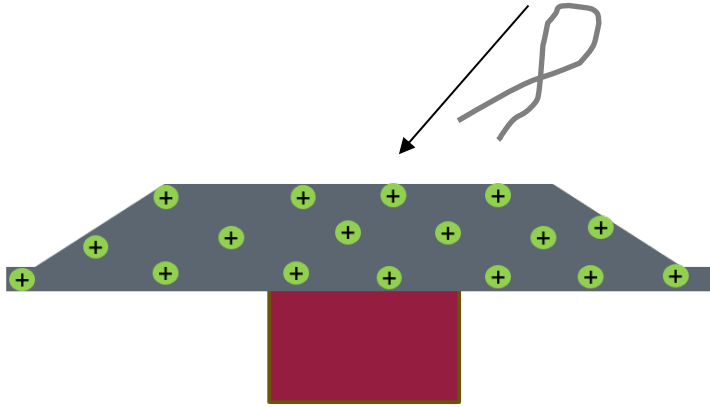


- When we brought another conductor nearby (our finger), the pan became positively charged

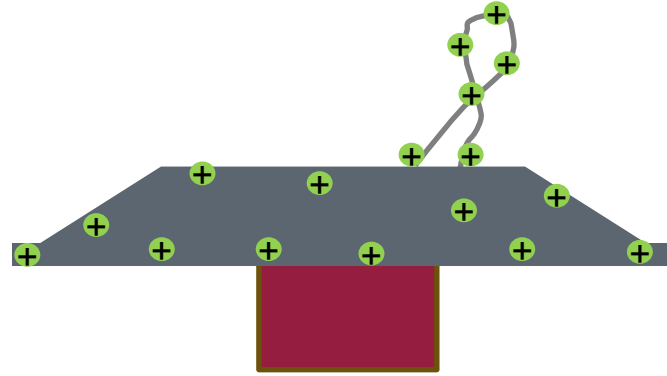


Moving Charges Onto The Tinsel...

- When we bring tinsel close to the pan, it's pulled towards it

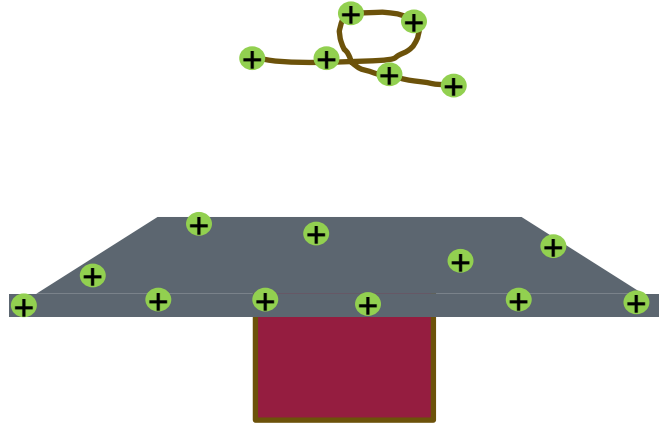


- If we let the tinsel touch the pan, the charges on the pan now have another place to redistribute themselves



- Those charges will move as far as they can from the charges on the pan – and they are strong enough to lift up the tinsel

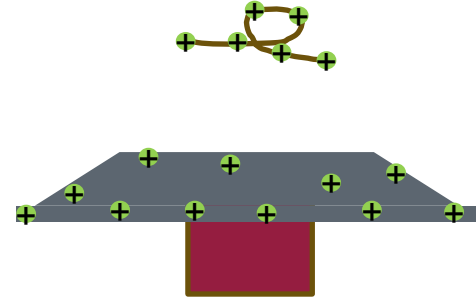
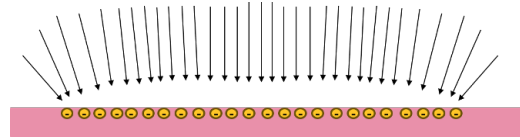
We've Created an *Electrostatic Repulsor*



- The charges all radiate a field, and so the charges still interact with each other even if they aren't touching.
- The tinsel and pan push each other apart, and how high the tinsel floats depends on how much charge we deposited

We've Captured the Base Properties of Electrostatics and Can Attach the Observations to Gauss's Law

- Everything has charge
- Charges can be transferred between dissimilar materials
- Insulators hold charge
- Conductors move them



- We imagine that the charges radiate an “electric field” – so charges can interact with other charges even if they aren’t touching
- Gauss’s Law tells us that the amount of electric field (amount of interaction) depends on how much charge we have
- The amount of interaction depends on how much field we can interact with (as we move farther away, we ‘add up’ less field)/

$$\oiint E \cdot dA = \frac{Q_{enc}}{\epsilon}$$

“Add up everything on the surface of a volume of interest”

“Specifically, the electric field through the surface”

“That equals”

“The total electric charge inside that volume”

The *permittivity of the material*

Gauss's Law of Magnetism

$$\oiint B \cdot dA = 0$$

“Zero!”

“That equals”

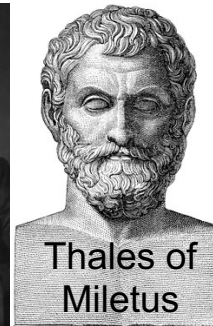
“Specifically, the
magnetic field
through the surface”

“Add up everything
on the surface of a
volume of interest”



Gauss

Faraday

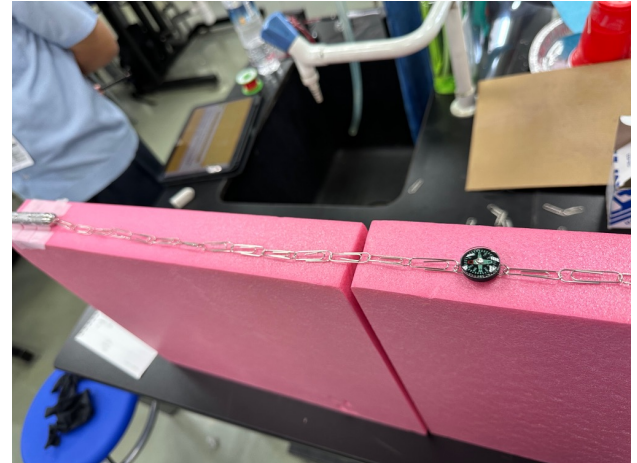


Thales of
Miletus

“Magnetic fields flow
in closed loops”

Key Properties of Magnetism

- Magnetic fields flow in closed loops – they leave North poles towards South poles
- When magnetic fields face each other (North to North) we get repulsion
- When a North faces a South, we get attraction.
- Magnetic fields can be controlled using *permeable* materials; forces add in strange ways; some materials become magnetic when exposed to large magnetic fields



Ampere's Law

$$\oint B \cdot d\ell = \mu I_{enc}$$

Current flowing
through the surface

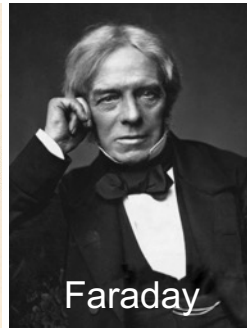
Permeability of
that surface

“Specifically, the
magnetic field on
that perimeter”

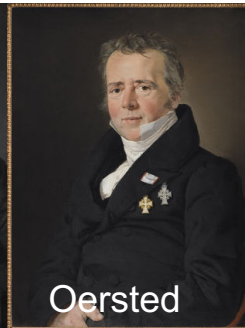
“Add up everything
on the perimeter of a
surface of interest”



Ampère



Faraday

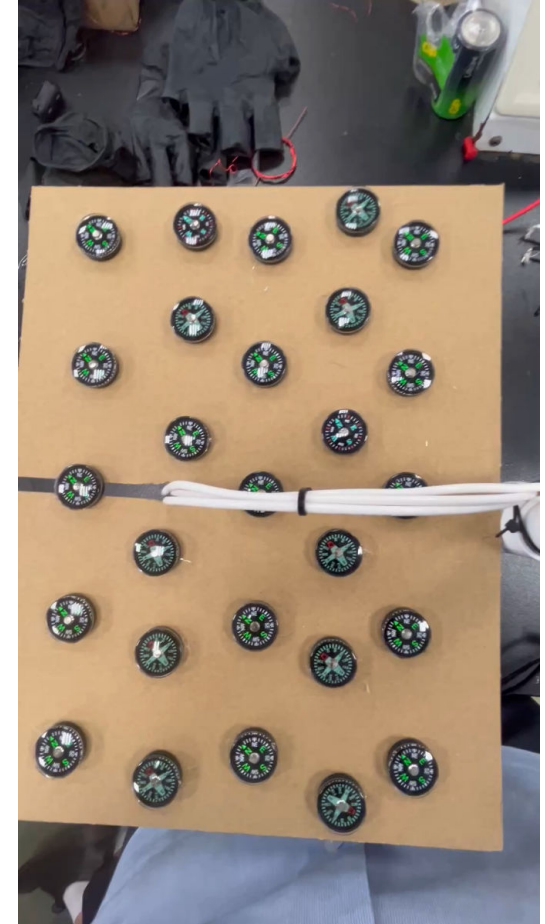


Oersted

“Electricity creates
magnetism”

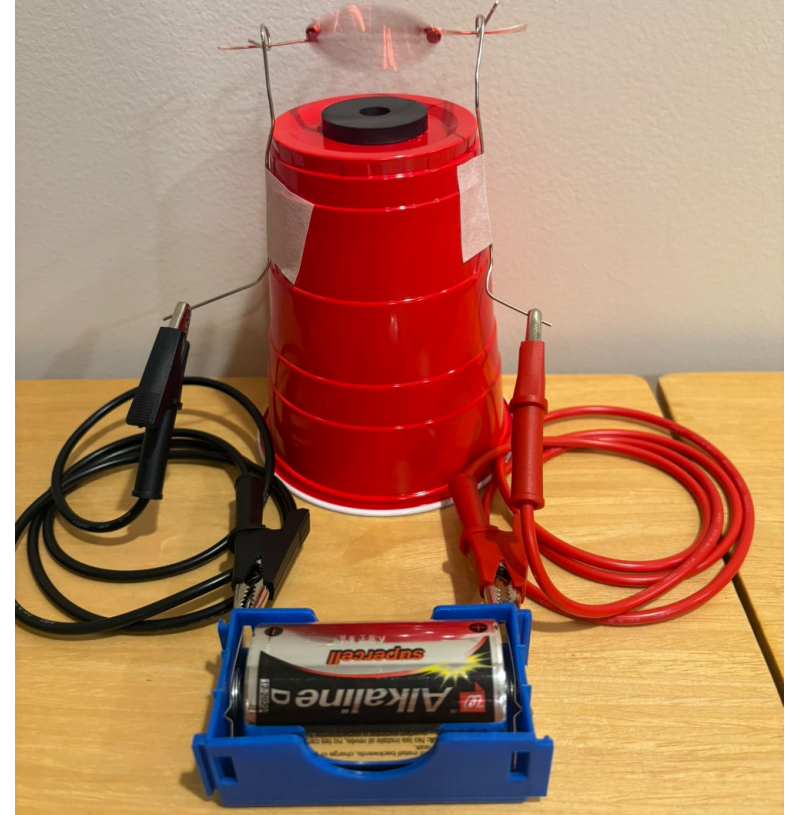
Moving Charges Create Magnetism

- Electric current creates circular magnetic fields
- Current-carrying wires can be pushed and pulled by magnets



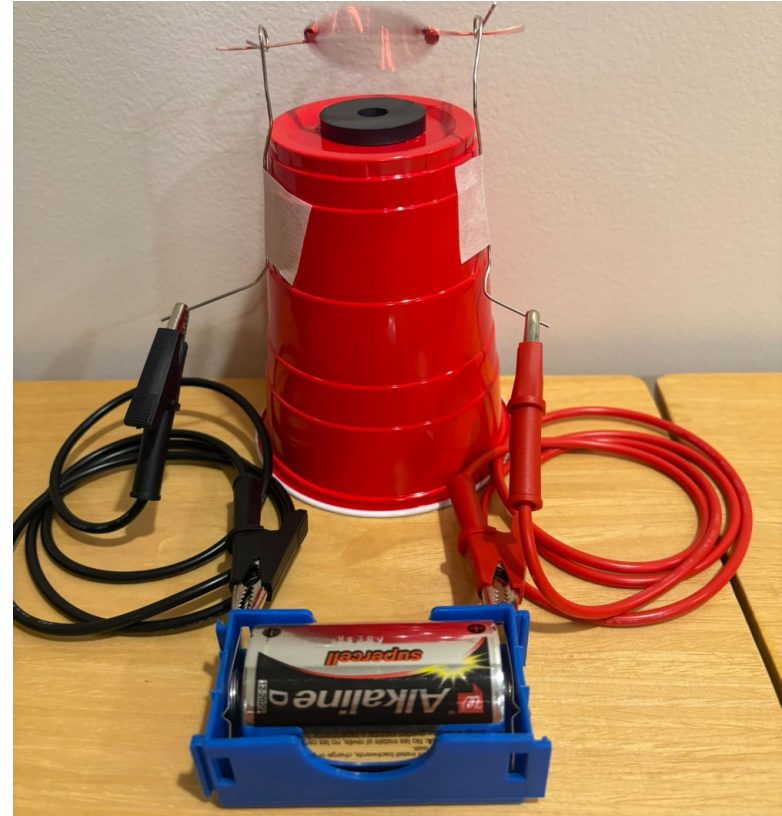
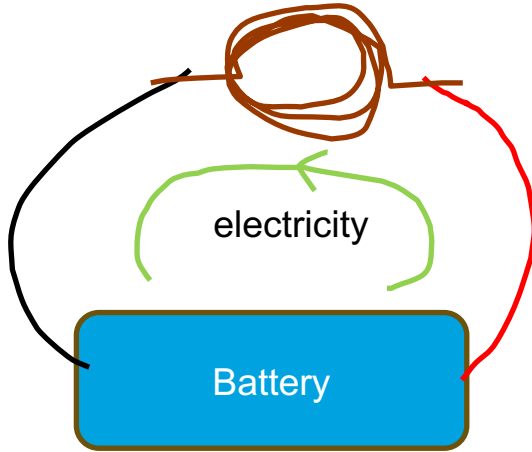
Engineering: Ampere's Law is the Heart of the dc Motor

- **Commutator:** carefully sanded copper wire
- **Brushes:** paper clips
- **Rotor:** Loops of copper wire
- **Stator:** ceramic disk magnet, battery exciter



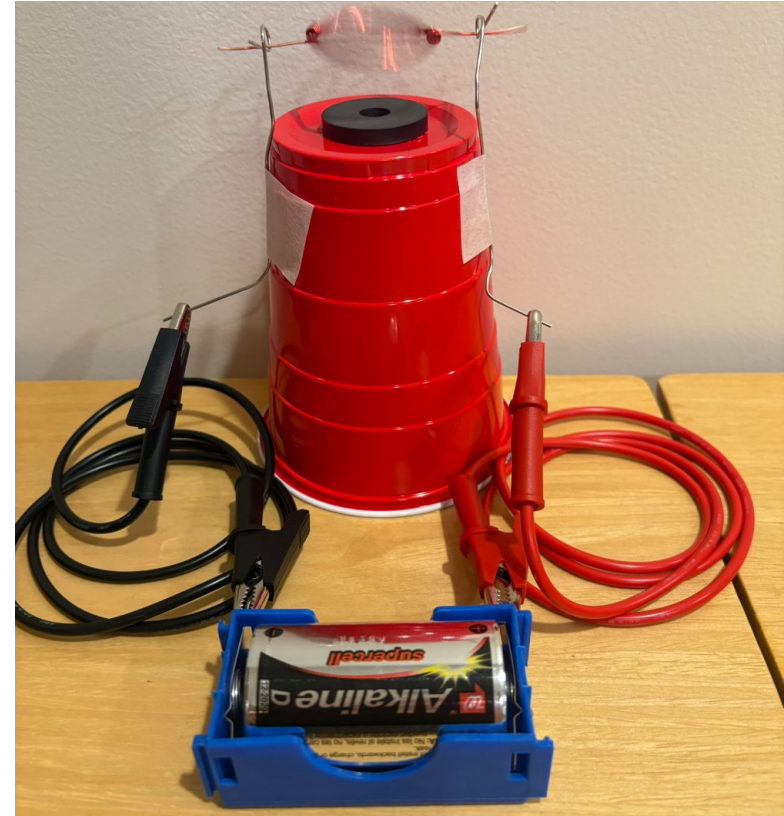
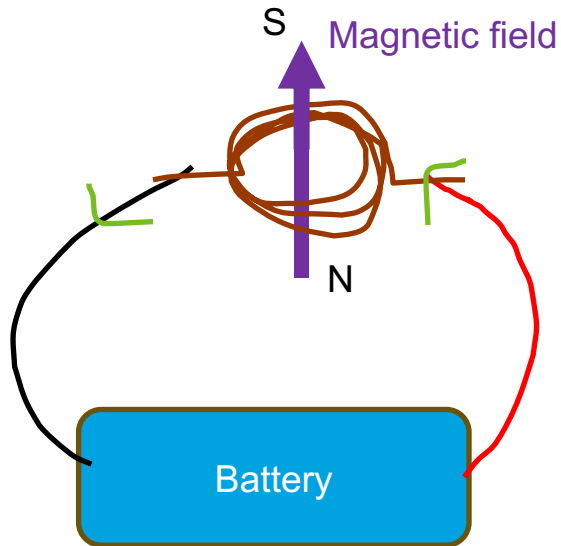
What We're Trying to Do

1. When we connect a wire to the battery, it carries electric current.



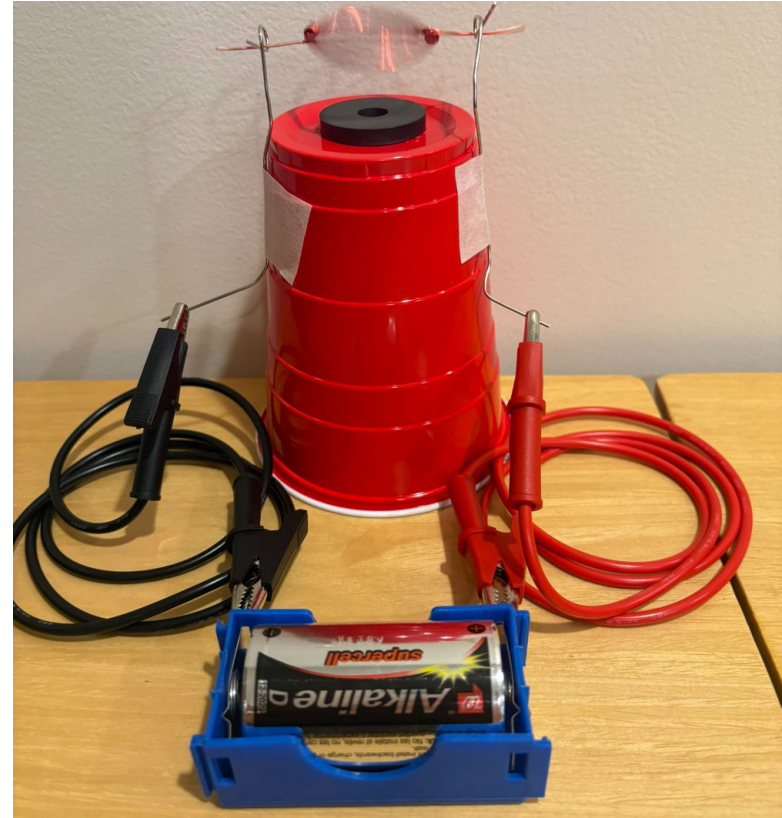
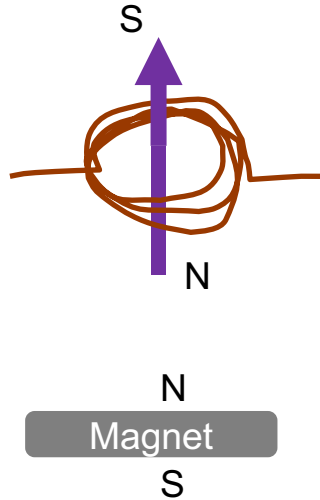
What We're Trying to Do

1. When we connect a wire to the battery, it carries electric current.
2. This electric current produces a magnetic field in the coil wire.



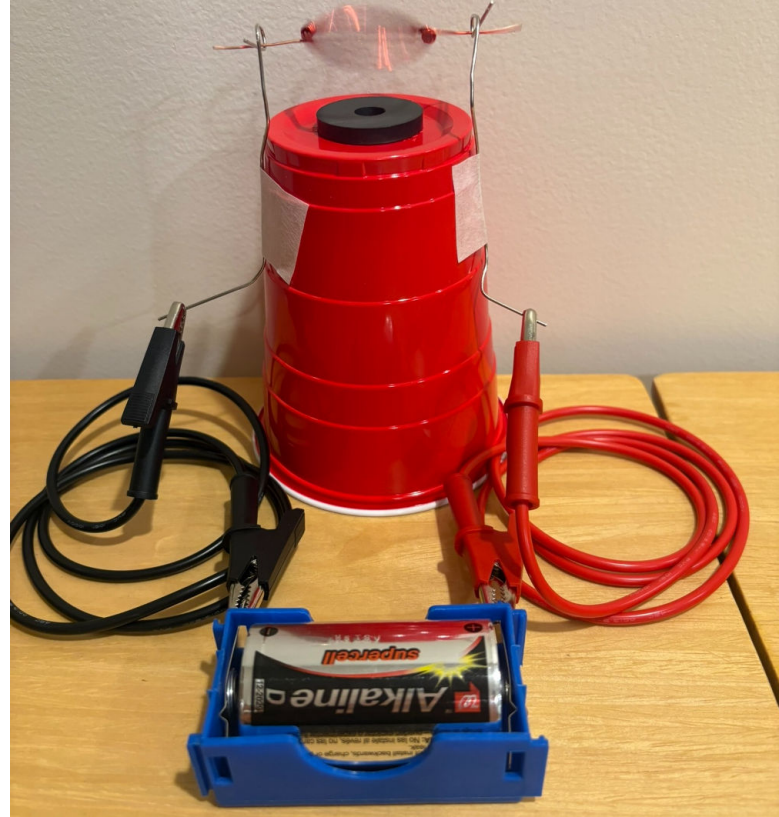
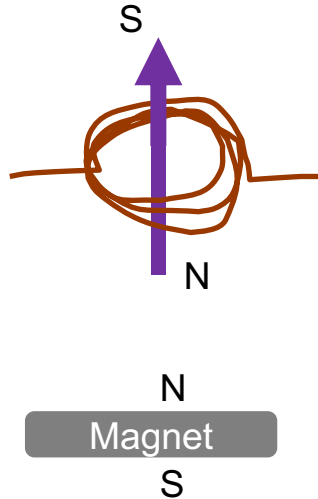
What We're Trying to Do

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2. This electric current produces a magnetic field in the coil wire.
3. This field will attract/repel a magnet below it – so we can *align* the coil to the magnet



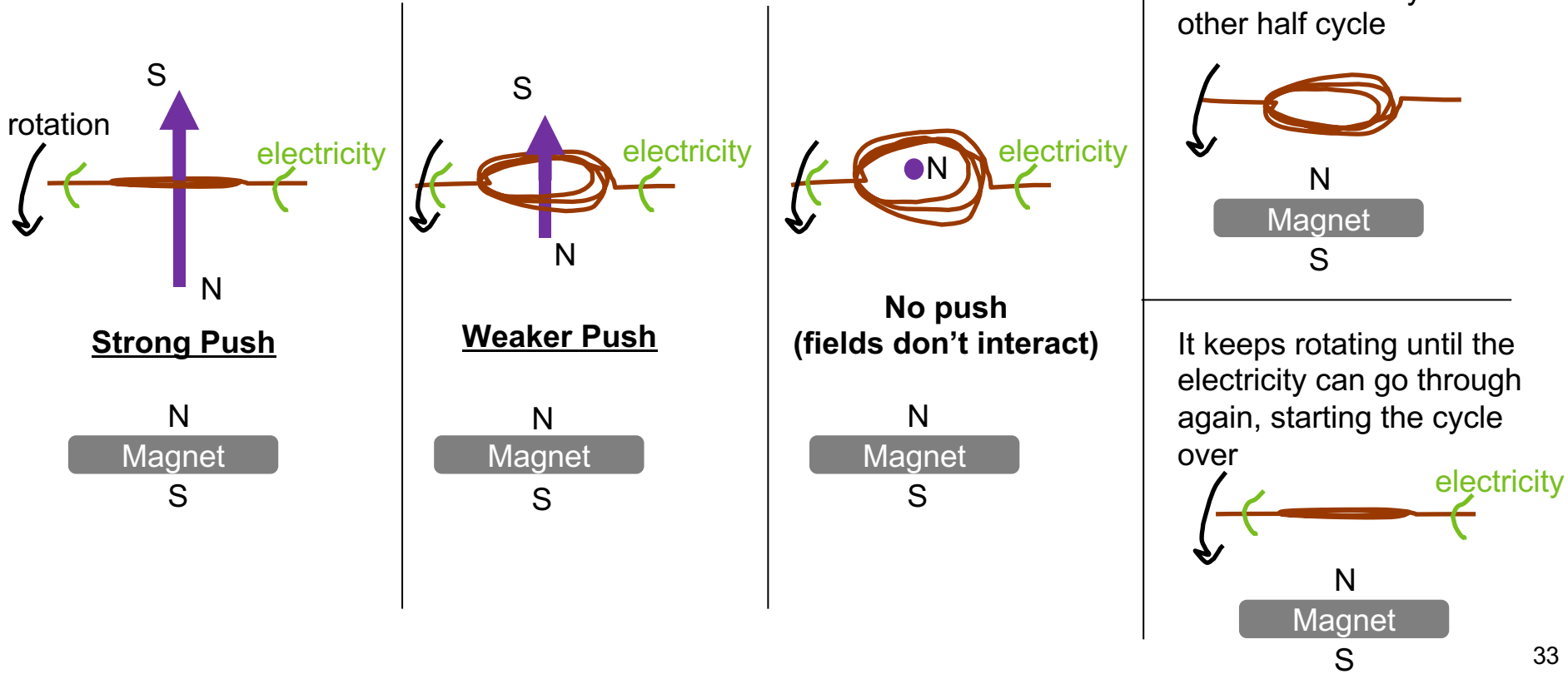
What We're Trying to Do

1. When we connect a wire to the battery, it carries electric current.
2. This electric current produces a magnetic field in the coil wire.
3. This field will attract/repel a magnet below it – so we can *align* the coil to the magnet.
4. If we could get the electricity in the wire to change direction... then we can get the wire to spin!



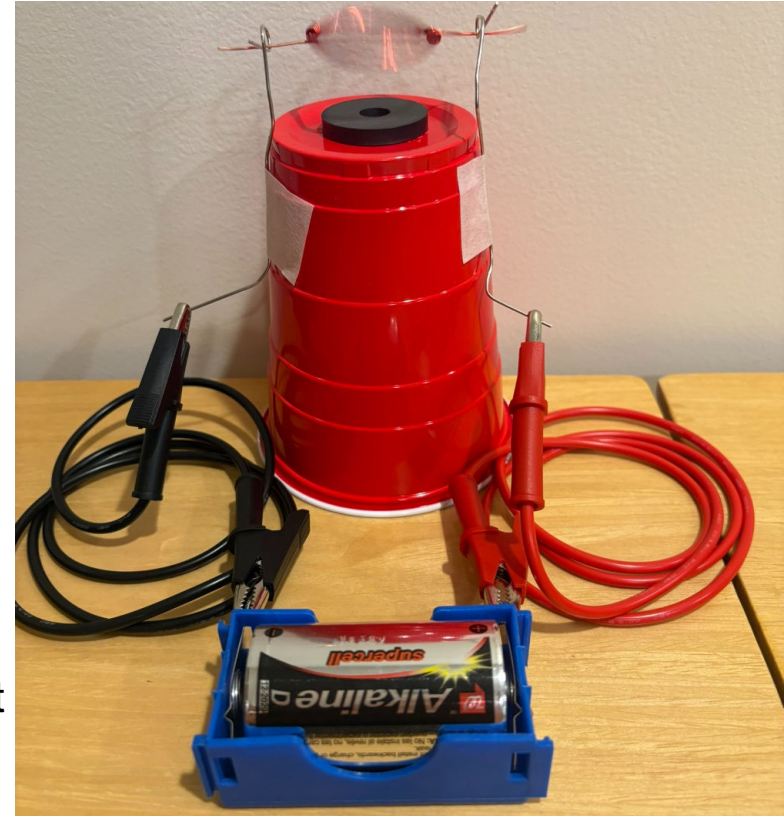
Create a Commutator to Toggle the Magnetism

- The trick: a “commutator” -- we only let current in the wire go in one direction.



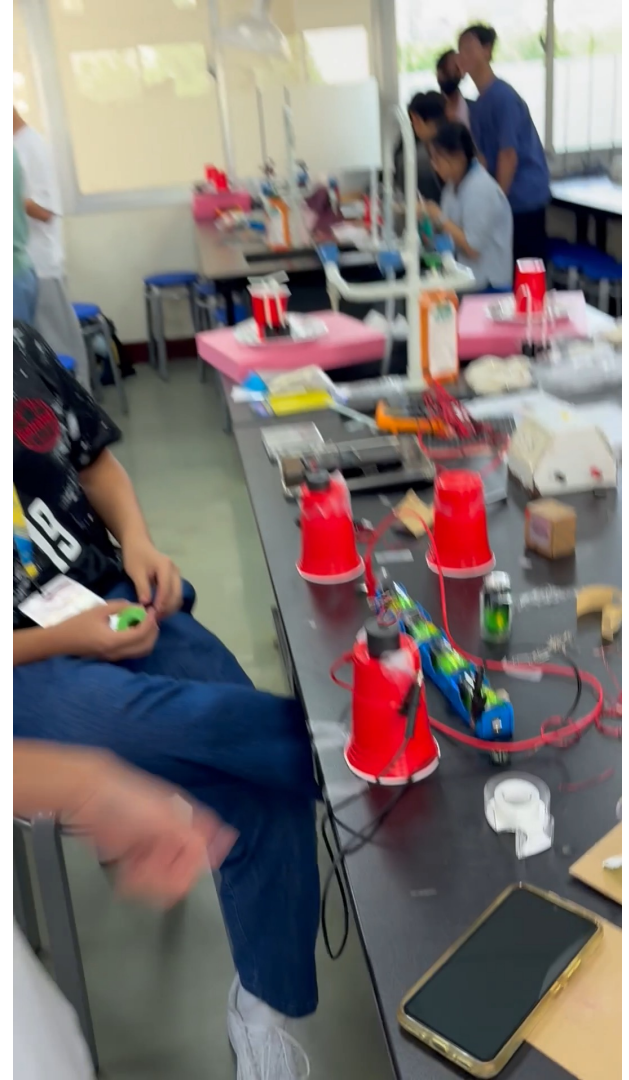
Construction Method

1. Wind 3 turns of wire (D cell battery is a nice 'former'), leave 2-3 cm of straight wire extending from each end (forms the axle).
2. Use sandpaper to completely strip the enamel insulation off one end of the wire (this is the 'always on' end).
3. Use sandpaper to strip ONLY the TOP HALF of the insulation (this is the "half on" end).
4. Place a disk magnet inside the cup and on its bottom.
5. Bend two paperclips into U-shaped cradles and attach them to the cup using tape.
6. Position the wire loop on these cradles – this takes some finagling. The loop should hang horizontally and balanced, and should be as close to the magnet as possible while not touching it through a rotation.
7. Connect the paperclips to the battery and give the coil a gentle push.



Engineering Exploration

- Competition: make the fastest motor. How?
- More magnetism? Try more magnets.
- More electricity? Try more batteries.
- A bigger loop, collecting more magnetic field?
- A smaller loop, so that it's lighter?
- More turns? Fewer turns?



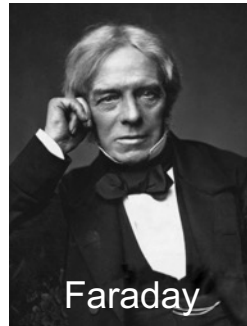
Faraday's Law

$$\oint E \cdot d\ell = - \frac{d}{dt} \iint B \cdot dA$$

Voltage on the
perimeter of a
surface of interest

Rate of
change

Sum of all the magnetic
field through that surface

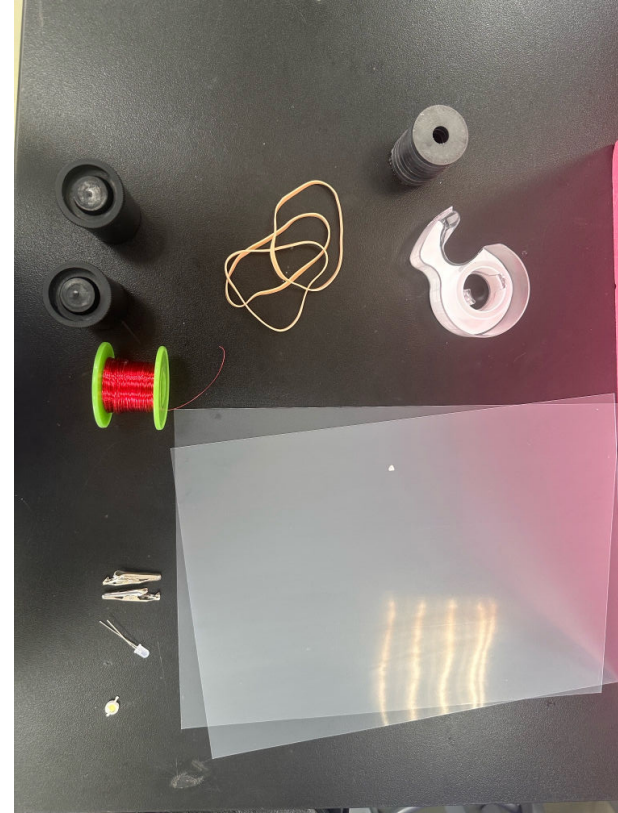


Faraday

“Magnetism creates
Electricity”

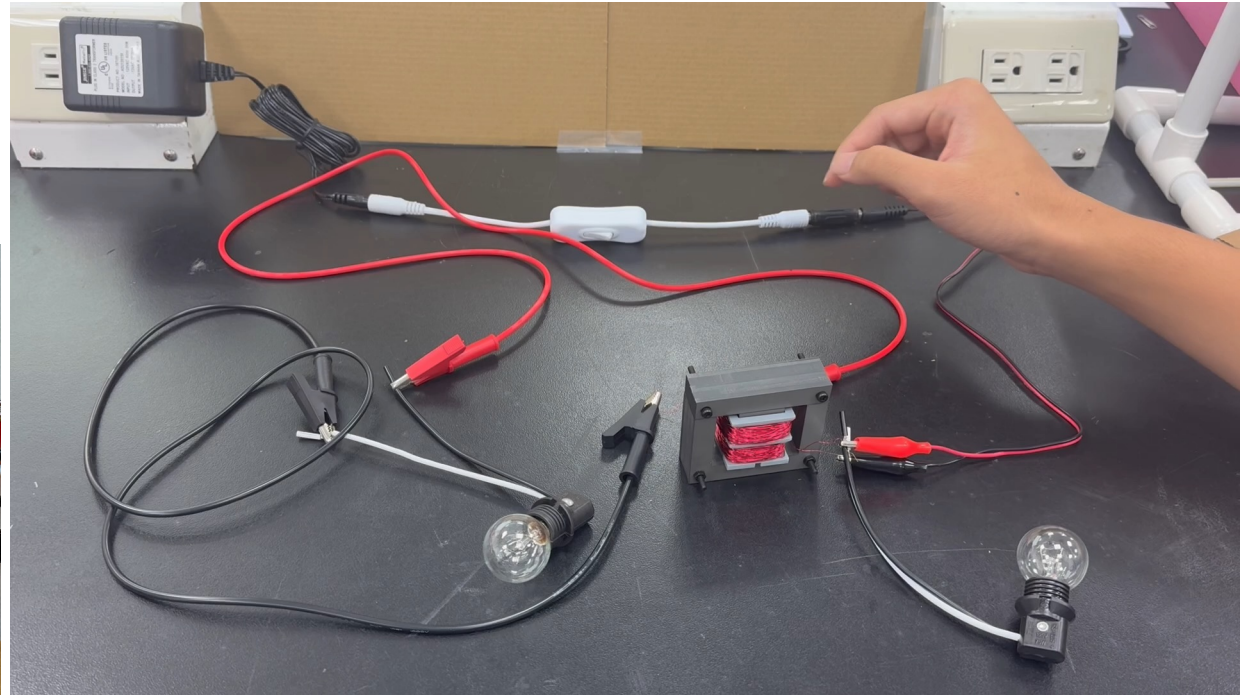
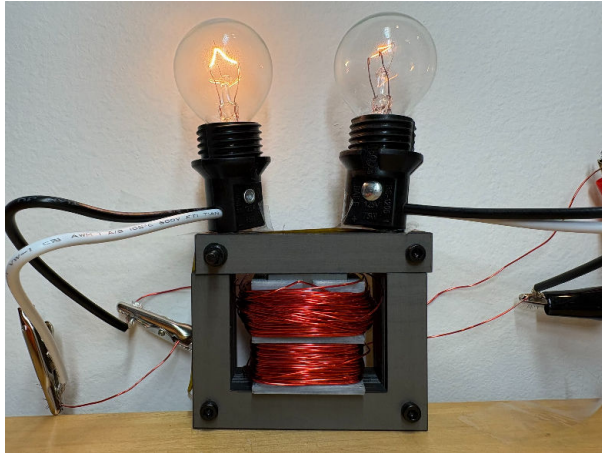
Faraday's Law Makes Electrical Generators Possible

- We can make electric generators by moving magnetic fields through electrical conductors



We can Change Electricity Using Transformers

- Our electricity is usually “alternating current” – it changes with time – this lets us use *transformers* to increase or decrease its voltage levels



A Summary of Maxwell's Equations

Name	Integral equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\epsilon_0} \iiint_{\Omega} \rho dV$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \left(\iint_{\Sigma} \mathbf{J} \cdot d\mathbf{S} + \epsilon_0 \frac{d}{dt} \iint_{\Sigma} \mathbf{E} \cdot d\mathbf{S} \right)$

Charges interact with other charges. We can imagine this using electric fields that radiate outwards. More charges means stronger effects.

Magnetic things produce magnetic fields – these fields always flow in closed loops.

Time-varying magnetic fields can induce electricity in wires – “magnetism creates electricity”

Moving charges (electricity) creates magnetic fields. These fields flow in circles around the charges.

On further study, we realized that if time-varying magnetic fields induce electricity, and electricity induces magnetic fields, then In the right situations, “electromagnetic fields” can exist and propagate through space (e.g., light!)