Transformers

More than meets the eye!

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Transformers

- Not the toy that my son was so fond of
- They have some similarities
    - something is ‘transformed’
- Easier than transforming that toy
    - my son made me do that
- Underrated device

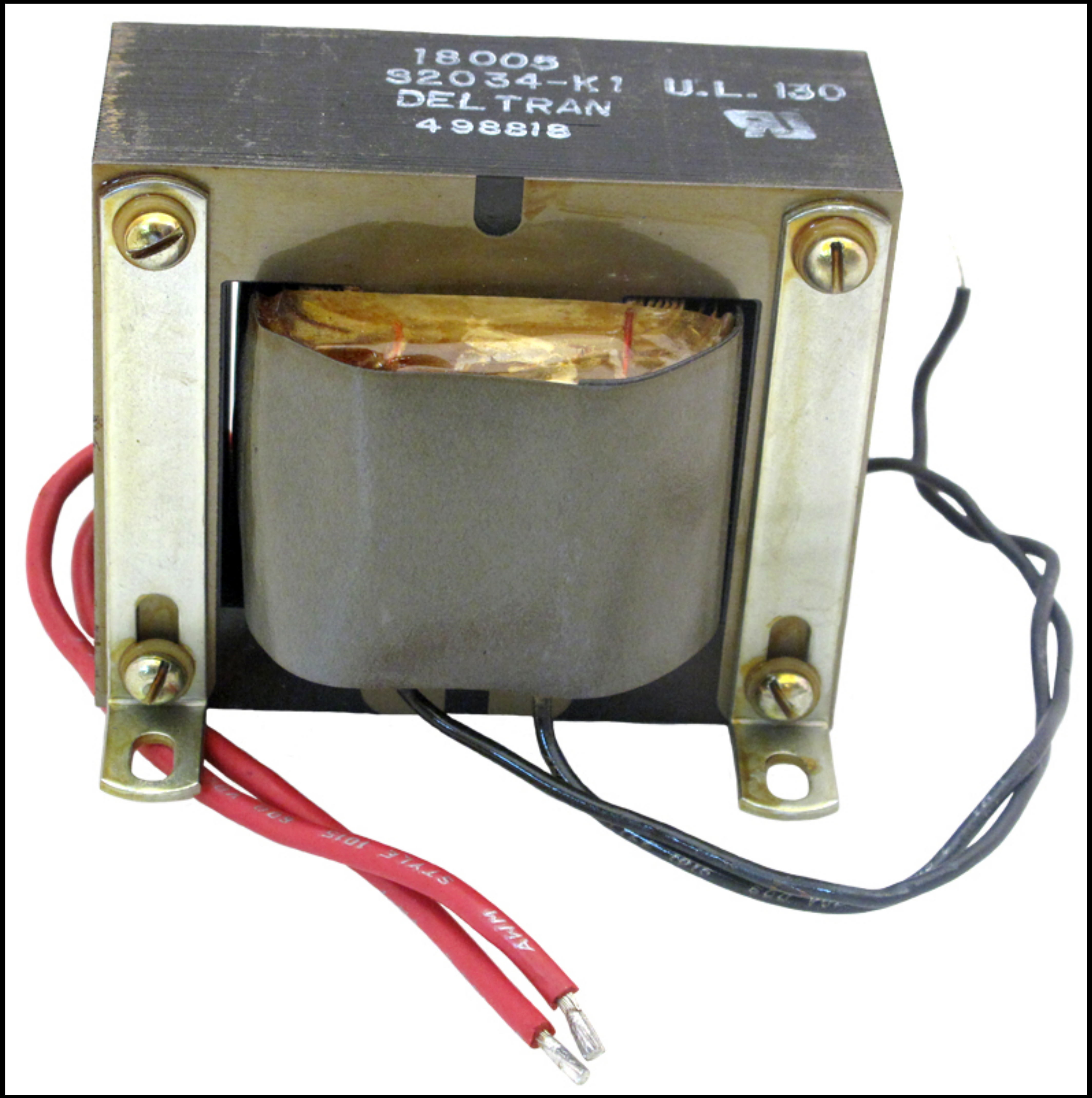
Transformers are sad

- Short shrift in texts
  - reduced to turns ratio
- Magnetic material properties
  - under explored or ignored
- Uninteresting because passive
- Seen as ‘old’ technology

What they do

What is ‘transformed’?

- Conserve energy
- Change V/I relationship
- Change Z_{in}/Z_{out} relationship
- Even regulate voltage!
- Teach us to count
- Make us stronger
  - lift that tube amp!



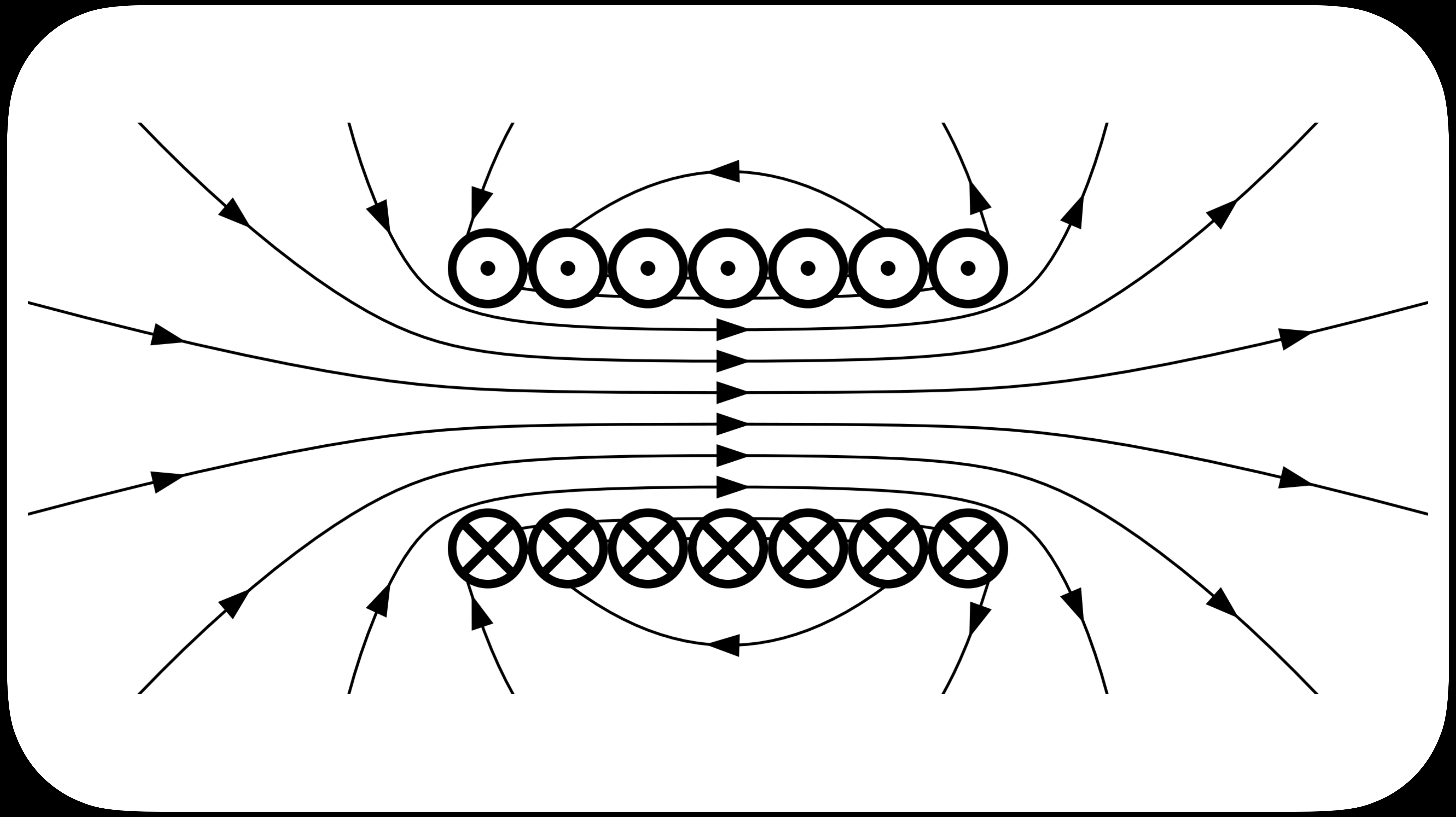
Let’s explore

- How they work
- How to make them
- Parameters and construction
- What they are good for
- Unusual manifestations

Theory

Maxwell, as always

- Faraday's Law of Induction
  - Maxwell-Faraday equation
- Links to Kirchhoff's Voltage Law
- Magnetic flux
  - time rate of change
- Lenz's law (equal and opposite)
- Basis of all electro-mechanical transformations too



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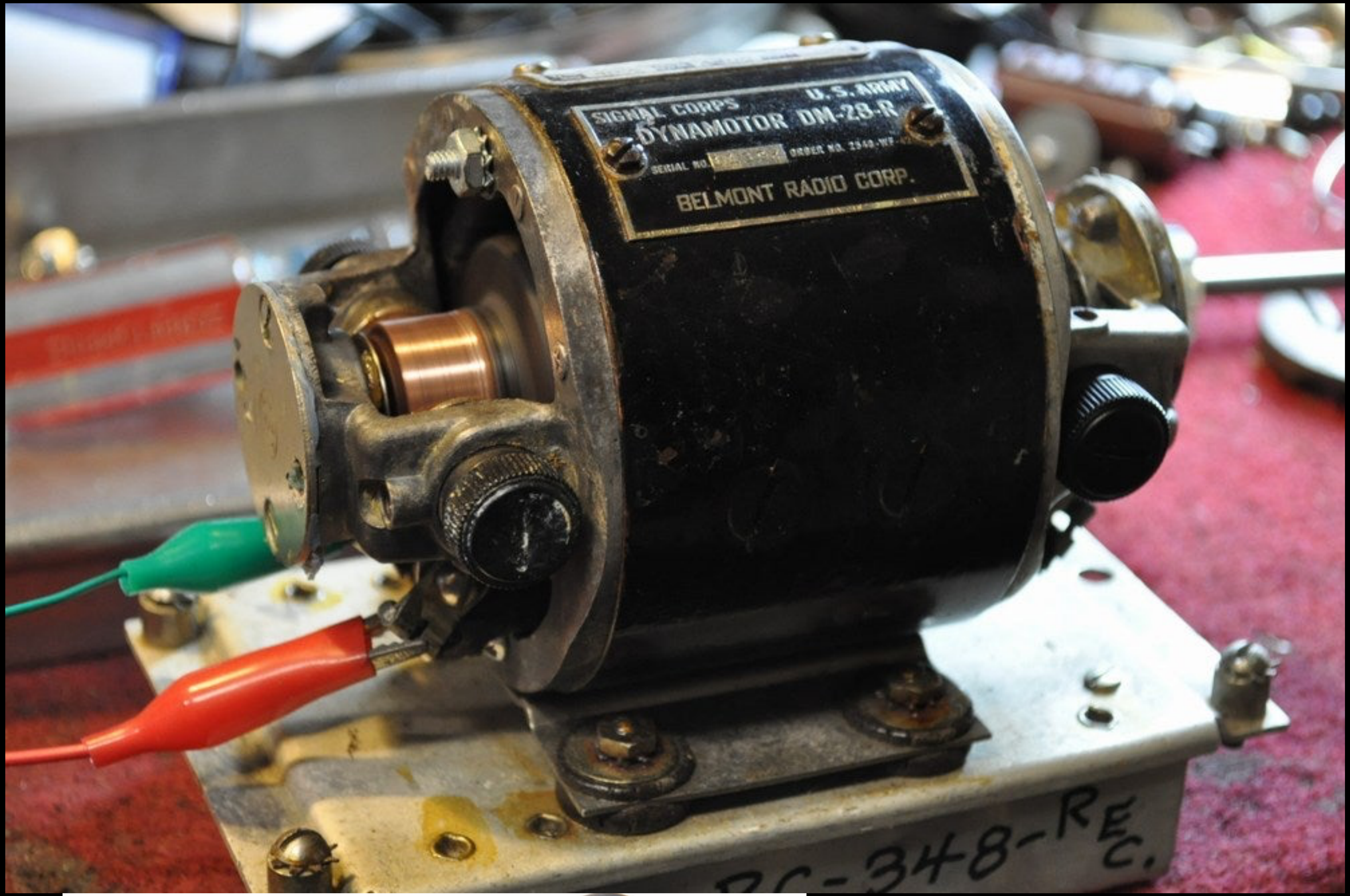
Mechanical Energy

Transform to Electrical Energy

- Loop of wire
- Magnet
- Requires $\frac{d\Phi_m}{dt}$ (a.k.a. flux)
- Motion + Force
  - ‘Work’ (work-energy theorem)
  - flux through a surface

Take away the magnet

- How else can we get a changing B field?
- Permanent magnets are inconvenient
  - limited field strength
  - but we could rotate them
- Solution: dynamotor!



What creates a B field?

More seriously, though

- Permanent magnet
  - aligned dipoles
  - tiny, tiny currents
- Ampere's Law
  - create magnetic flux
  - make it change with time
- Create a nice concentrated field
  - use a solenoid (Maxwell)

Current (density)

$$\nabla \cdot \overrightarrow{H} = J + \frac{\partial \overrightarrow{D}}{\partial t}$$

$$\oint \overrightarrow{H} \cdot dl = I + \frac{d}{dt} \oint \overrightarrow{D} \cdot dA$$

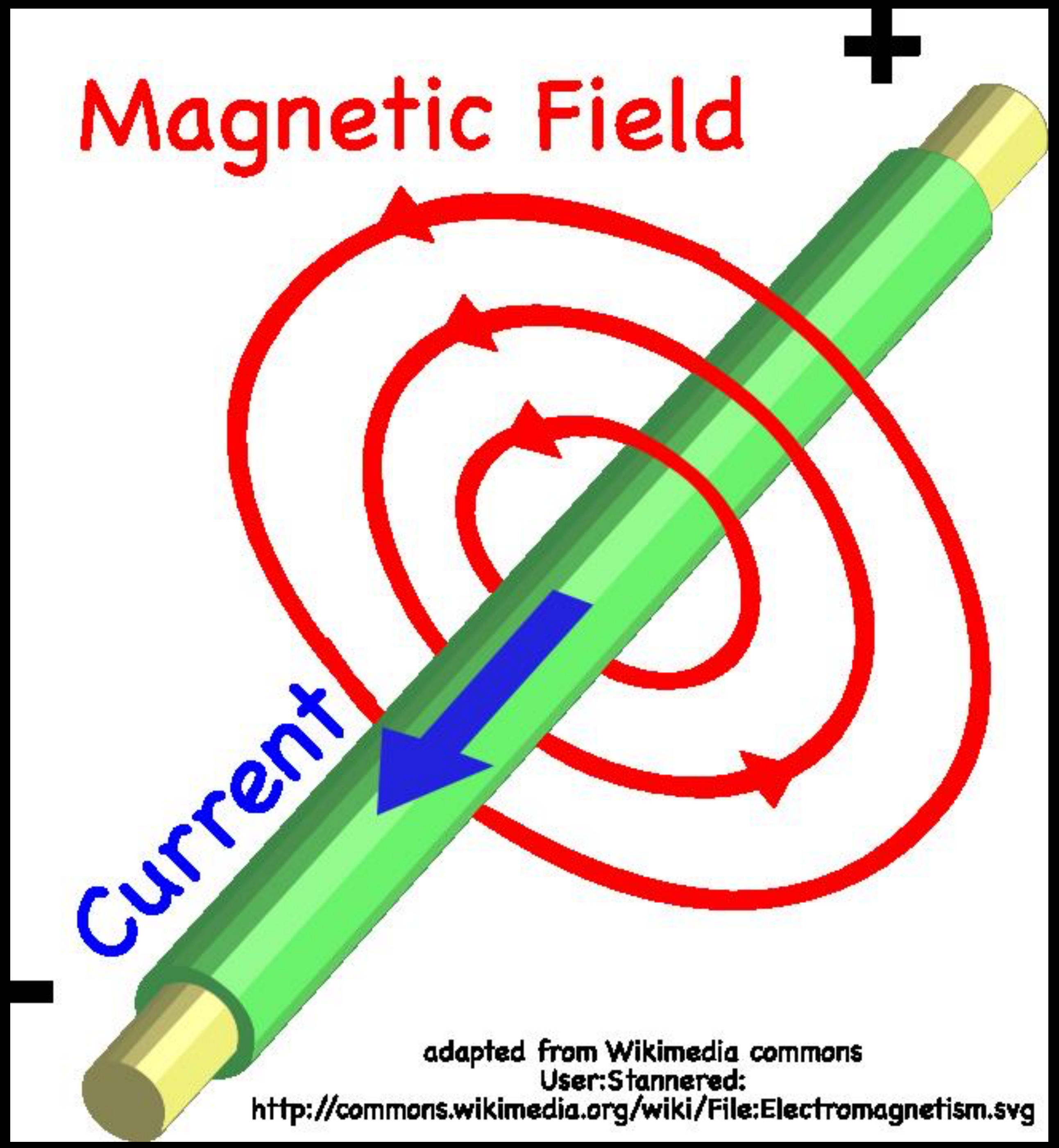
Current

$$B_z = \frac{\mu_0}{4\pi} \frac{2\pi R^2 I}{\left(R^2 + z^2\right)^{\frac{3}{2}}}$$

R: radius

z: distance in axial direction

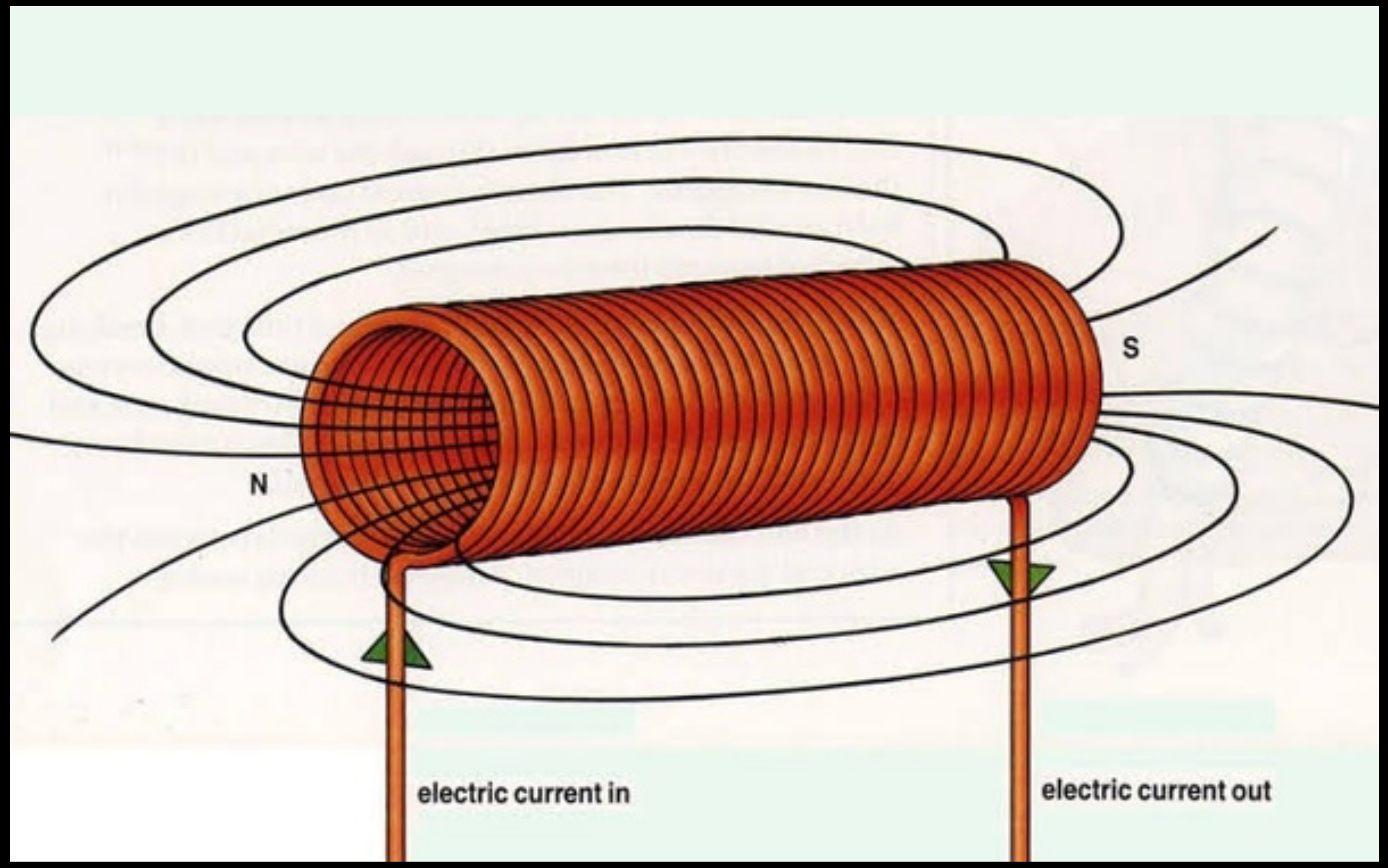
Biot-Savart for solenoid

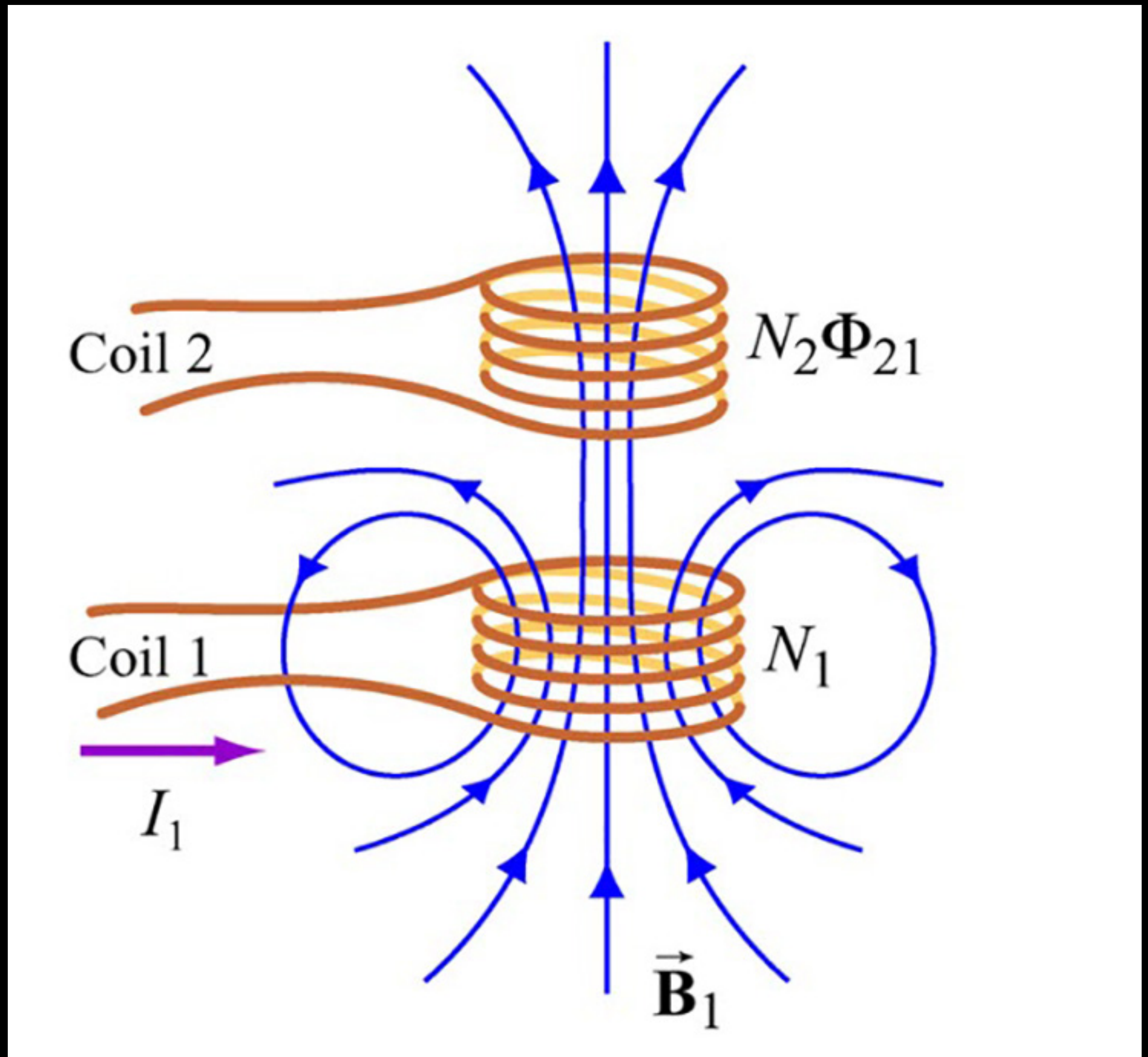


Use another coil!

Bright idea

- Make a current flow
  - creates a B field from one
- Must be close
  - capture that magnetic flux Φ_m
- Should be strong
  - we can manipulate this
- What’s missing?

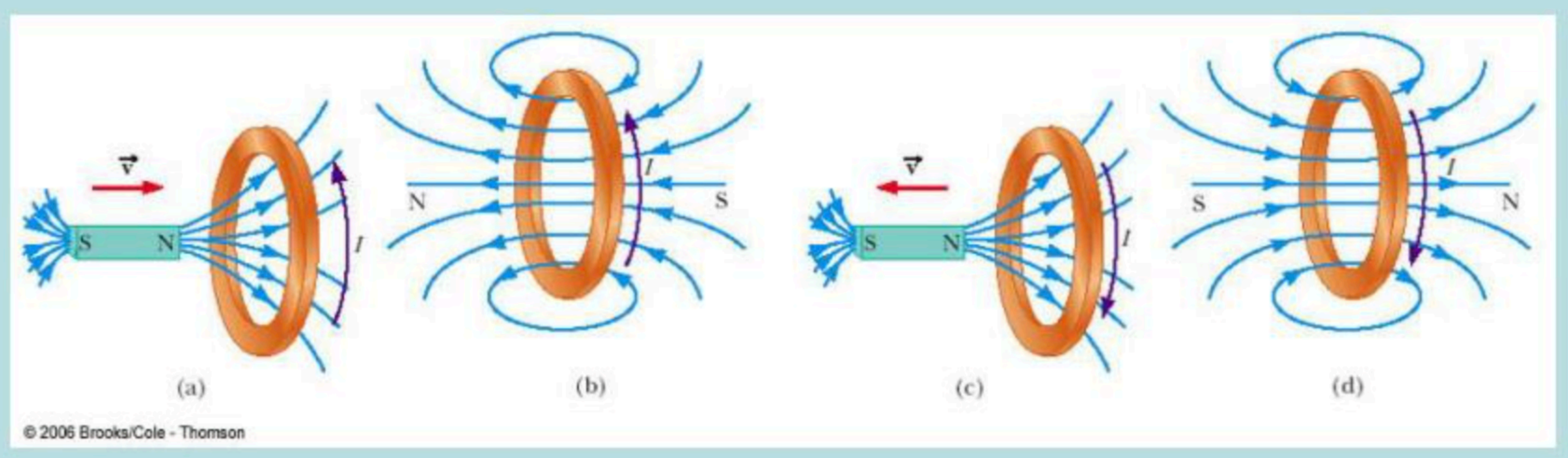




Changing flux

EMF is a misleading name

- Field must change with time
- Remember Maxwell
  - Faraday's Induction Law
- EMF is needed to do work
  - needs electric potential
  - not just current / B field
  - work done on charges $\vec{F} \cdot \vec{d} = W$
- This is why DC doesn't work with a transformer



Bar magnet does work: $\vec{F} \cdot \vec{d} = W$

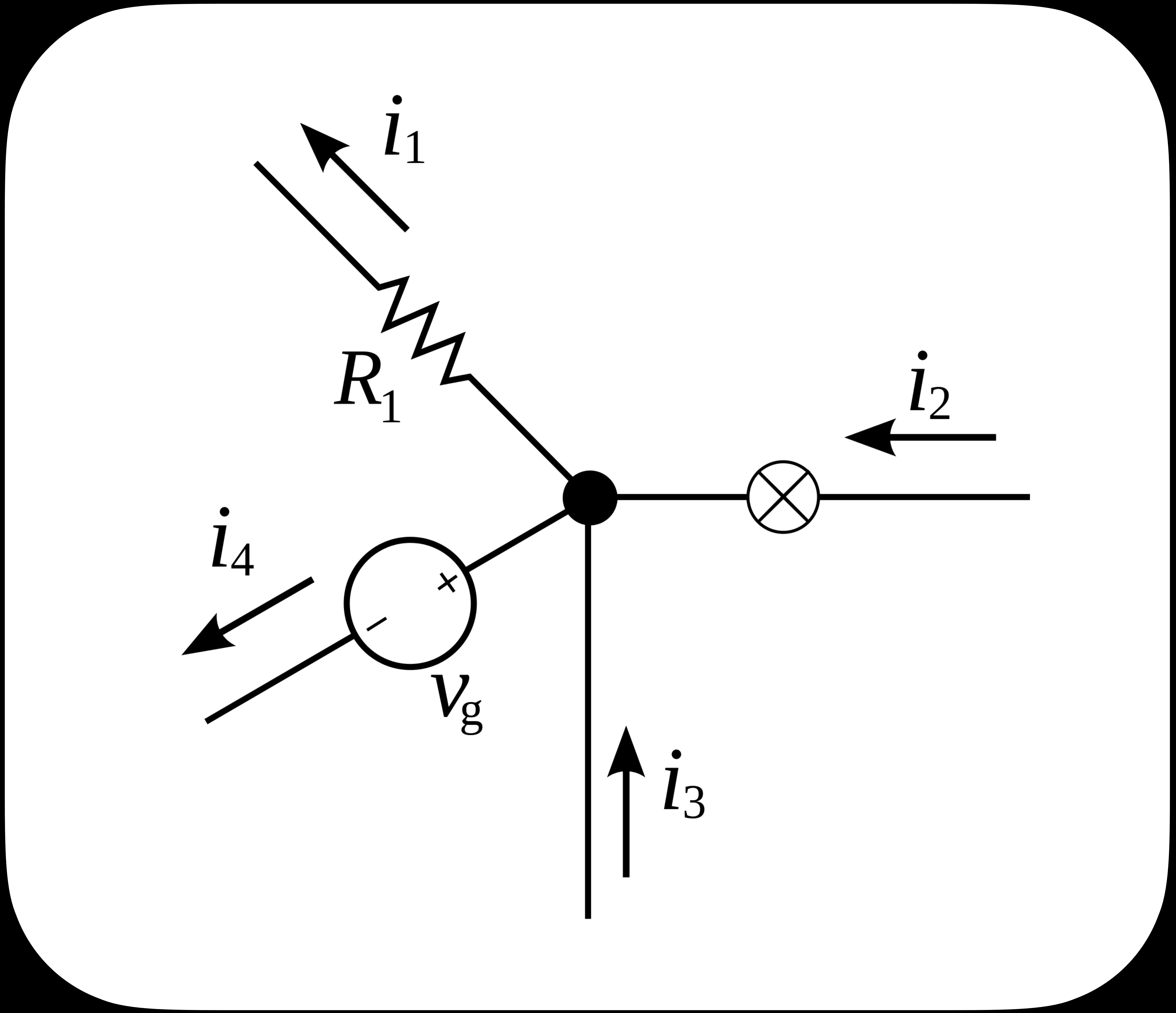
$$\mathcal{E}_C = \oint_C \vec{E} \cdot dL = -\int_A \frac{\partial \vec{B}}{\partial t} \cdot dA$$

$$= -\frac{d}{dt}\oint_C \mathscr{A} \cdot dl = -\frac{d\Phi_m}{dt}$$

Kirchhoff's 'Laws'

Diversion - Current

- Current Law is straightforward
- Energy is conserved
- Charge is conserved
    - assume uniform distribution
    - $I = \frac{dq}{dt}$
    - current = time varying charge
- Uniform distribution breaks for AC

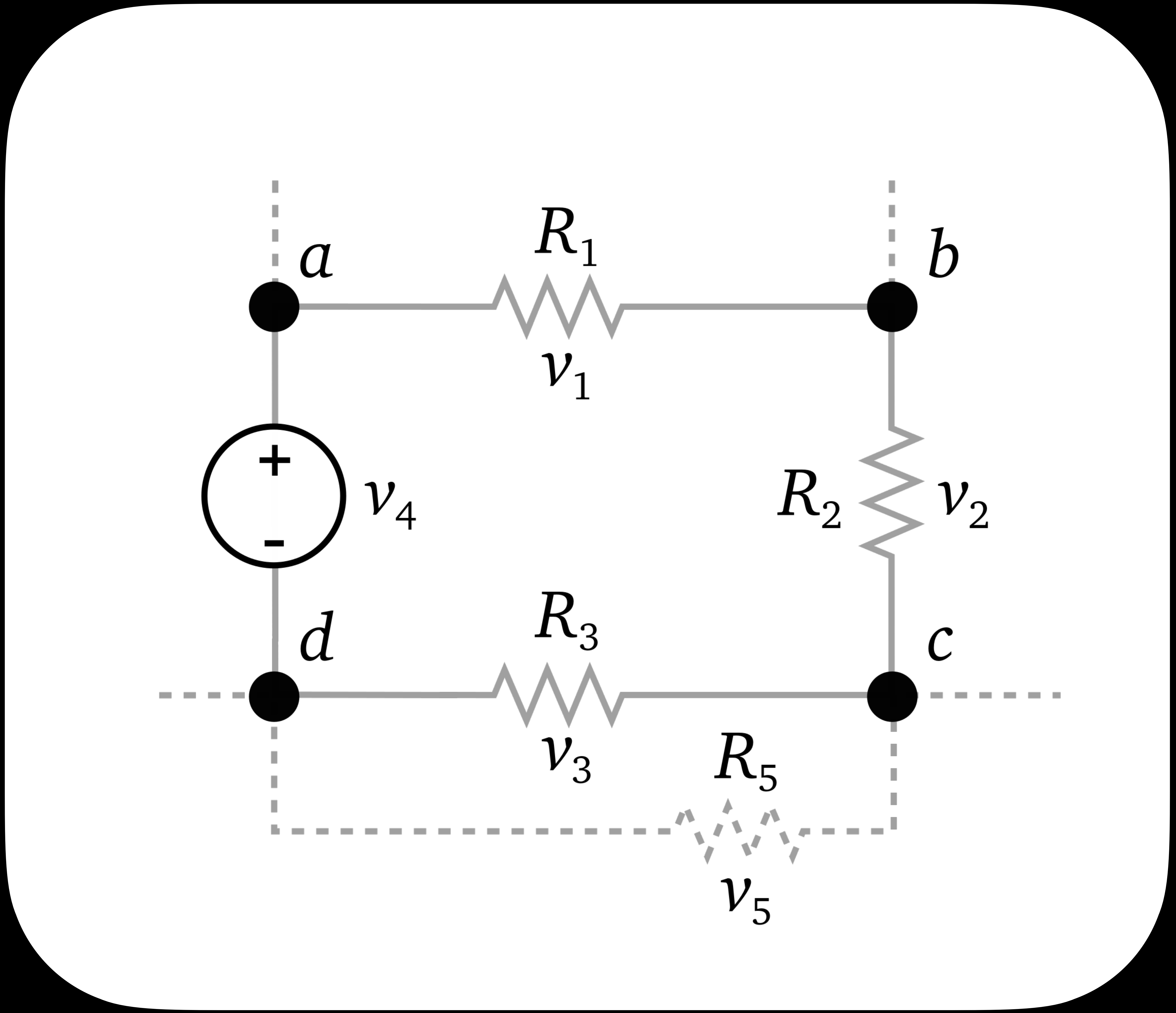


Wikipedia: KCL.png: Pflodo derivative work: M0tty (talk) - KCL.png

Kirchhoff's 'Laws'

Diversion - Voltage

- Based on Electromotive Force
  - EMF or $\mathscr{E}$
- $\mathscr{E} = \oint_C \overrightarrow{E} \cdot dL = -\int_A \frac{\partial \overrightarrow{B}}{\partial t} \cdot dA$
- Assume $\frac{\partial \overrightarrow{B}}{\partial t} = 0$
  - so breaks for AC



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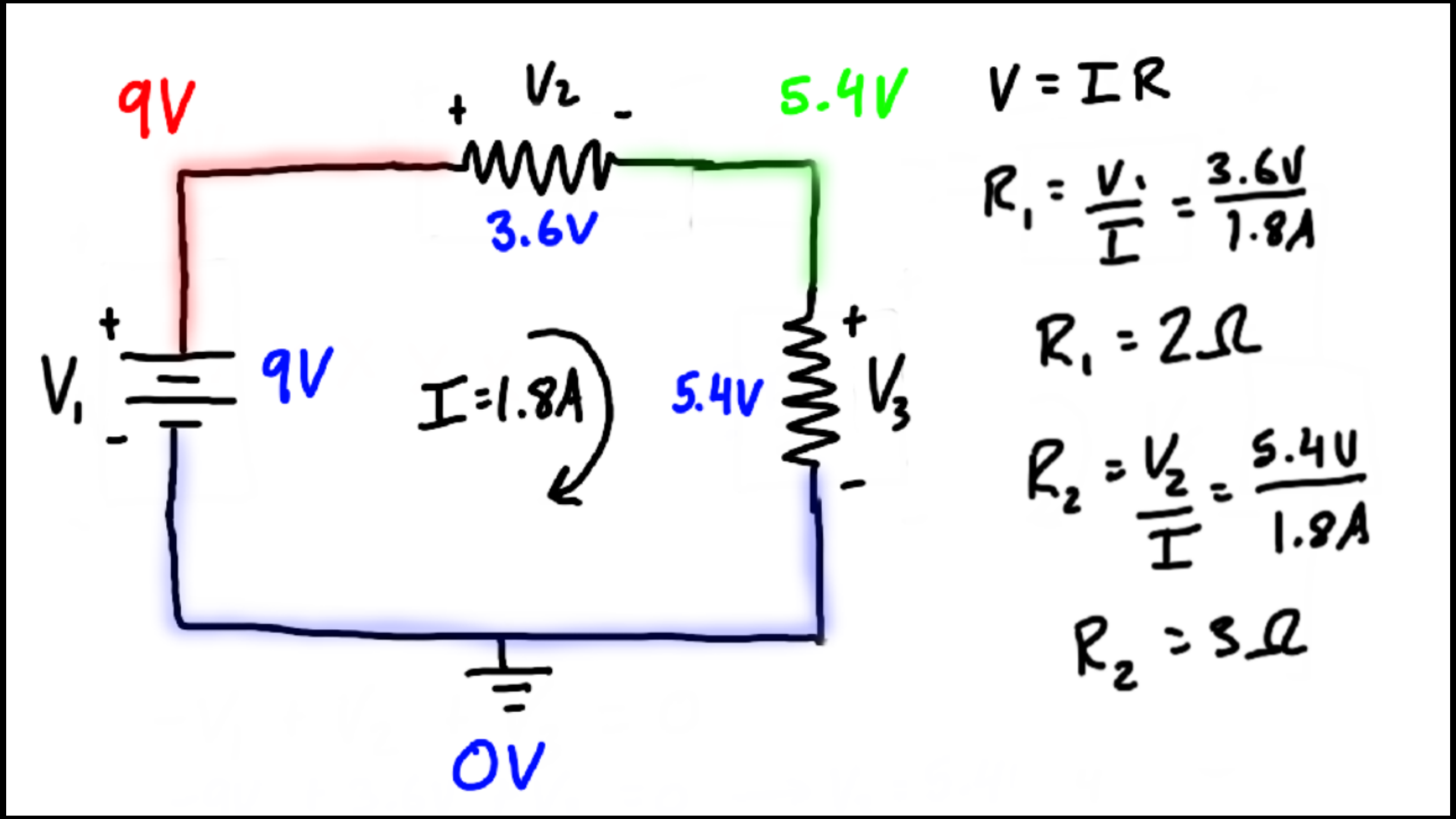
Kirchhoff's 'Laws'

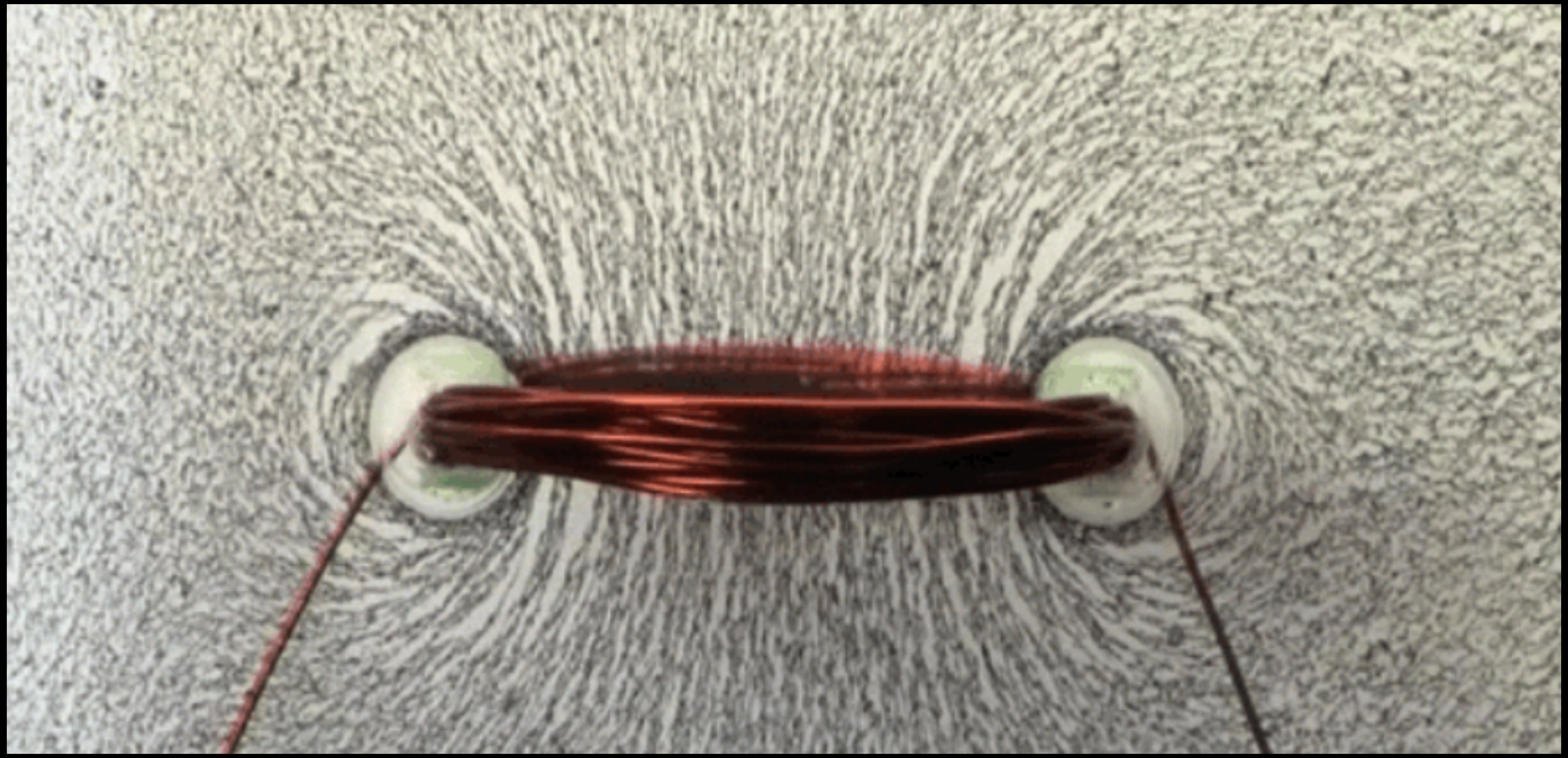
- Like Ohm's Law, not laws at all
- Valid only for some conditions
- Break for AC / RF
- Still useful for quasi-static calculations
- Not useful for transformers
  - How they break is what matters!



What about that B field?

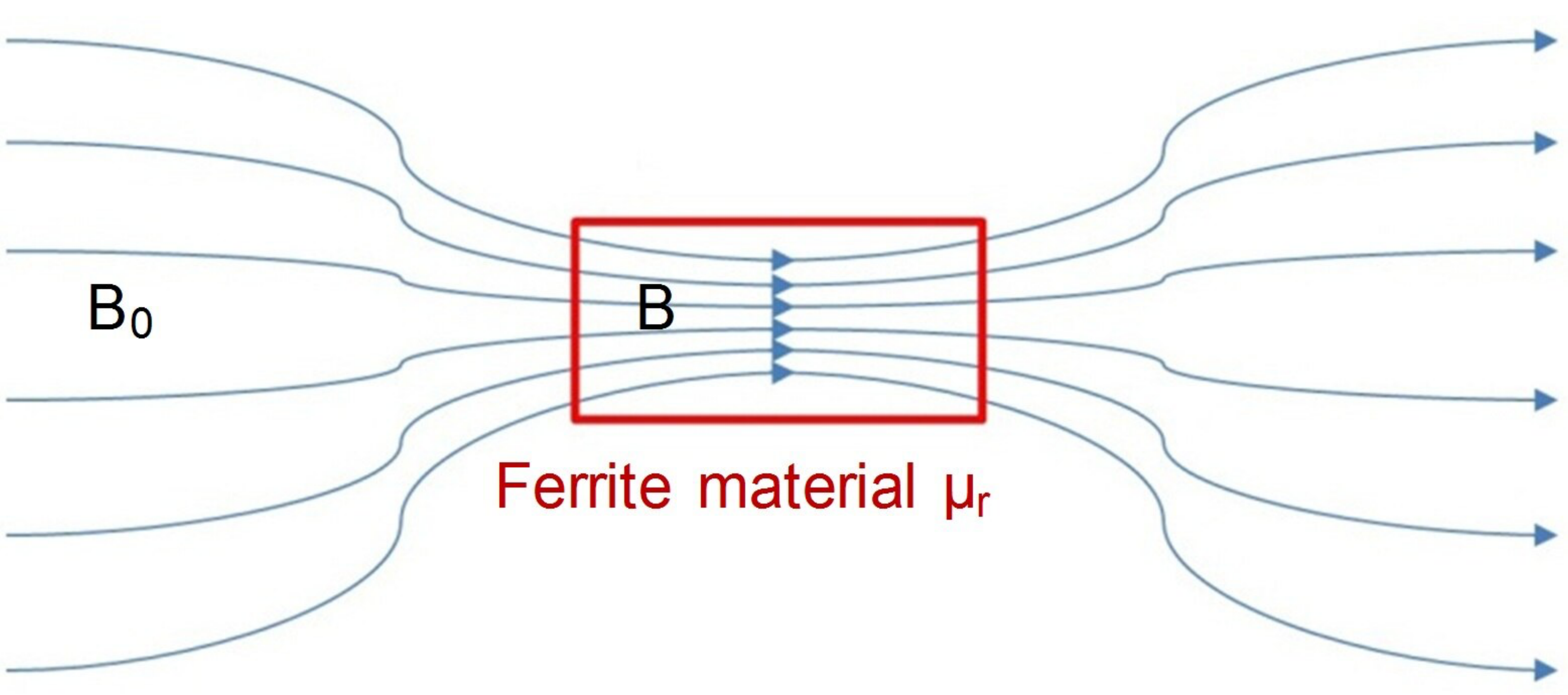
Kind of leaky

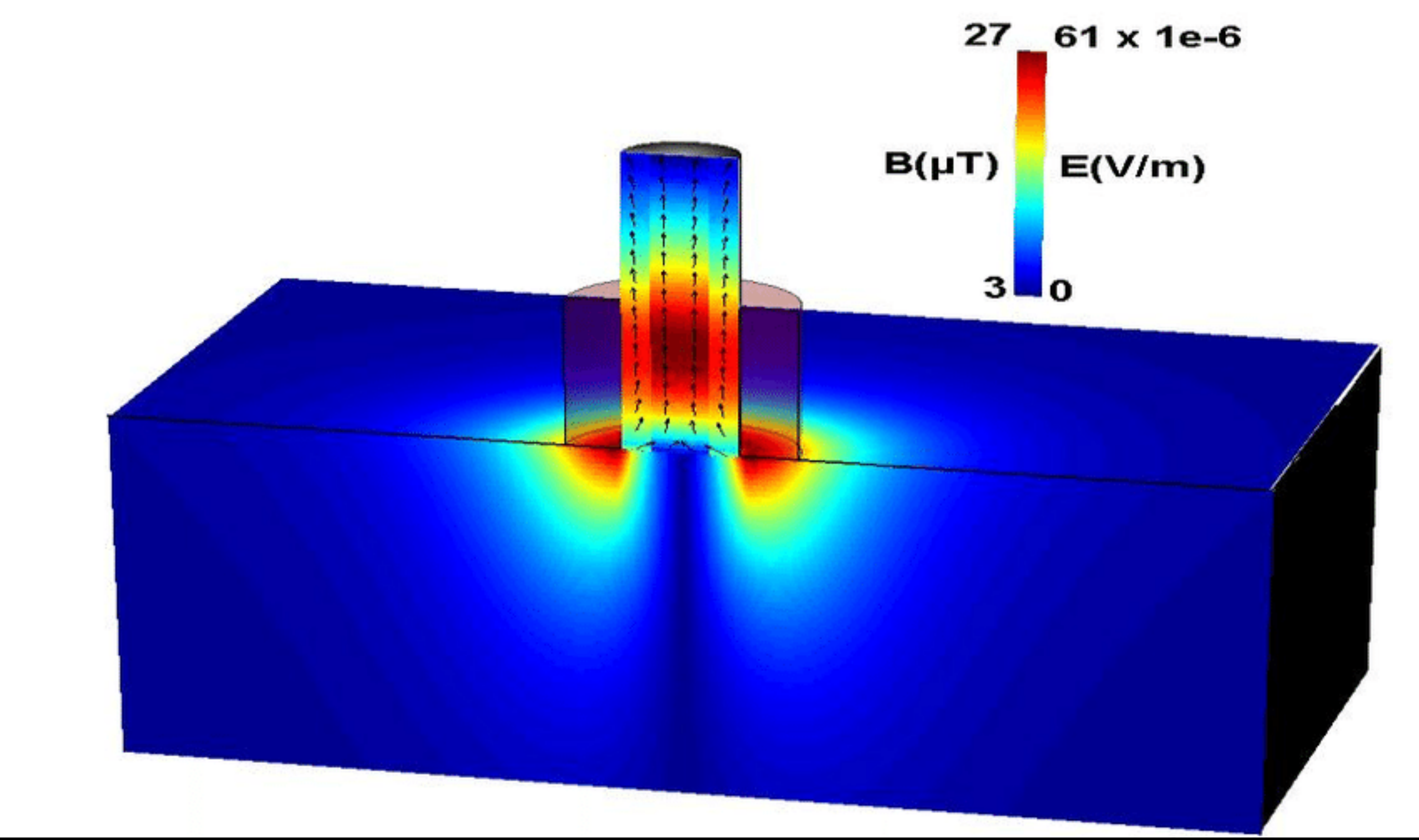
- Want to keep all of the flux
- Pass the flux through the coil center
- Careful positioning
  - still fields leak :(
- Can we direct the field lines?
  - change material properties



$\overrightarrow{B}$ vs $\overrightarrow{H}$ in the world

- $\overrightarrow{H}$ is the magnetic field strength
  - intensity independent of media
- $\overrightarrow{B}$ is the magnetic flux density
  - intensity mediated by media
- In a vacuum $\overrightarrow{B} = \mu_0 \overrightarrow{H}$
  - μ_0 means for a vacuum
- We can change μ and change $\overrightarrow{B}$

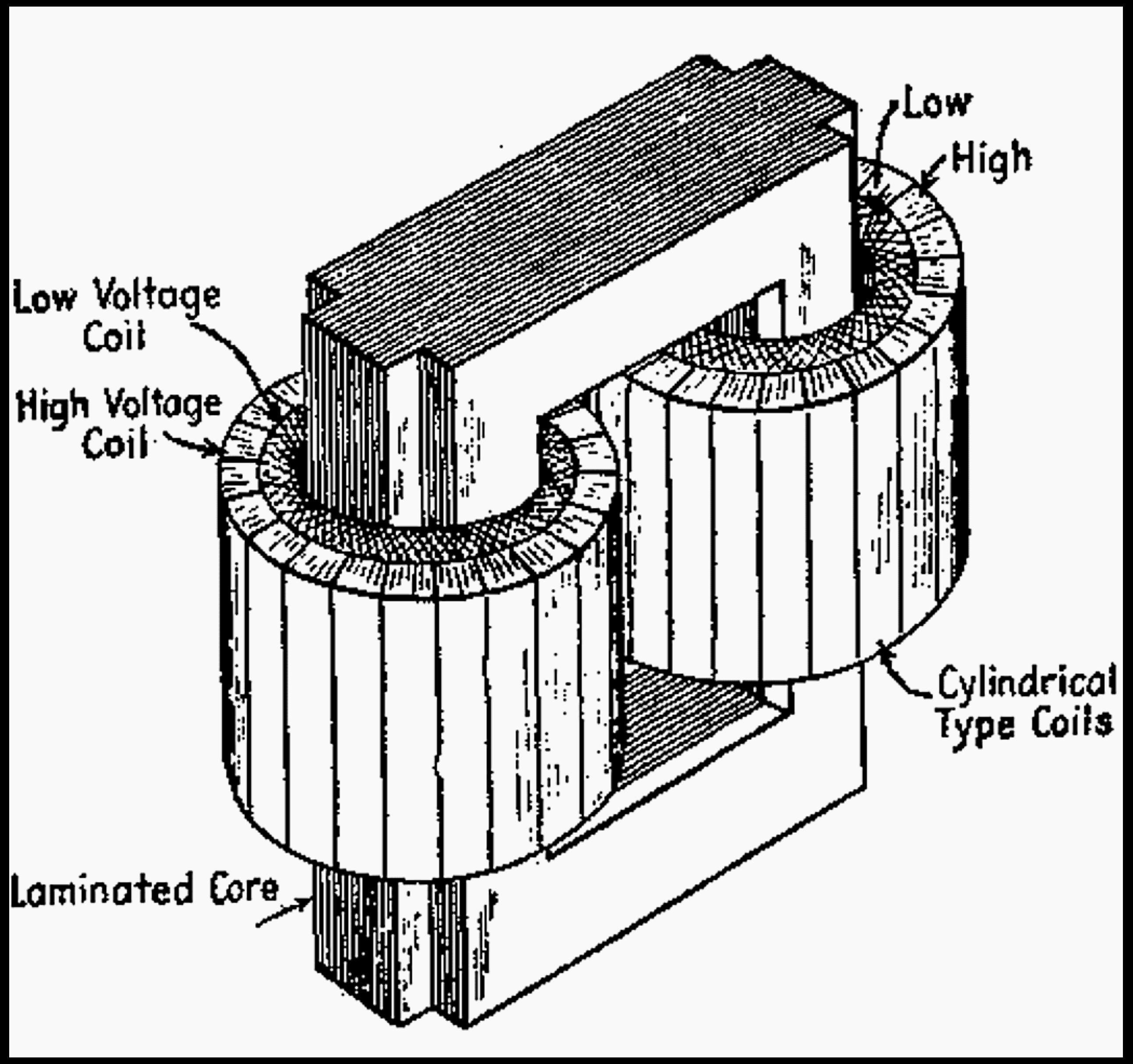


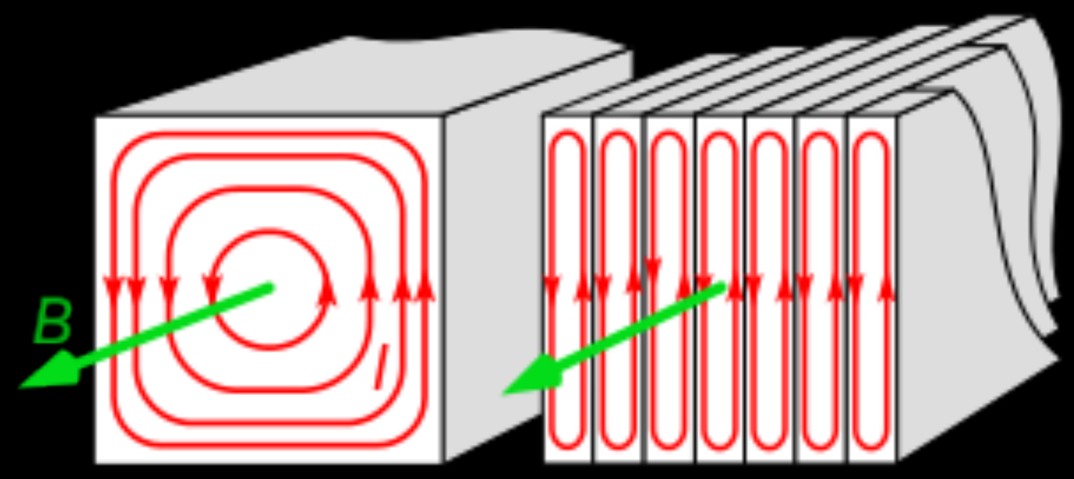


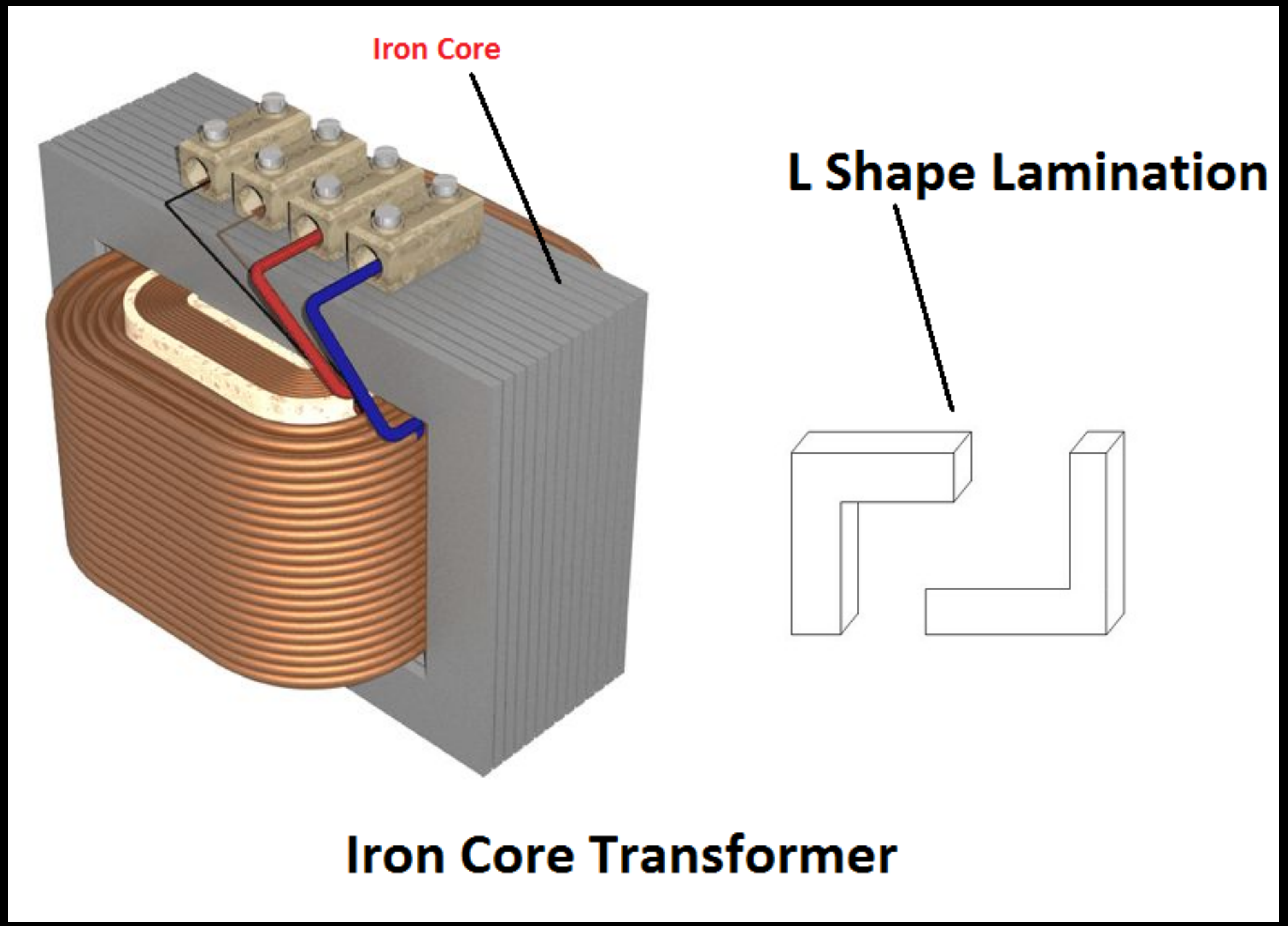
Materials Science

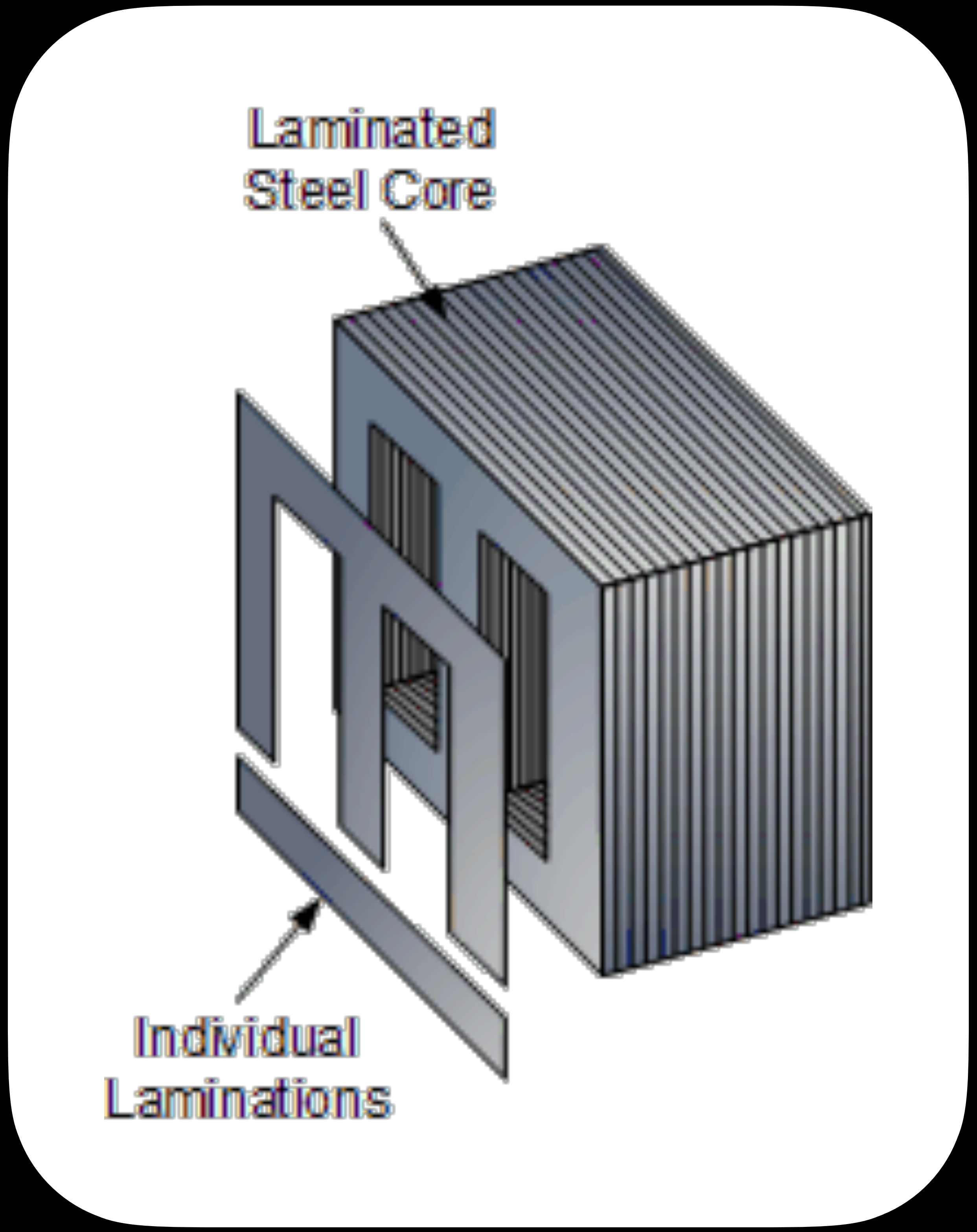
Try something with big μ

- Metal; maybe Iron!
- Problem - iron
  - conductive, magnetizable
  - iron is less conductive
  - eddy currents
  - loss -> heat
- Solution - iron
  - slice it thinly to minimize





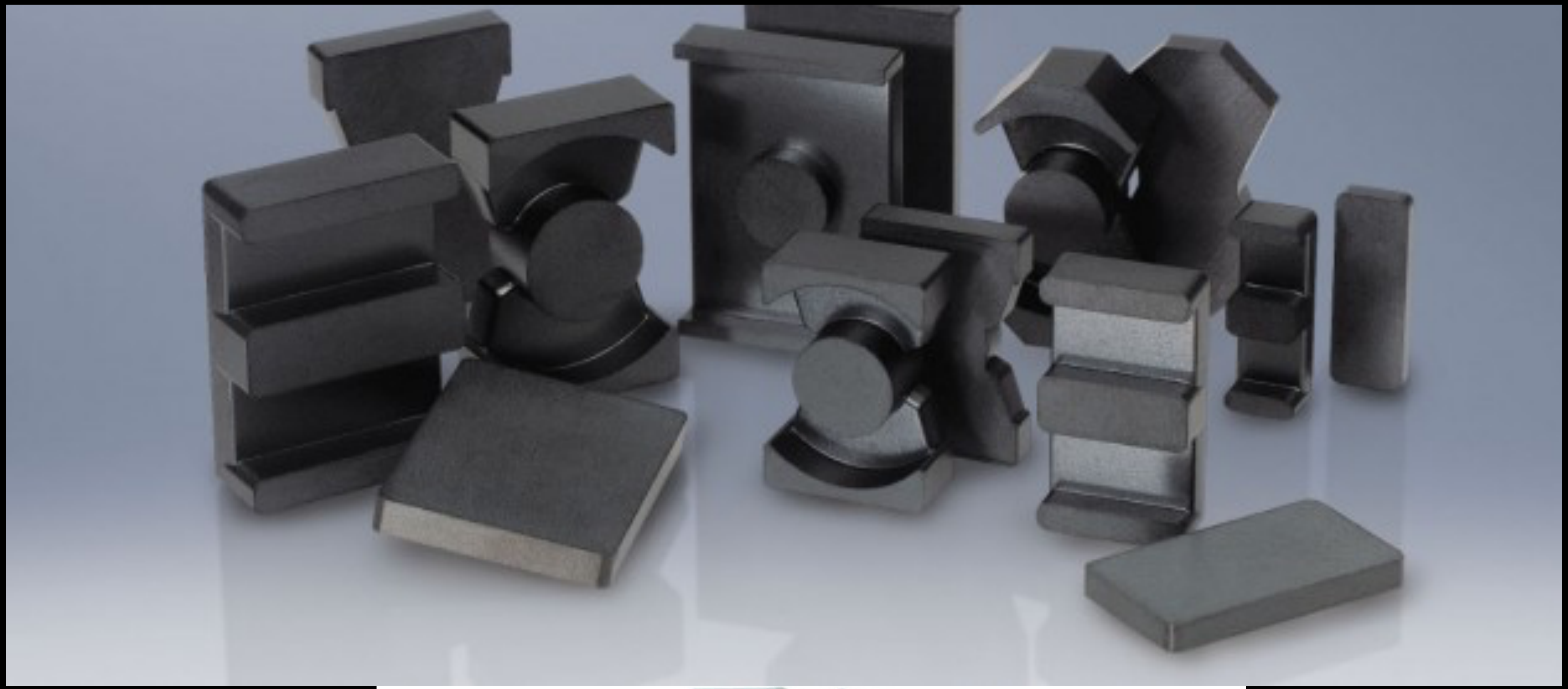


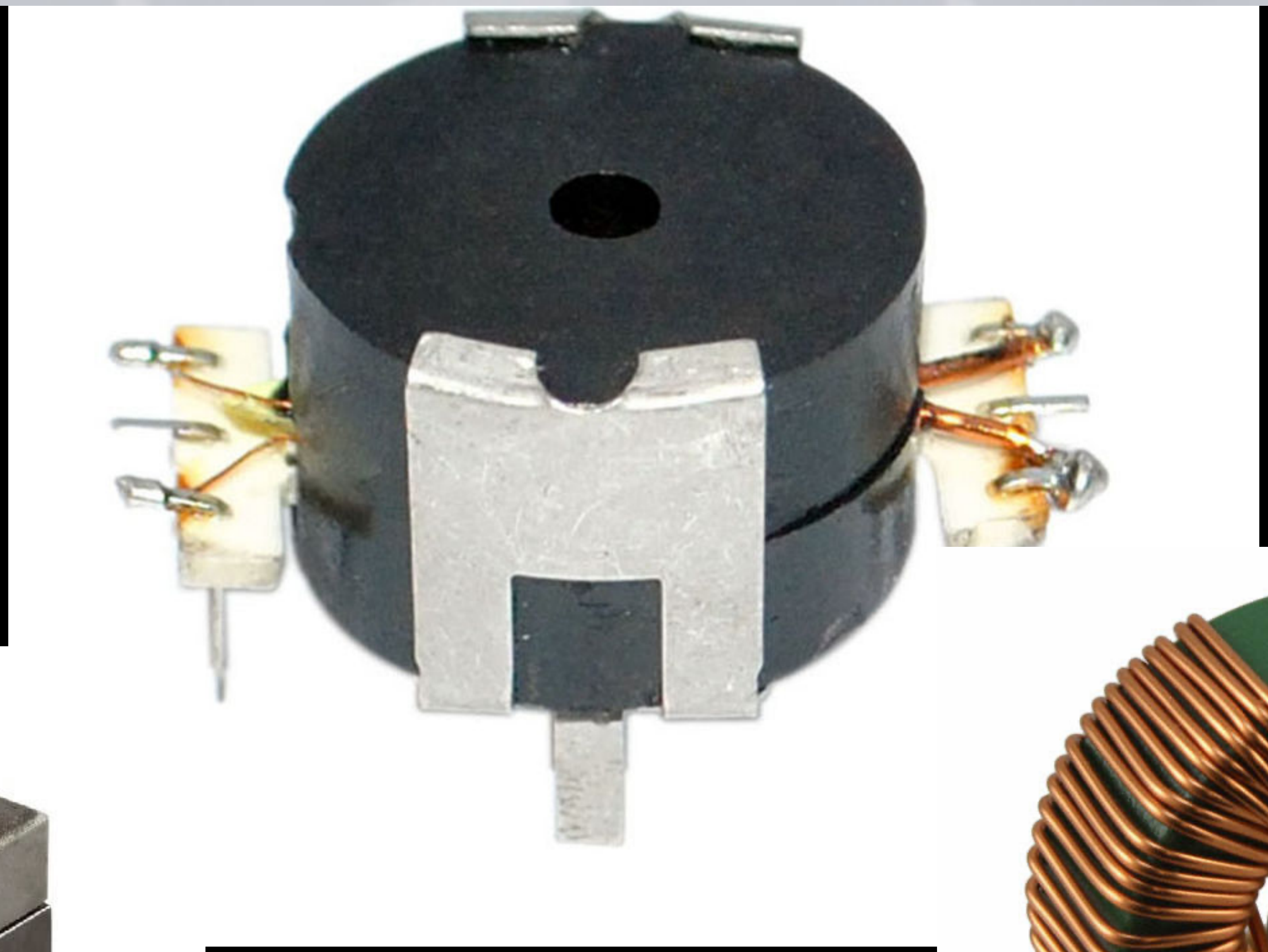


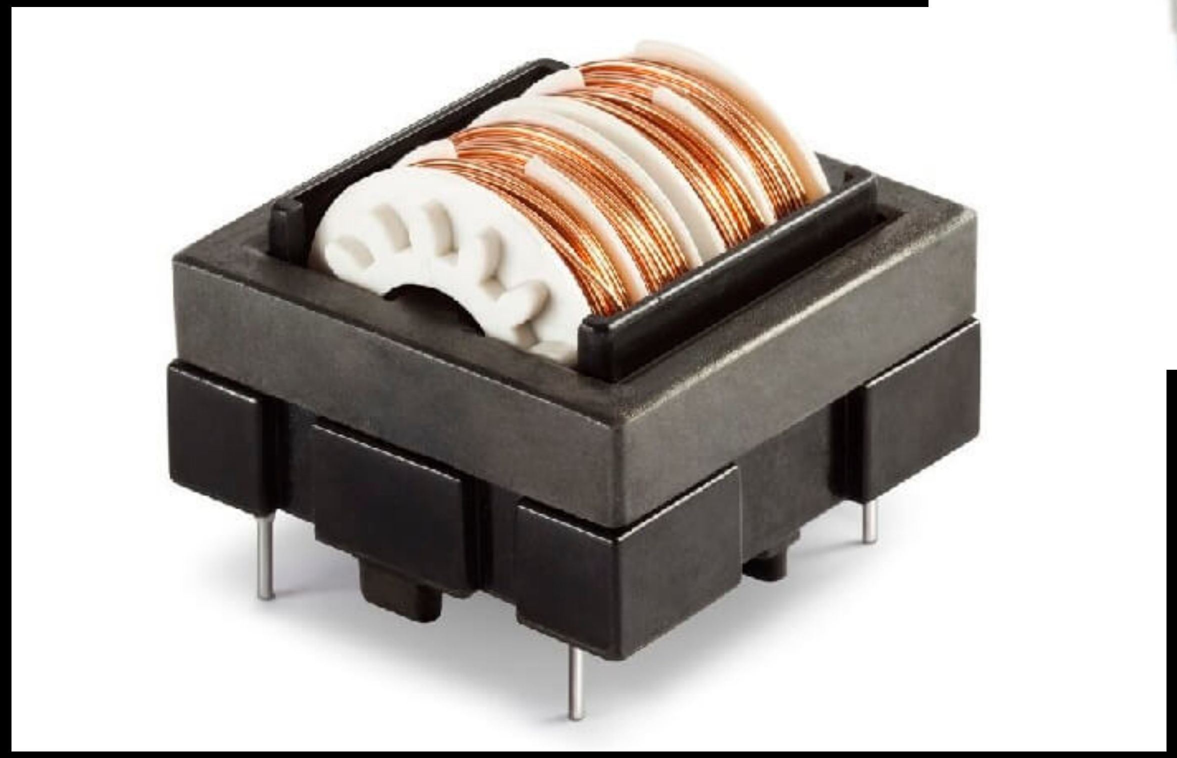
Okay, but not great

What else can we use?

- Take the slicing further
- Embed iron oxide in ceramic
    - non-conductive
    - low coercivity
    - tune the material for high μ
- We call this material ‘ferrite’

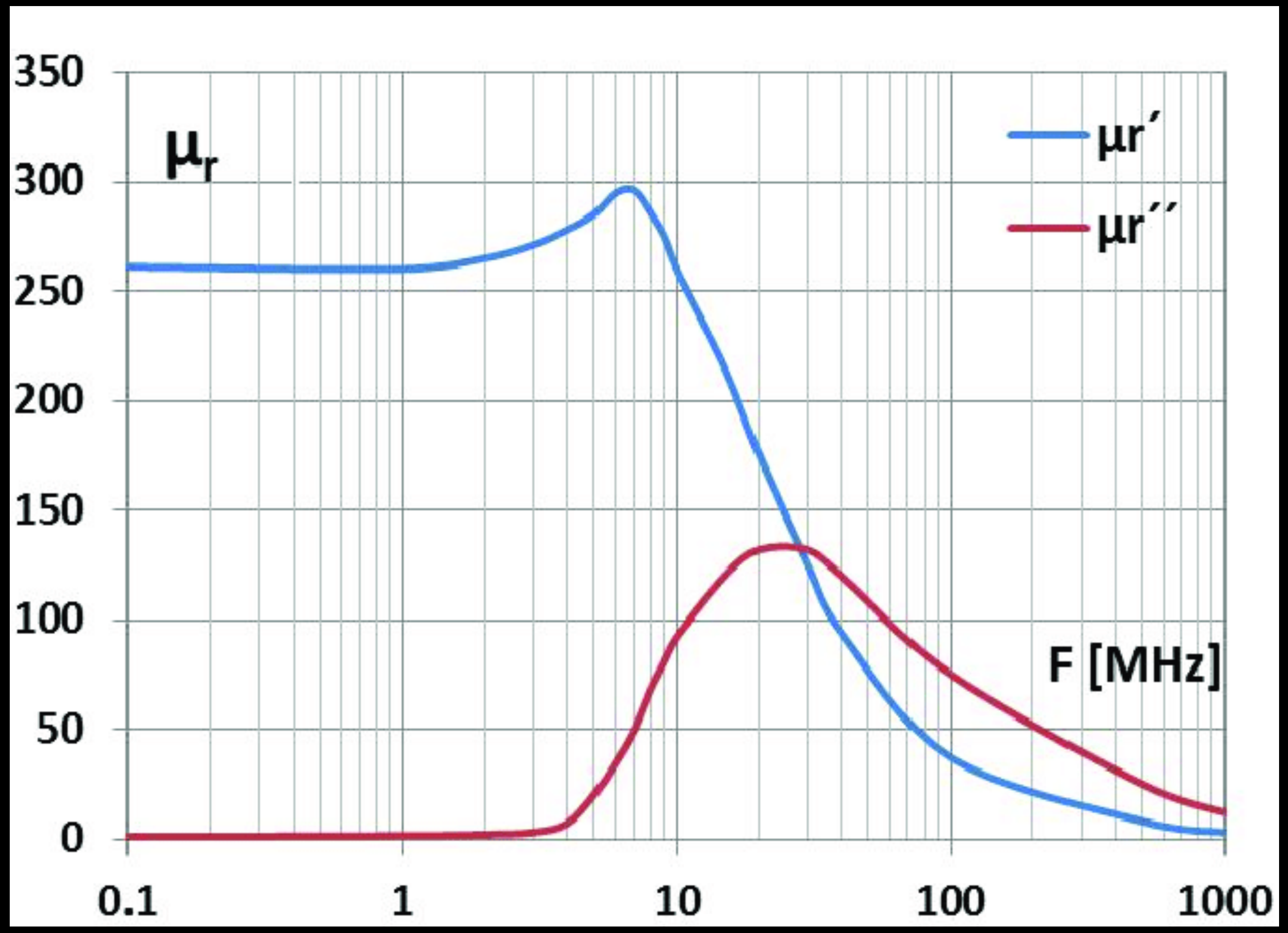


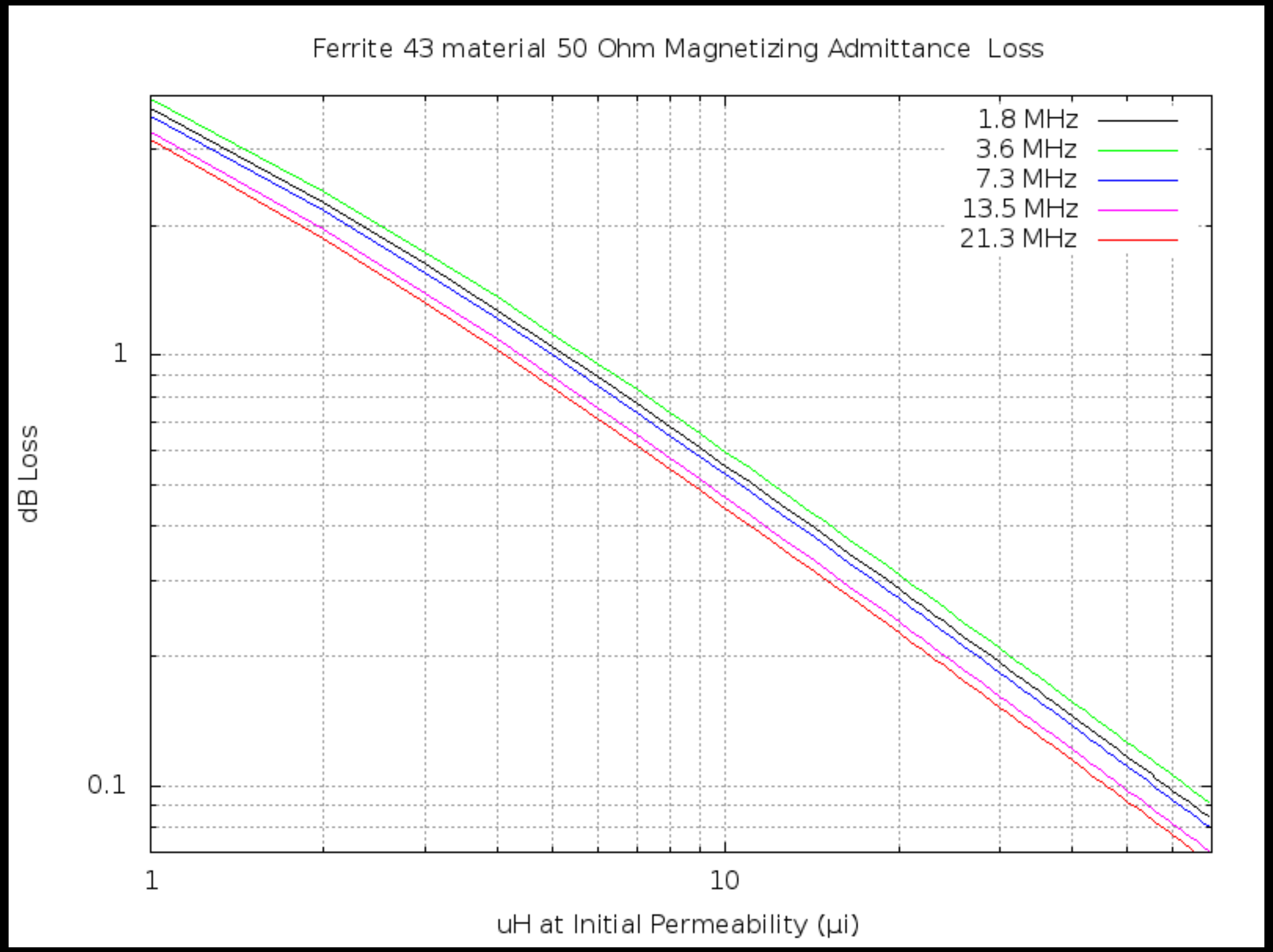


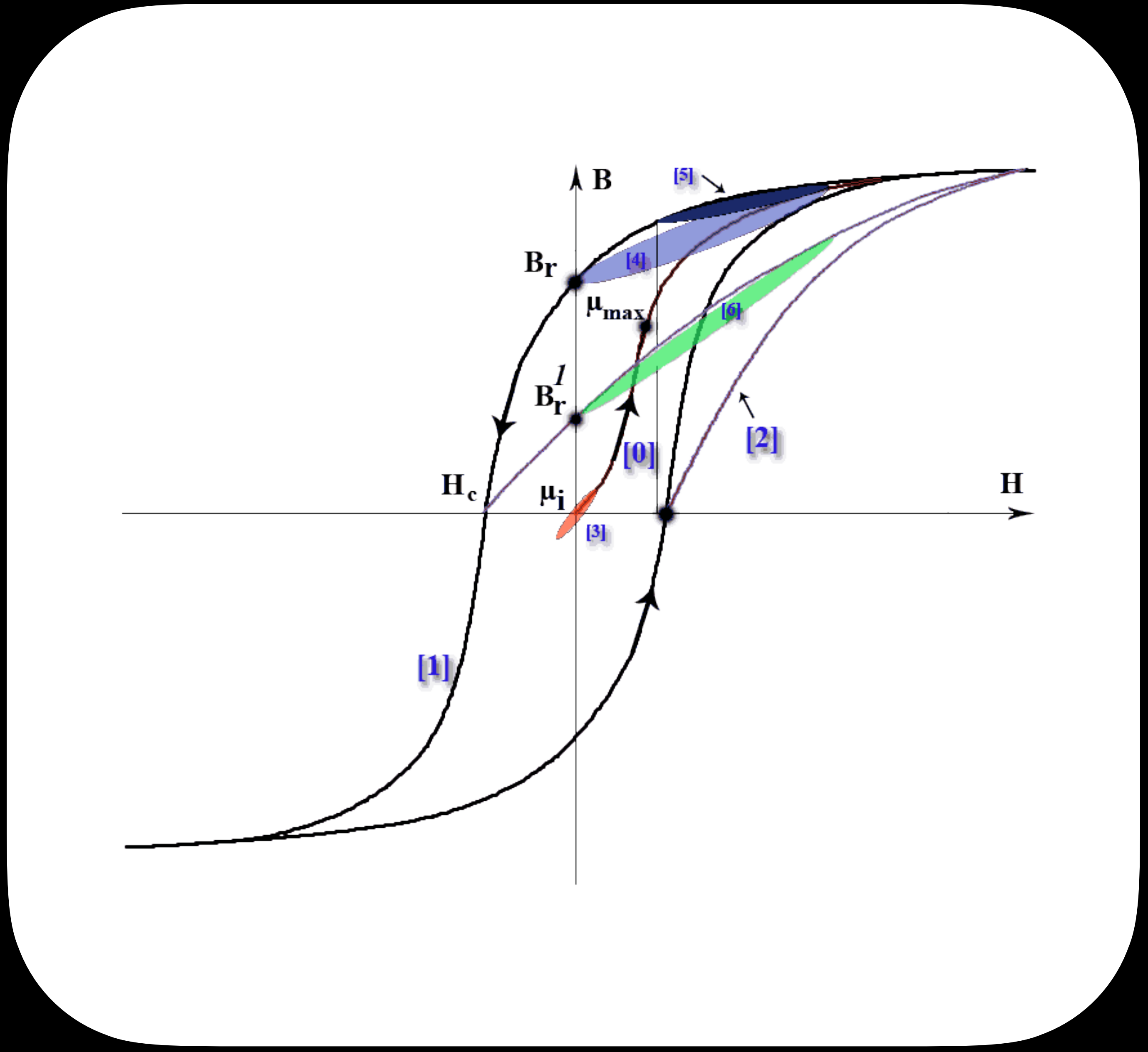


What matters
Material characteristics

- Linearity
    - does μ change with H field
- Losses
    - hysteresis
- Frequency response
    - both might change
- Nothing is ideal

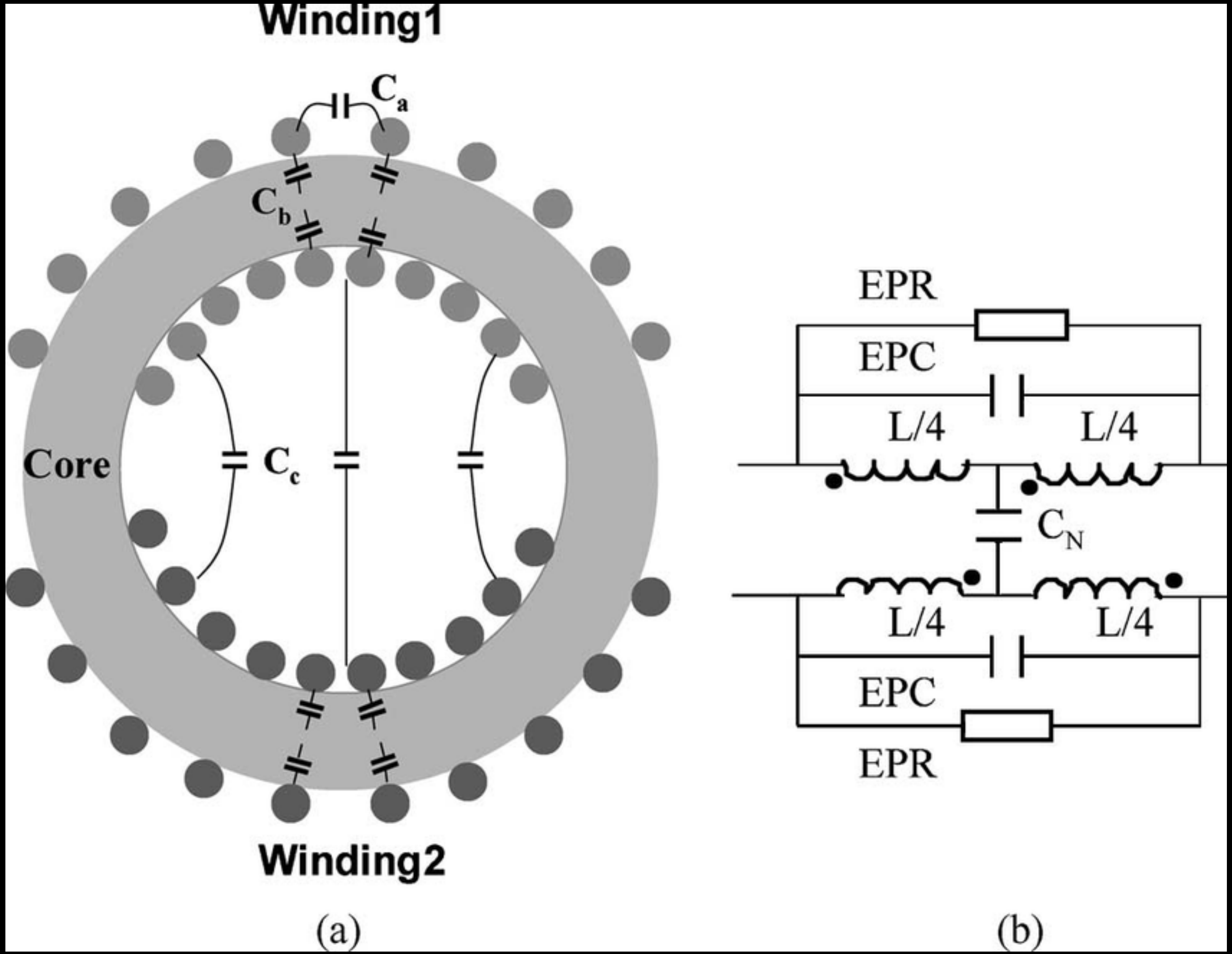






Parasitic Capacitance

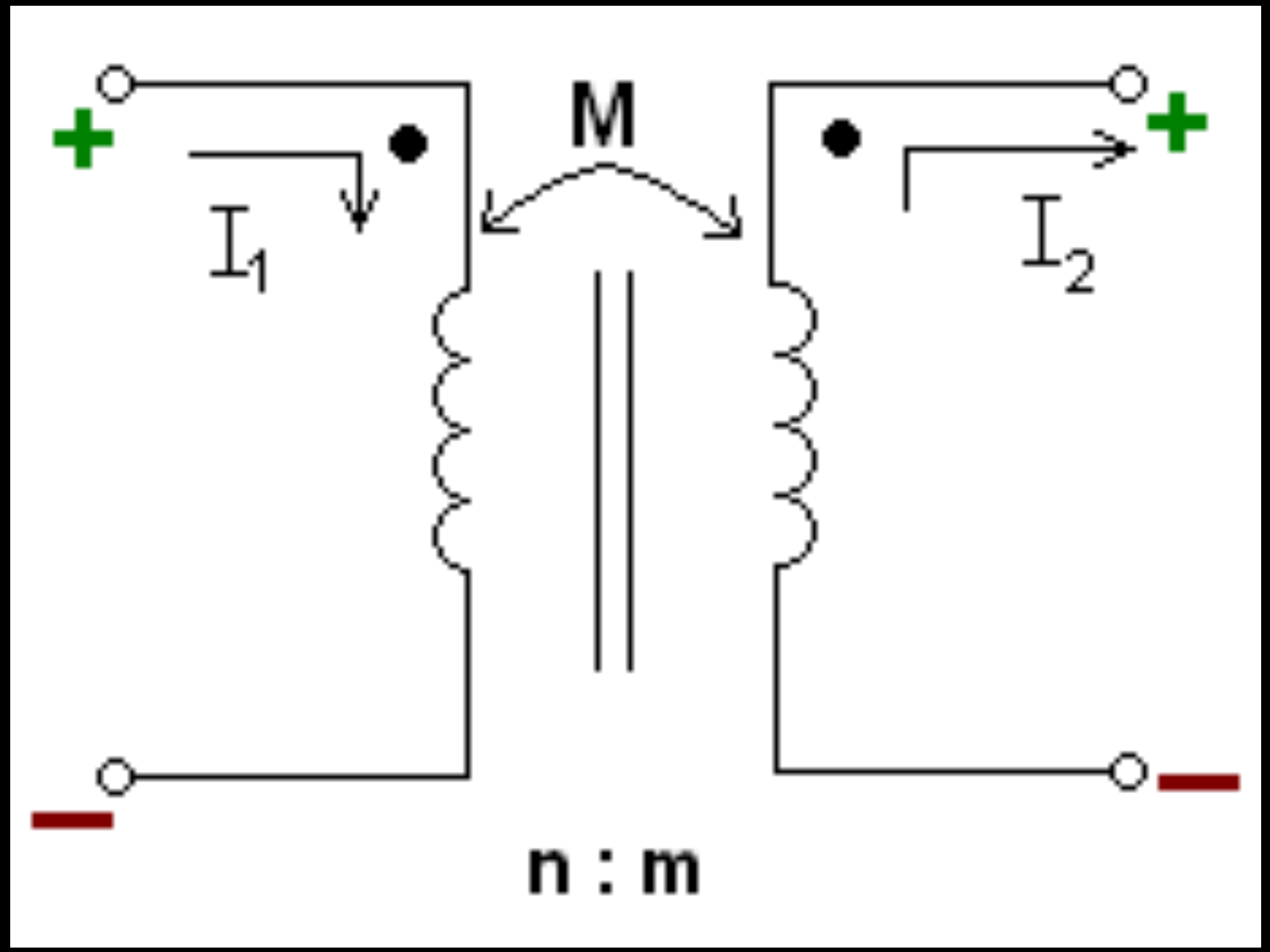
- Each wire in a coil has charge
- Interaction of E fields
  - capacitance
  - can cause resonance
  - can limit performance
- Ways to minimize
  - winding methods



Coupling

- Coupling coefficient: k
  - how much flux is captured
  - ratio of OC voltage measured to ideal coupling (turns ratio)
- Defines how well power moves through the magnetic field
  - to the other coil of wire
- Flux linkage $\lambda = \int_S \overrightarrow{B} \cdot d\overrightarrow{S}$
  - for a coil: Φ_m

Mutual Inductance: M



$$\frac{V_2}{V_1} = \sqrt{\frac{L_2}{L_1}}$$

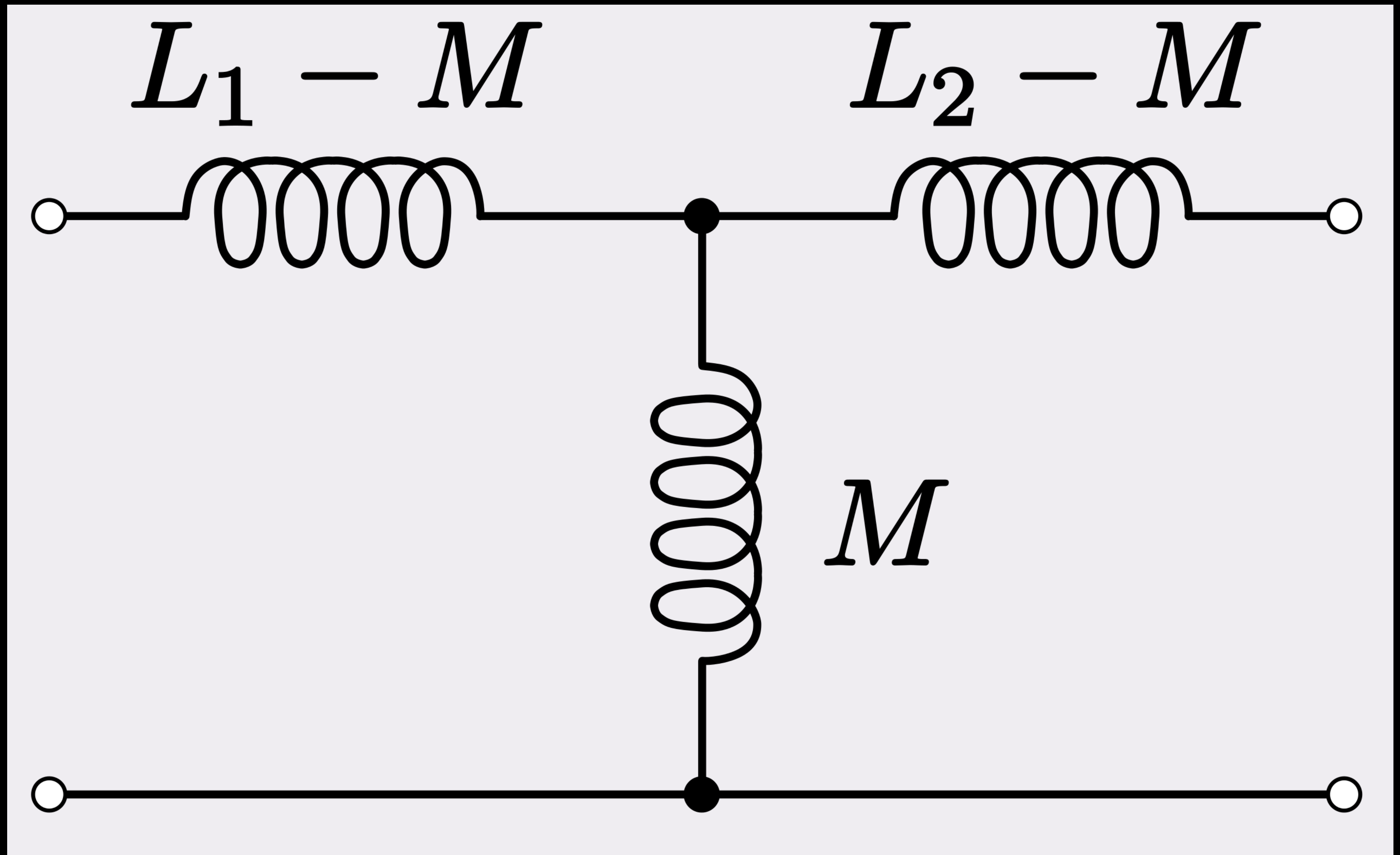
$$M = k\sqrt{L_1 L_2}$$

$$\frac{V_1}{V_2}\text{(open circuit)} = \frac{M}{L_1}$$

Mutual Inductance

- Change in current in one inductor -> voltage in other
- Uses the coupling coefficient k
- Another measure of coupling efficiency
- Extension of inductor V/I relationship
- Self Inductance - conventional L
  - proportional to the energy in B

Mutual Inductance: M



$$v_1 = L\frac{di_1}{dt} - M\frac{di_2}{dt}$$

$$\frac{V_2}{V_1} = \sqrt{\frac{L_2}{L_1}}$$

$$M = k\sqrt{L_1 L_2}$$

$$\frac{V_1}{V_2}(\text{open circuit}) = \frac{M}{L_1}$$

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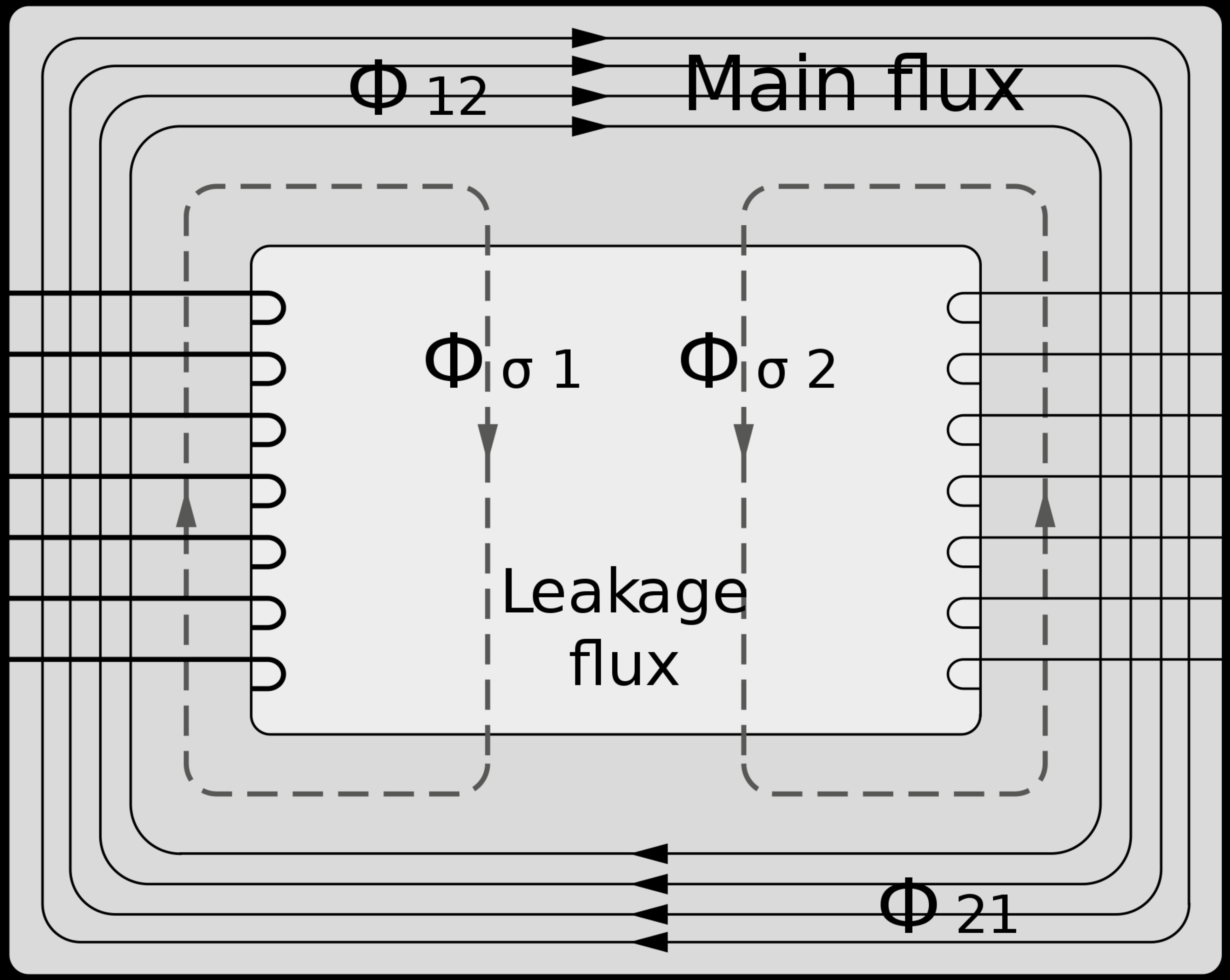
Magnetizing Current

- Losses in the core
  - hysteresis
  - eddy current ohmic
- Losses outside
  - leakage flux
  - wire ohmic
- Magnetizing current: core losses
  - maintains the mutual flux



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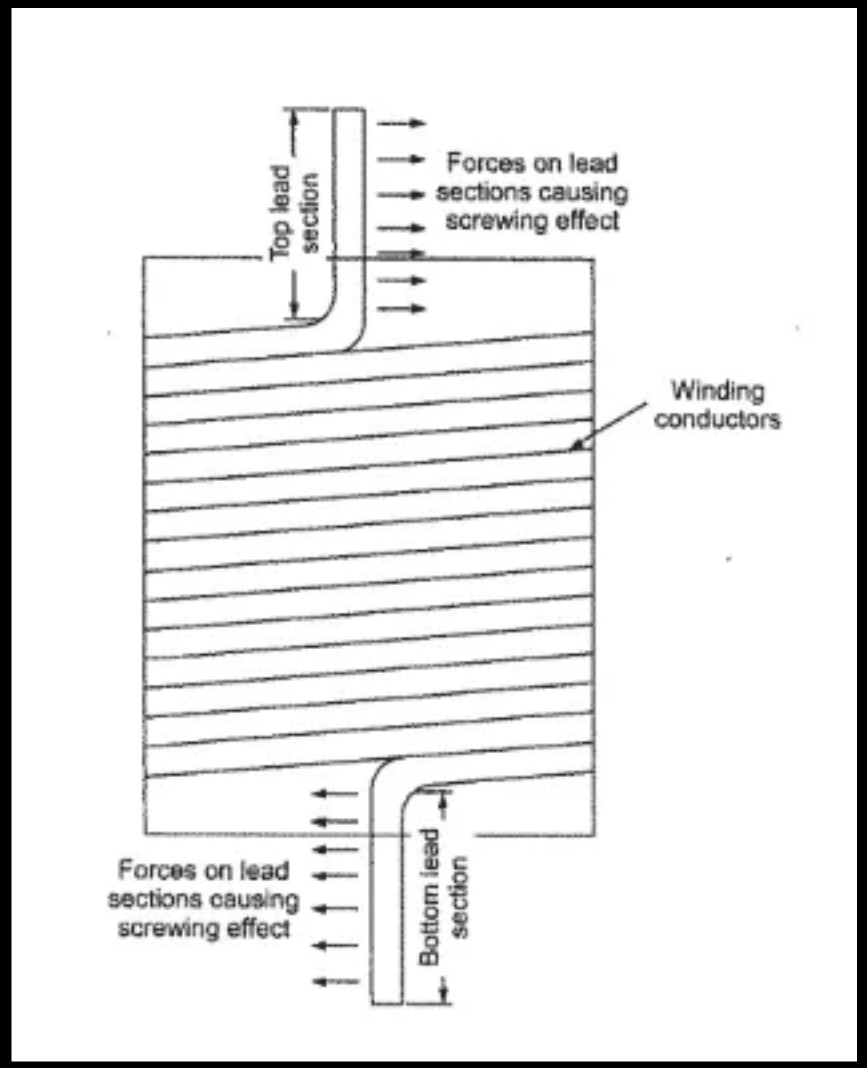
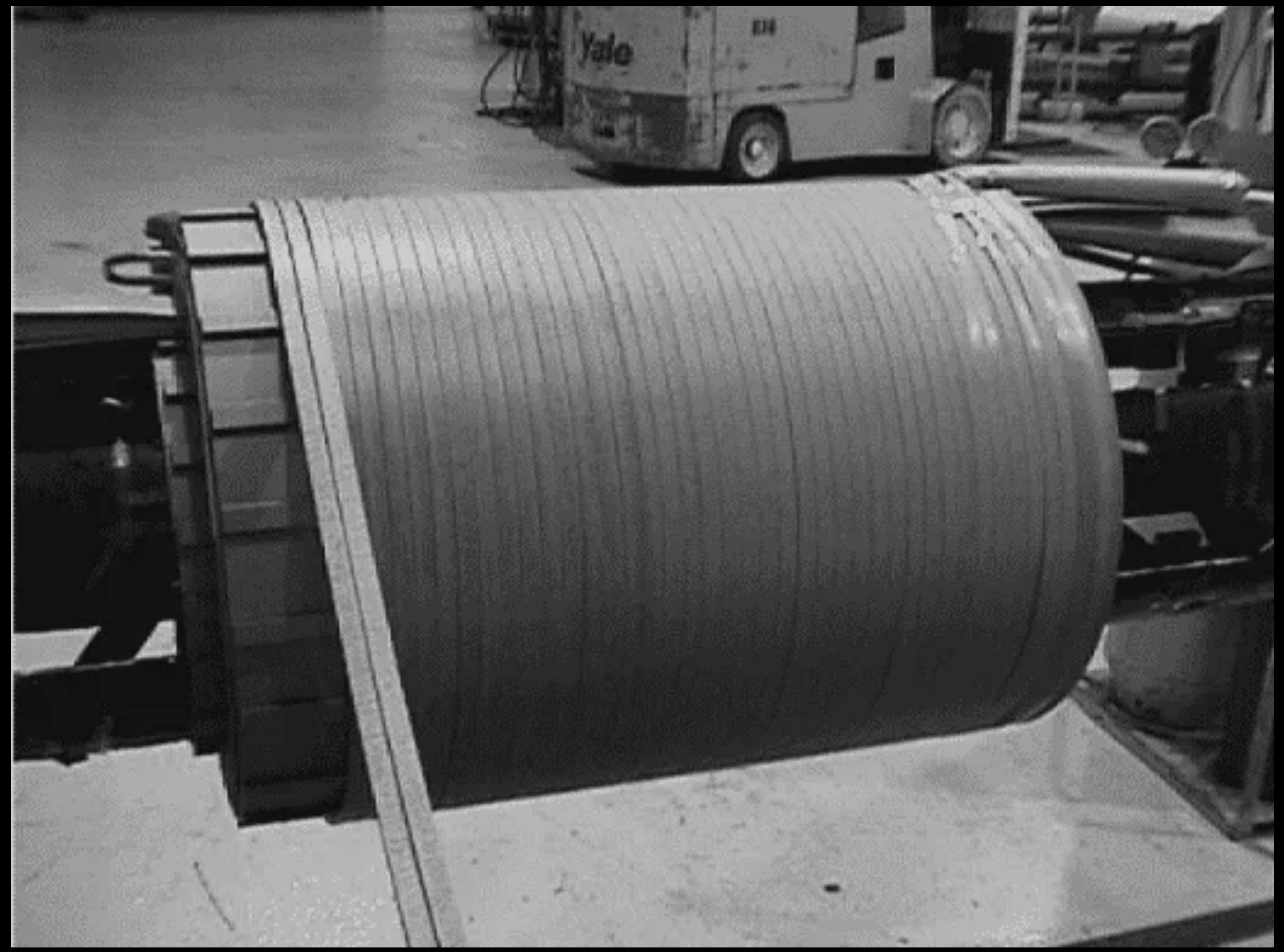
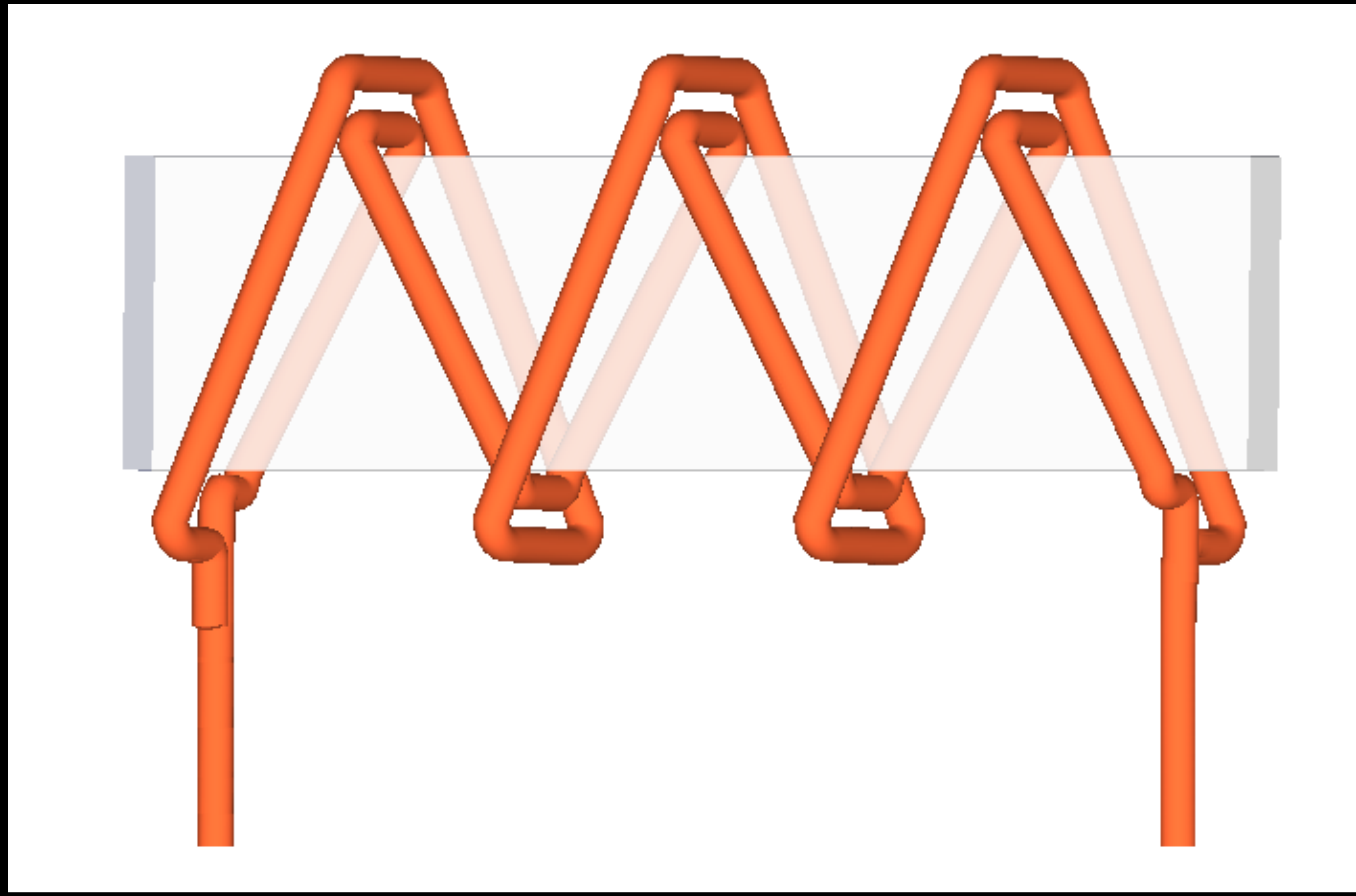
Winding Styles

- Layer / cylindrical winding
- Helical / spiral
- Transposing conductors
- Basket winding
- Bifilar / N-filar
- Ayrton-Perry winding?
  - low parasitics



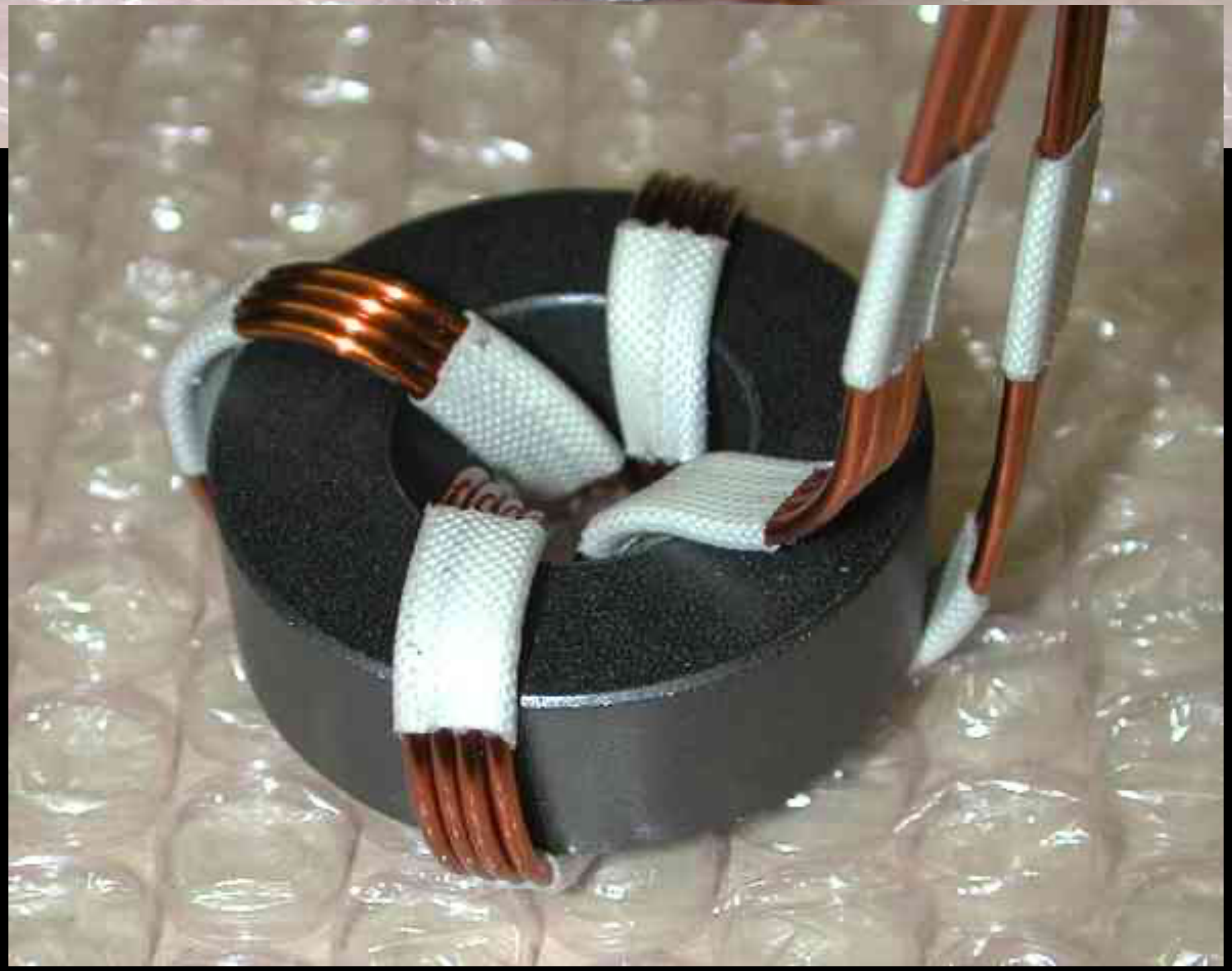




Bifilar Winding

Why?

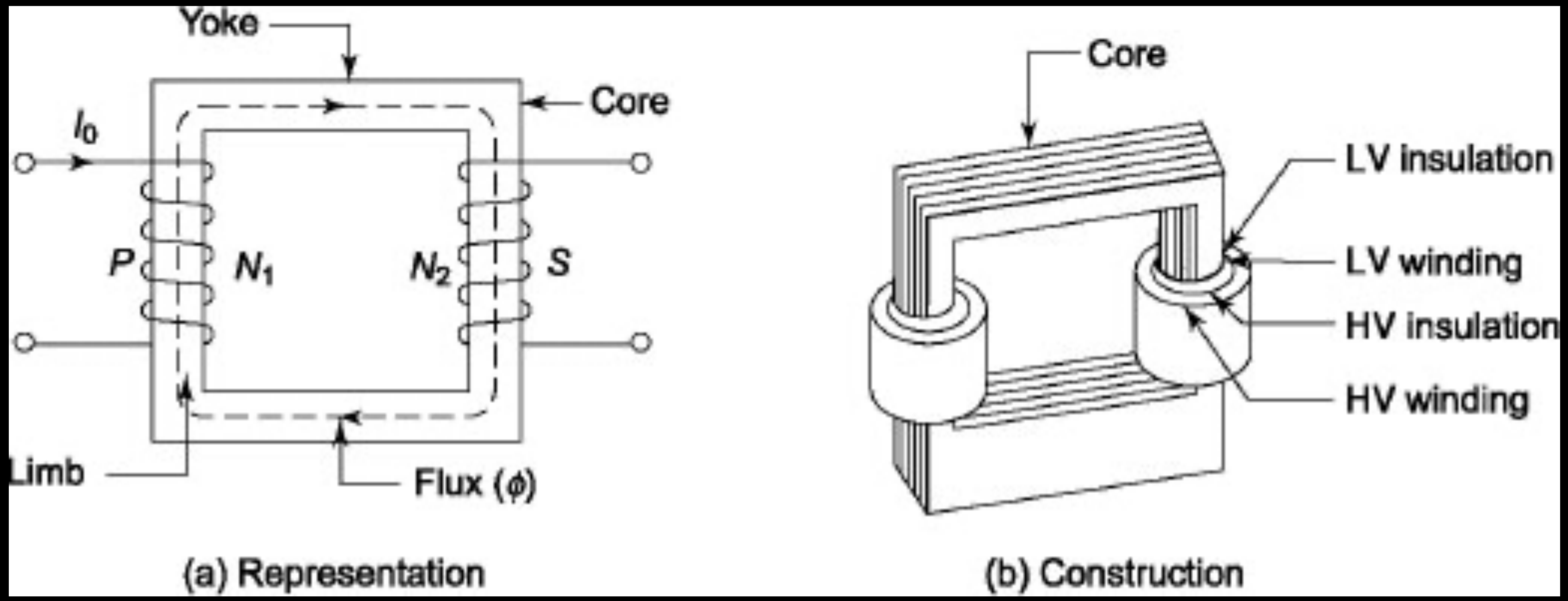
- Two (or more) parallel windings
  - quadrifilar in pic
- Can increase energy storage
  - also in the E field
- Non-inductive WW resistors
- Can be used to block back EMF
  - short one winding
- No differential inductance
  - blocks common mode
  - choke balun

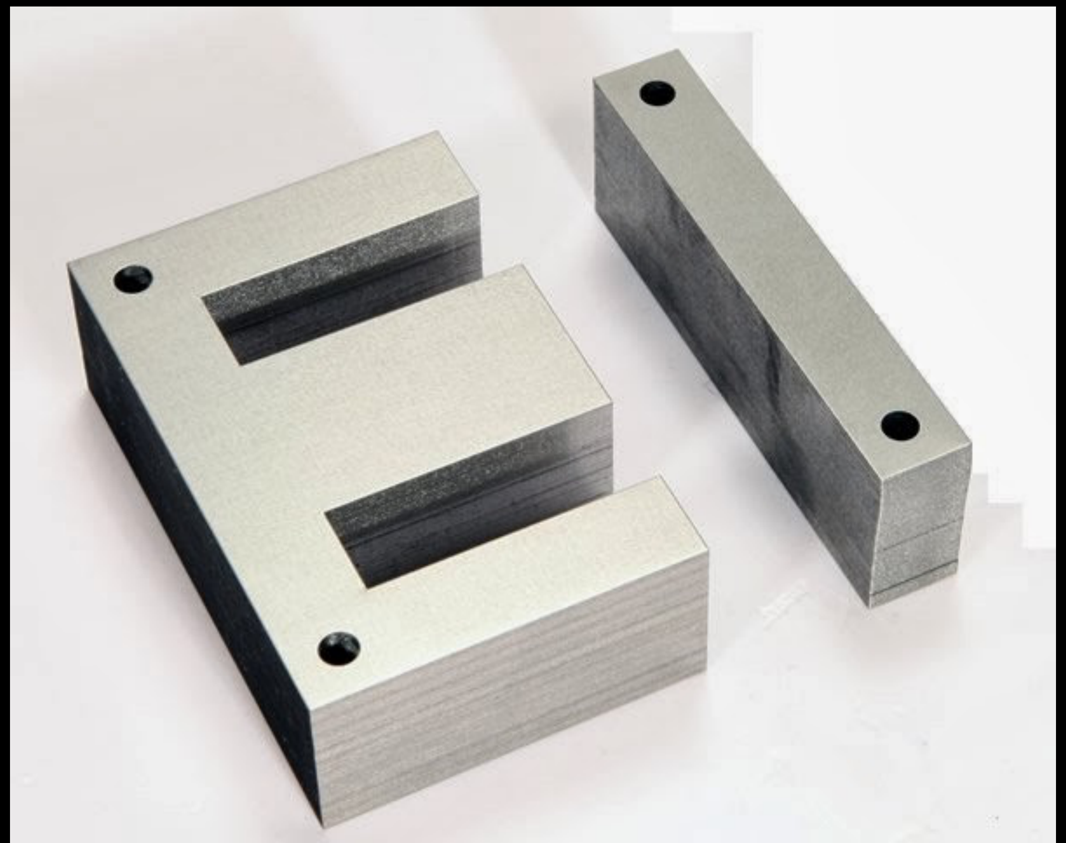


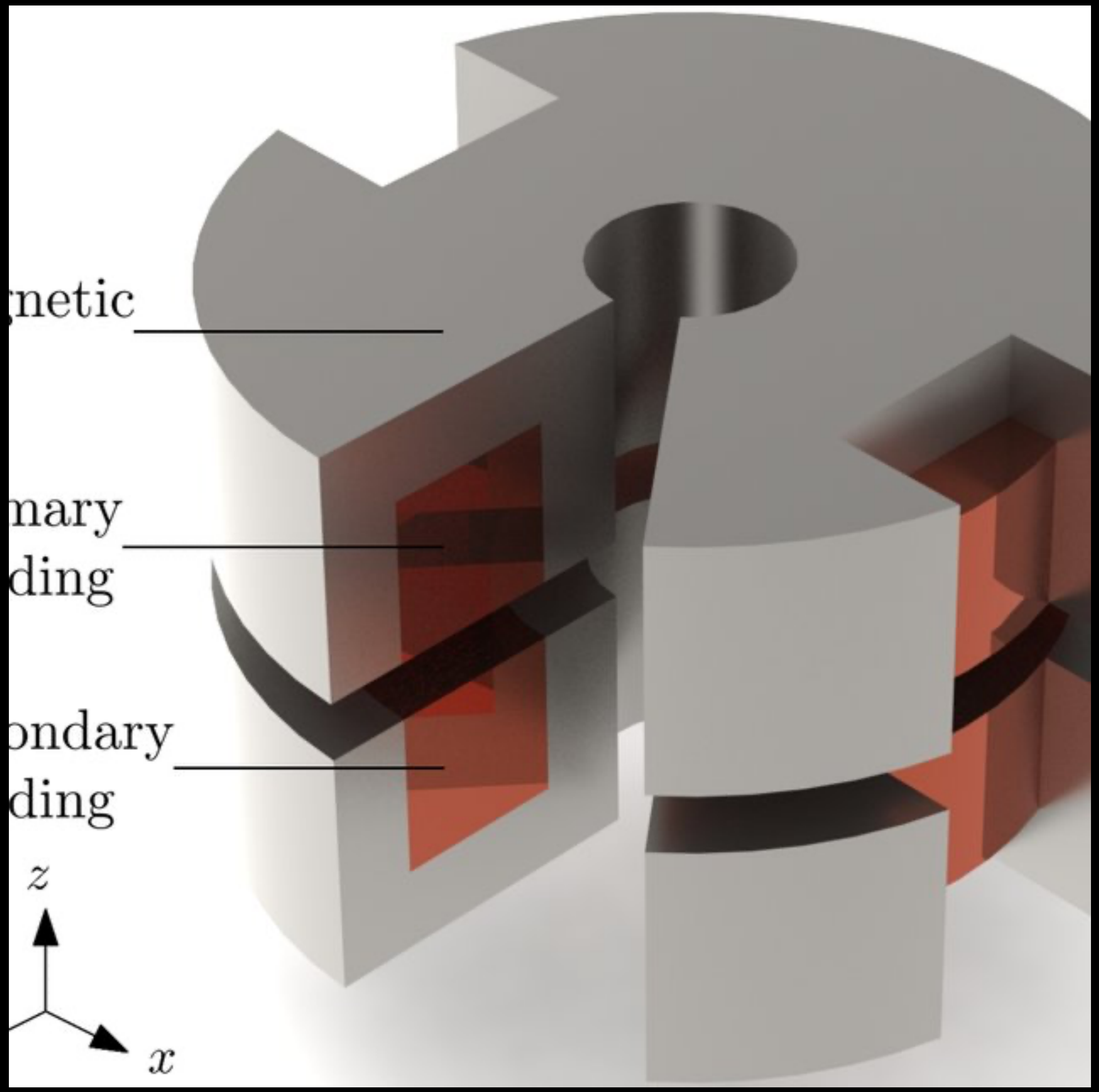
WB6ZQZ Triple Ratio Balun

Core shapes

- Keep the flux inside the core
- Direct the flux to the windings
- Common geometries
  - square core
  - ‘E’ or ‘EI’ core
  - toroidal
  - ‘pot’ core / enclosed core

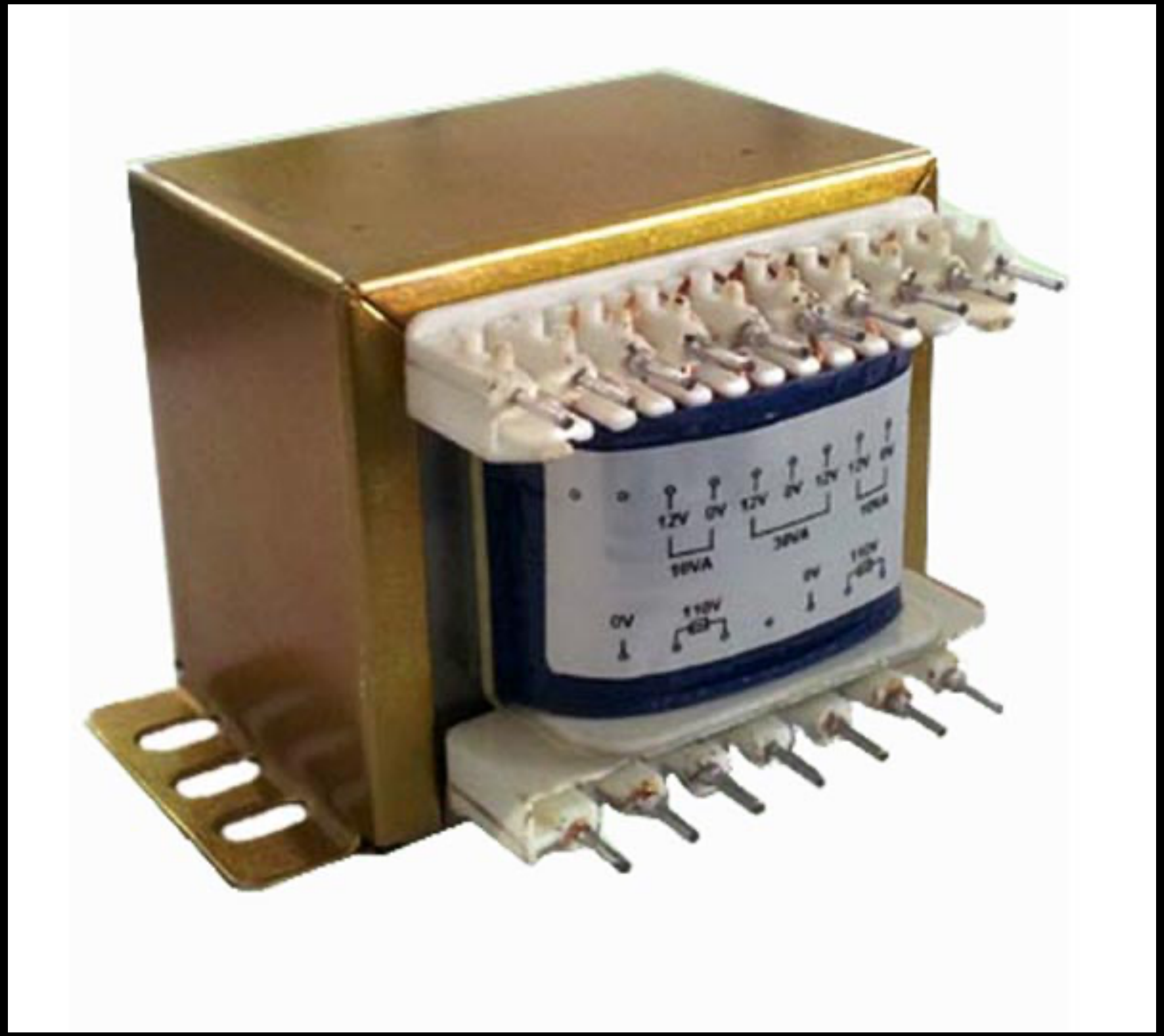






Now what?
What is it for?

- Two coils of wire
  - mutually coupled
- Coupled by magnetic flux
  - this has possibilities
- Can vary that flux's effect
  - energy is conserved, though
- Can seemingly change ratios



Power

Change I to V relationship

- Power = Voltage x Current
- Energy = $\int_{t_0}^{t_1} P(t)\ dt$
- Energy is conserved
  - so power is too, sort of
  - $P_{in} = P_{out}$, $V_{in} \cdot I_{in} = V_{out} \cdot I_{out}$
- Ratio of windings N
  - primary : secondary

Faraday's Induction Law

$$V_p = -N_p \frac{d\Phi}{dt} \qquad V_s = -N_s \frac{d\Phi}{dt}$$

Combine: Assume the flux is equal

$$\frac{V_p}{N_p} = -\frac{d\Phi}{dt} \qquad \frac{V_s}{N_s} = -\frac{d\Phi}{dt}$$

$$\frac{V_p}{N_p} = \frac{V_s}{N_s}$$

$$\boxed{\frac{V_p}{V_s} = \frac{N_p}{N_s}} \qquad \boxed{\frac{V_p}{V_s} = \frac{I_s}{I_p}}$$

Impedance

Change I to V relationship

- Since power is ‘conserved’
    - impedance follows similarly
- Use Ohm’s Law
    - it’s a ‘Law’
    - assume linearity
- Crank the algebra
    - turns ratio squared

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = a \qquad \frac{V_p}{V_s} = \frac{I_s}{I_p}$$

$$V = I \cdot Z$$

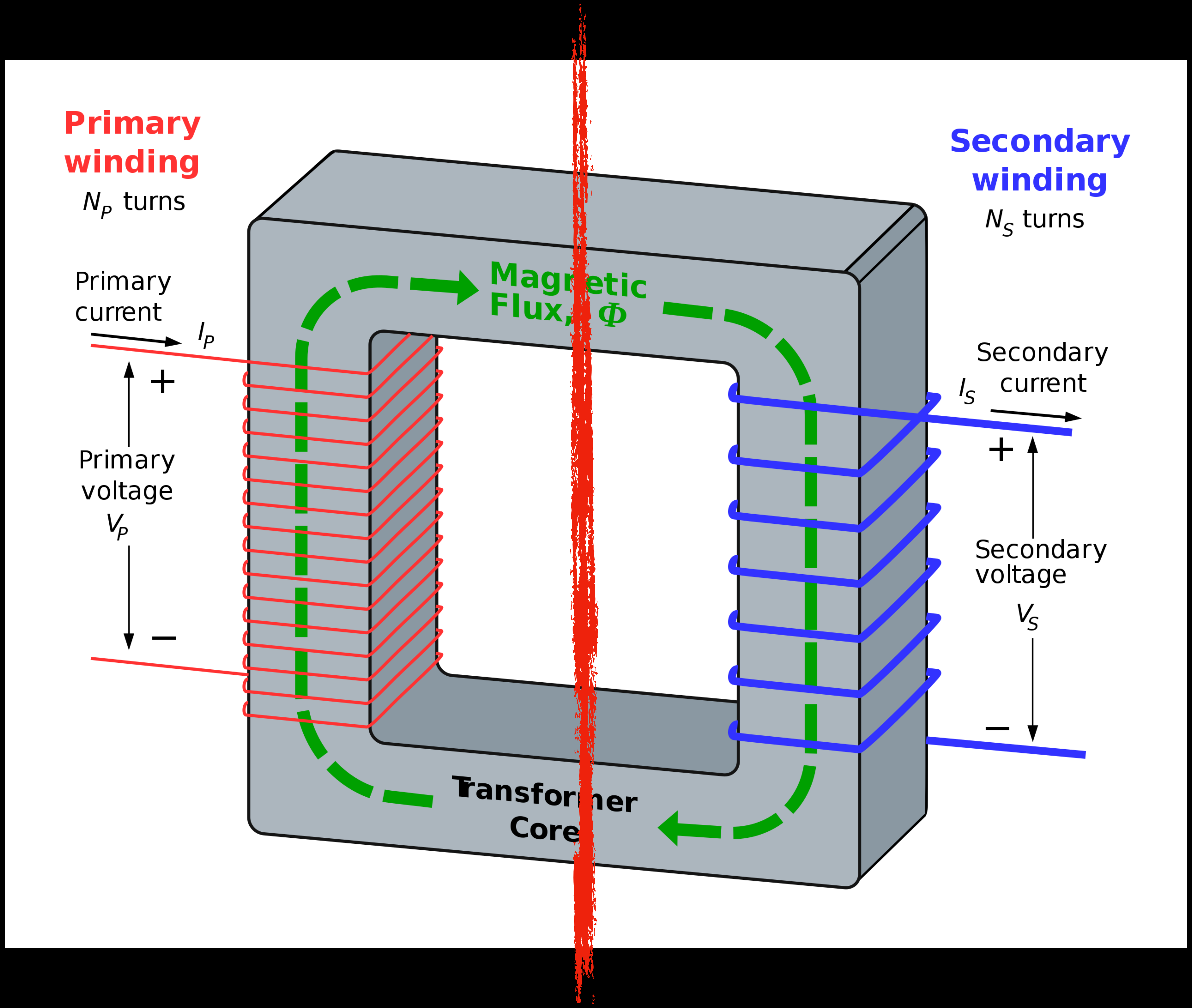
$$Z_{in} = \frac{V_p}{I_p} \qquad Z_{out} = \frac{V_s}{I_s}$$

$$\boxed{\frac{Z_{in}}{Z_{out}} = \frac{V_p}{I_p} \cdot \frac{I_s}{V_s} = a^2}$$

Isolate

- Transfer power
- No voltage relationship
  - how?
- Magnetic coupling ++
- Electric coupling --
- Frequency can't be too high
  - couples through E field

No Voltage Relationship



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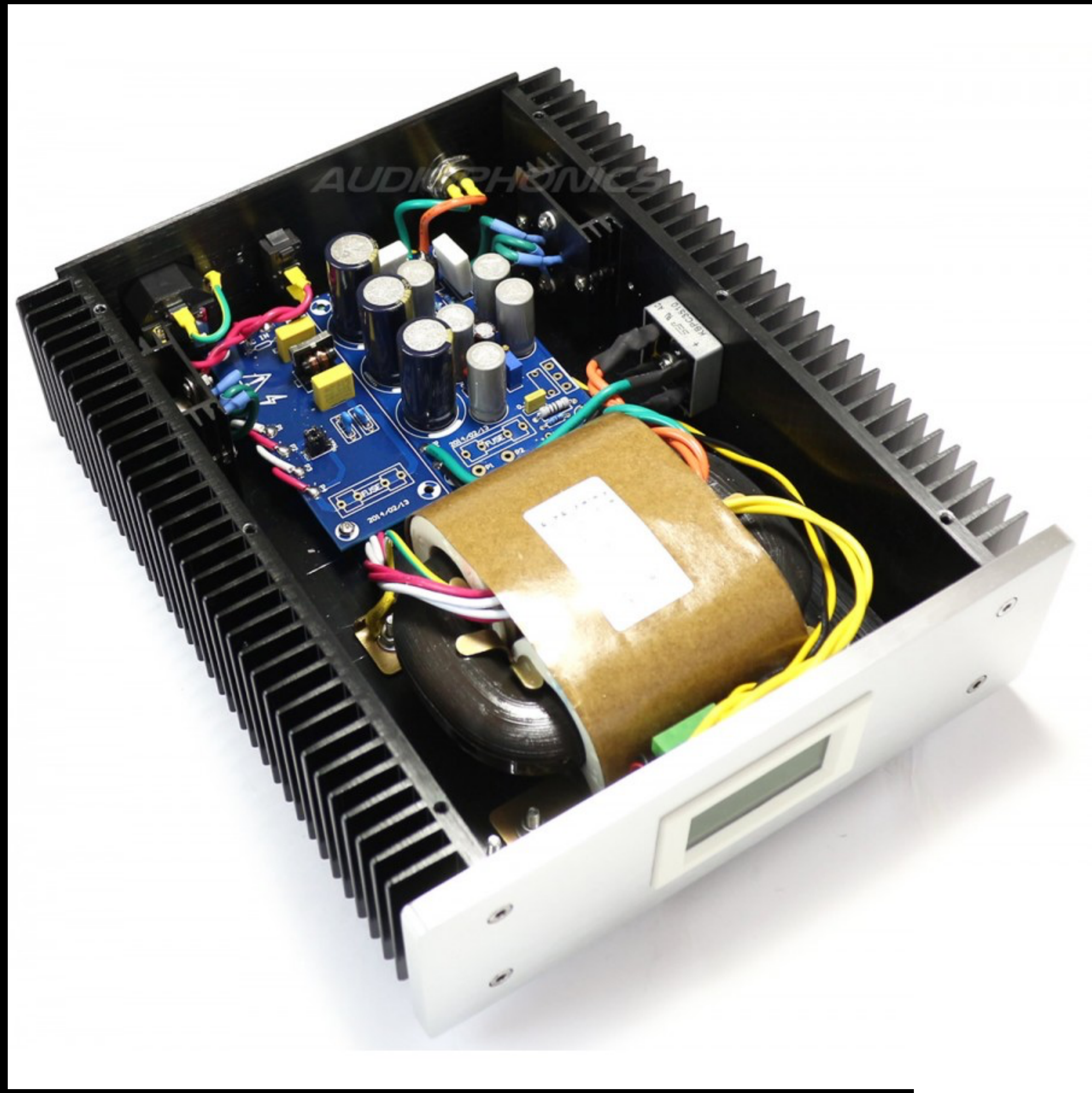
Making them Smaller

Why are switch mode PSs small?

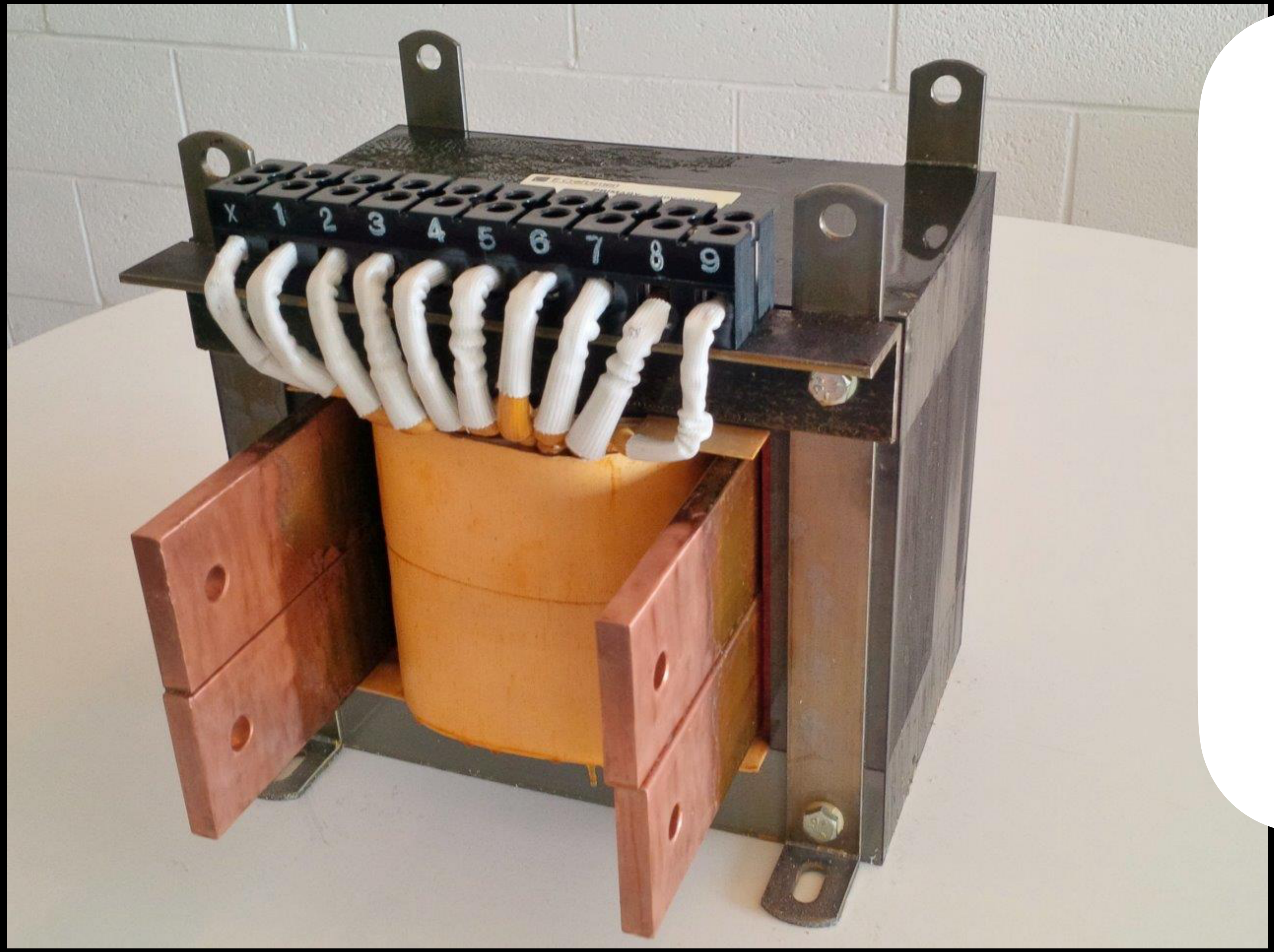
- It's all in the magnetics
- Remember $\dfrac{d\Phi}{dt}$ is what matters
- Increase the frequency (>10 kHz)
    - what increases?
- Better magnetic coupling
- Automatic adjustment
    - power factor correction
    - V & I in phase

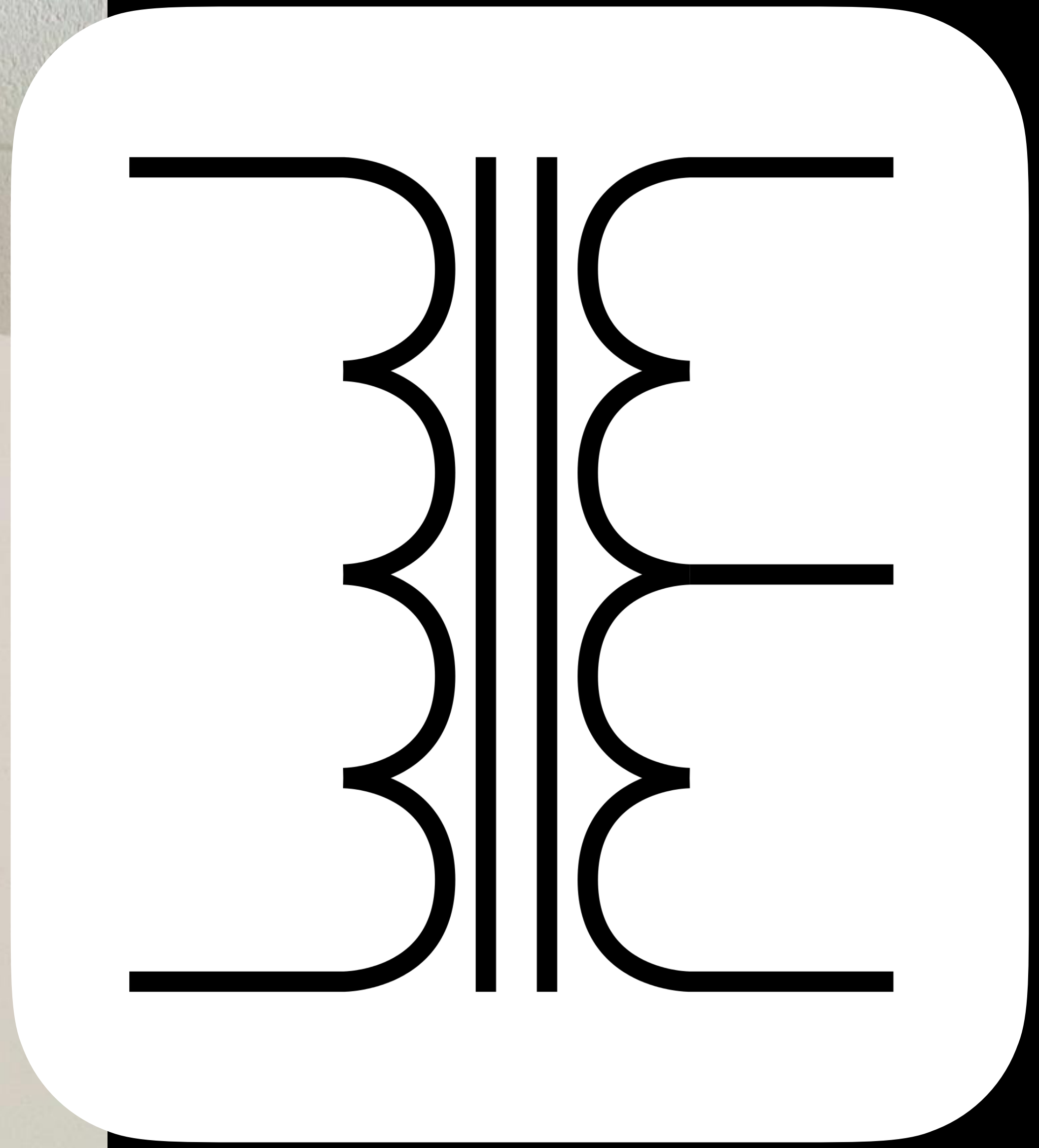


5V, 11A, 55VA

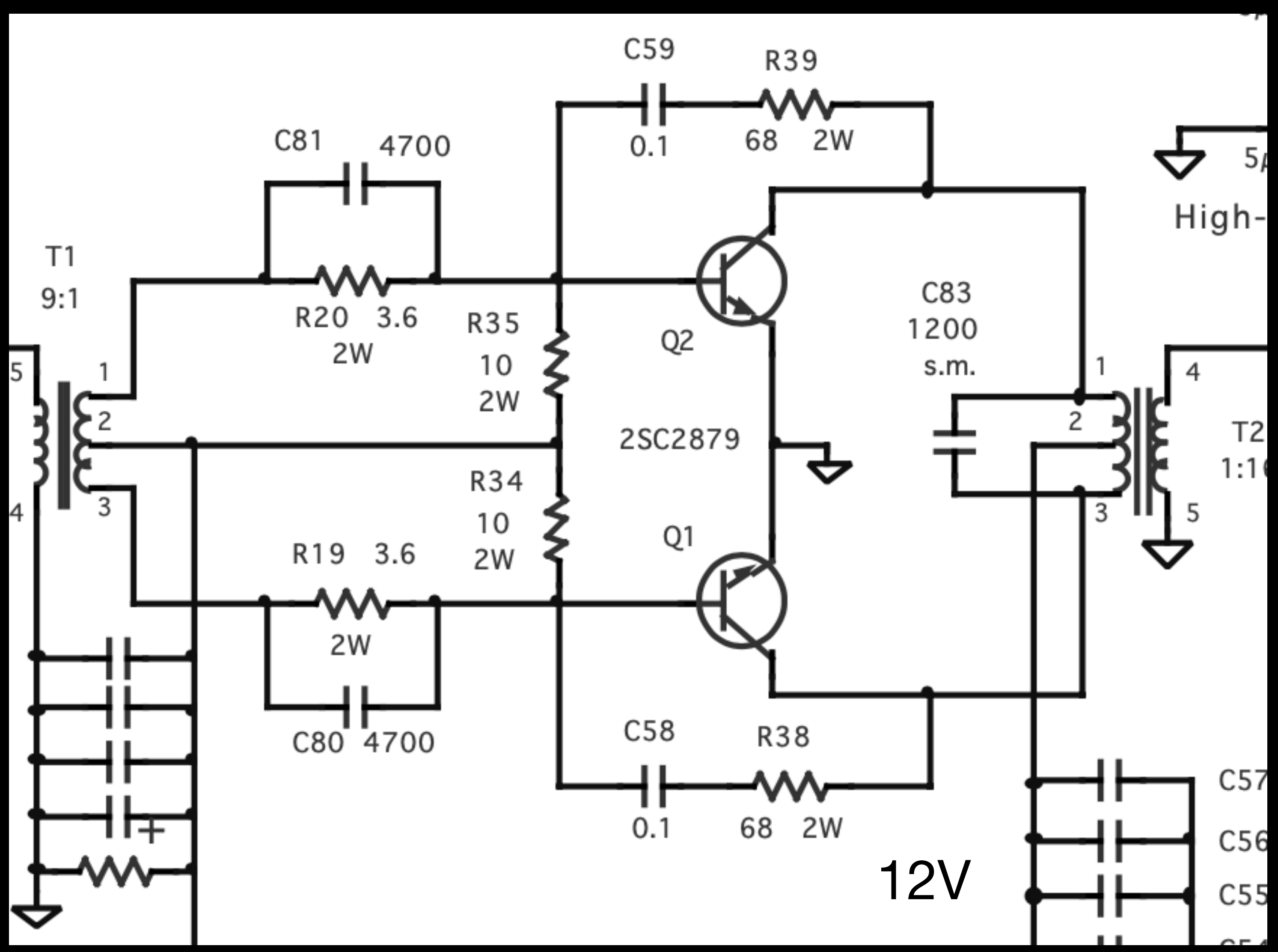
5V, 10A, 50VA

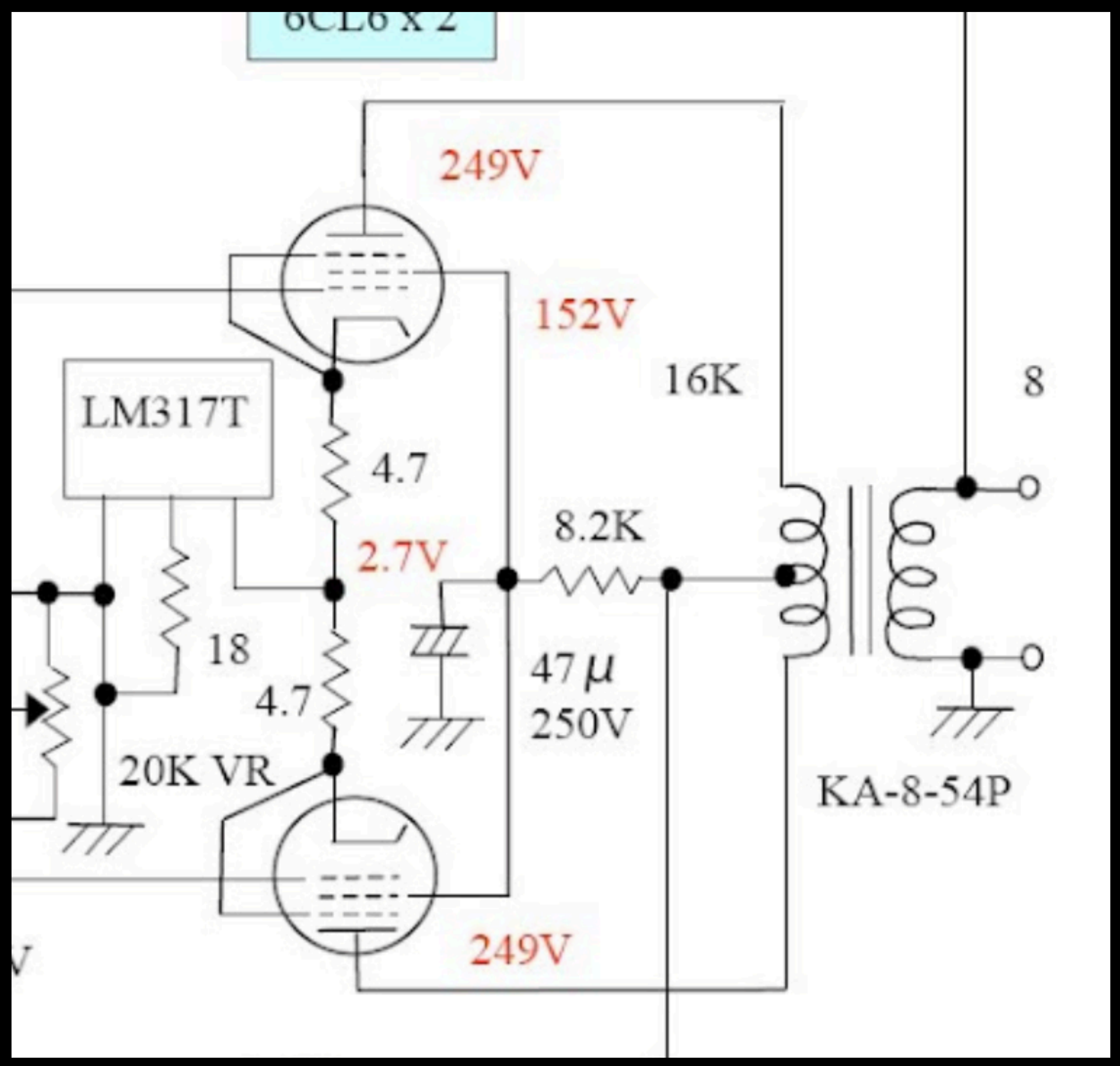
Taps and Tricks





- Multiple input or output voltages
  - multiple currents too
- Was used to select 110V / 220V
- B+ and filament from same transformer
- Push-pull with one type of driver
  - polarity reversal!



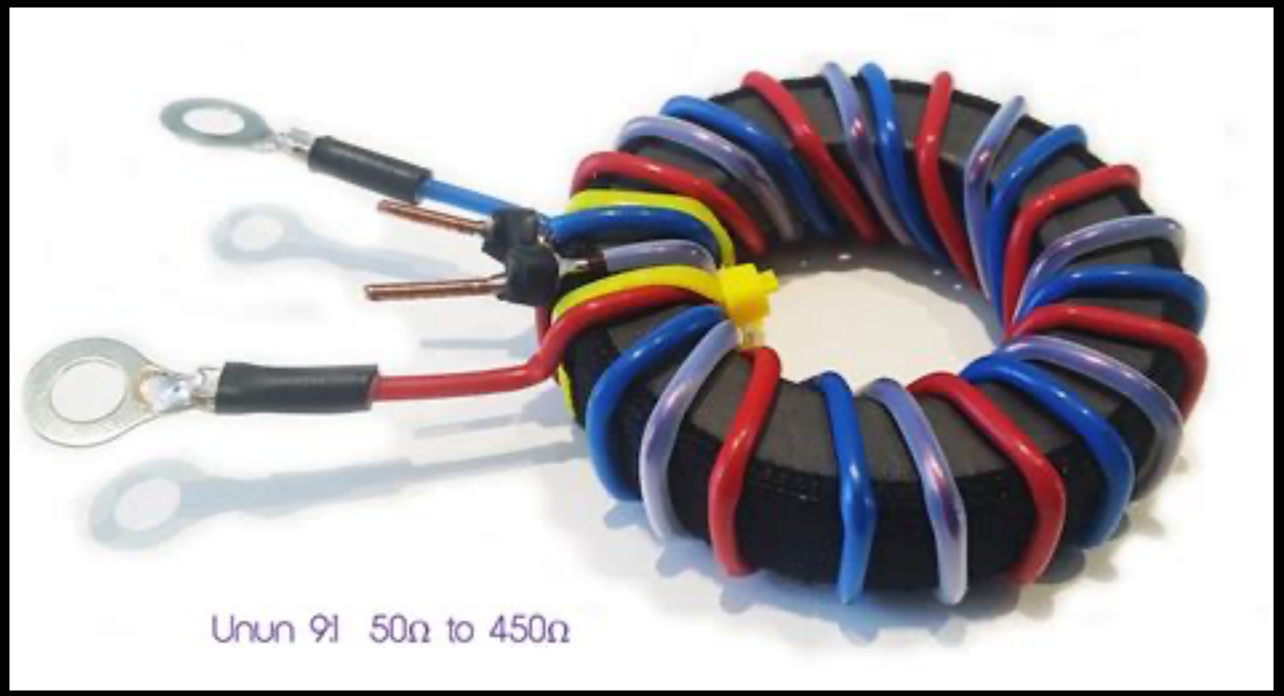


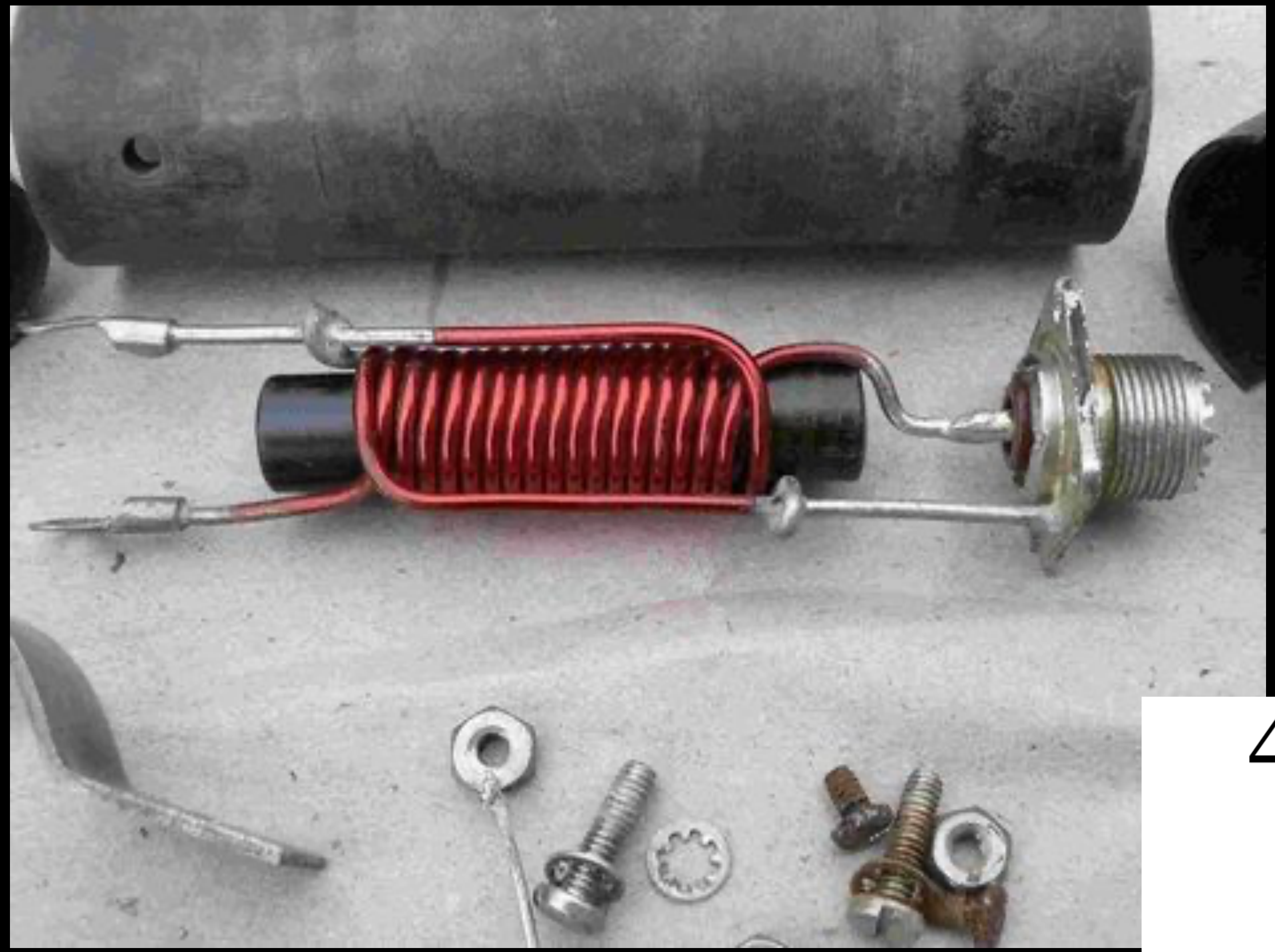
Look familiar?

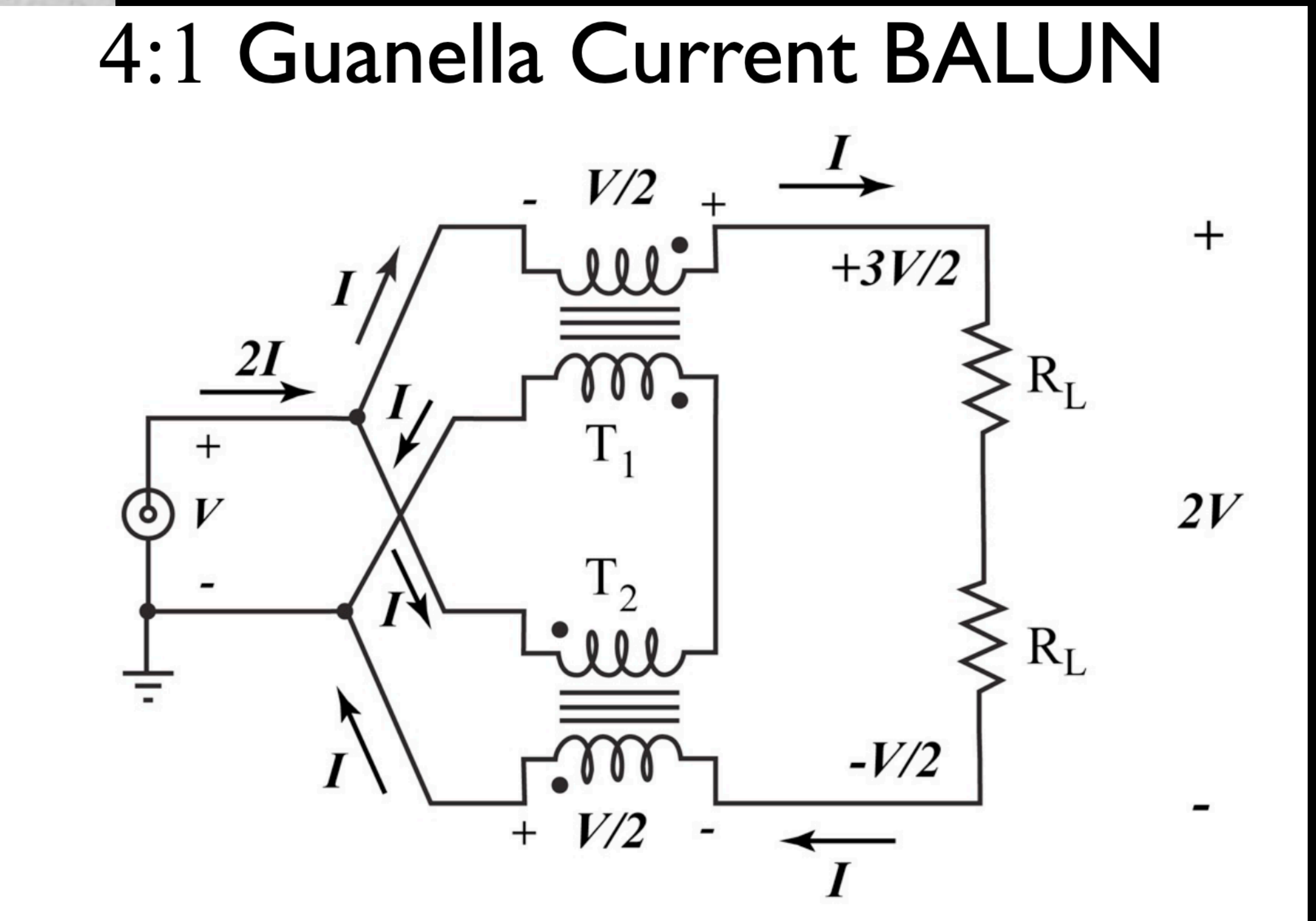
Baluns and Ununs

Basically transformers

- So-called Voltage Baluns/Ununs
  - fancy name for transformer
  - isolation and impedance transformation
- So-called Current Baluns
  - different principle 1:1
  - uses transformer
  - voltage not ‘severed’

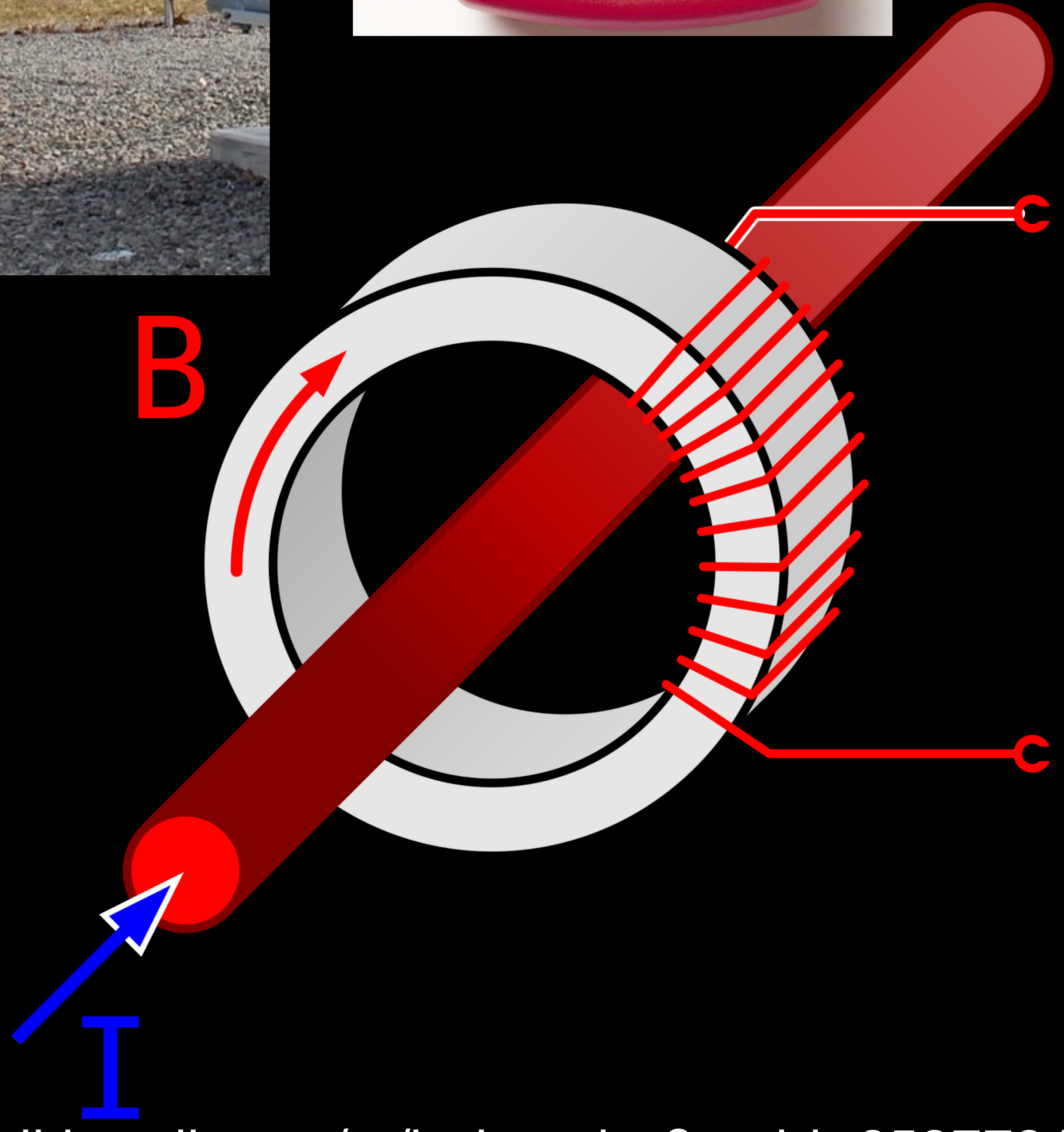






‘Current’ Transformer

- For measurement in power systems
- Basically sensing the changing magnetic flux
- Amprobe is a small-scale example
- Fast and loose terminology
    - not simply current-based



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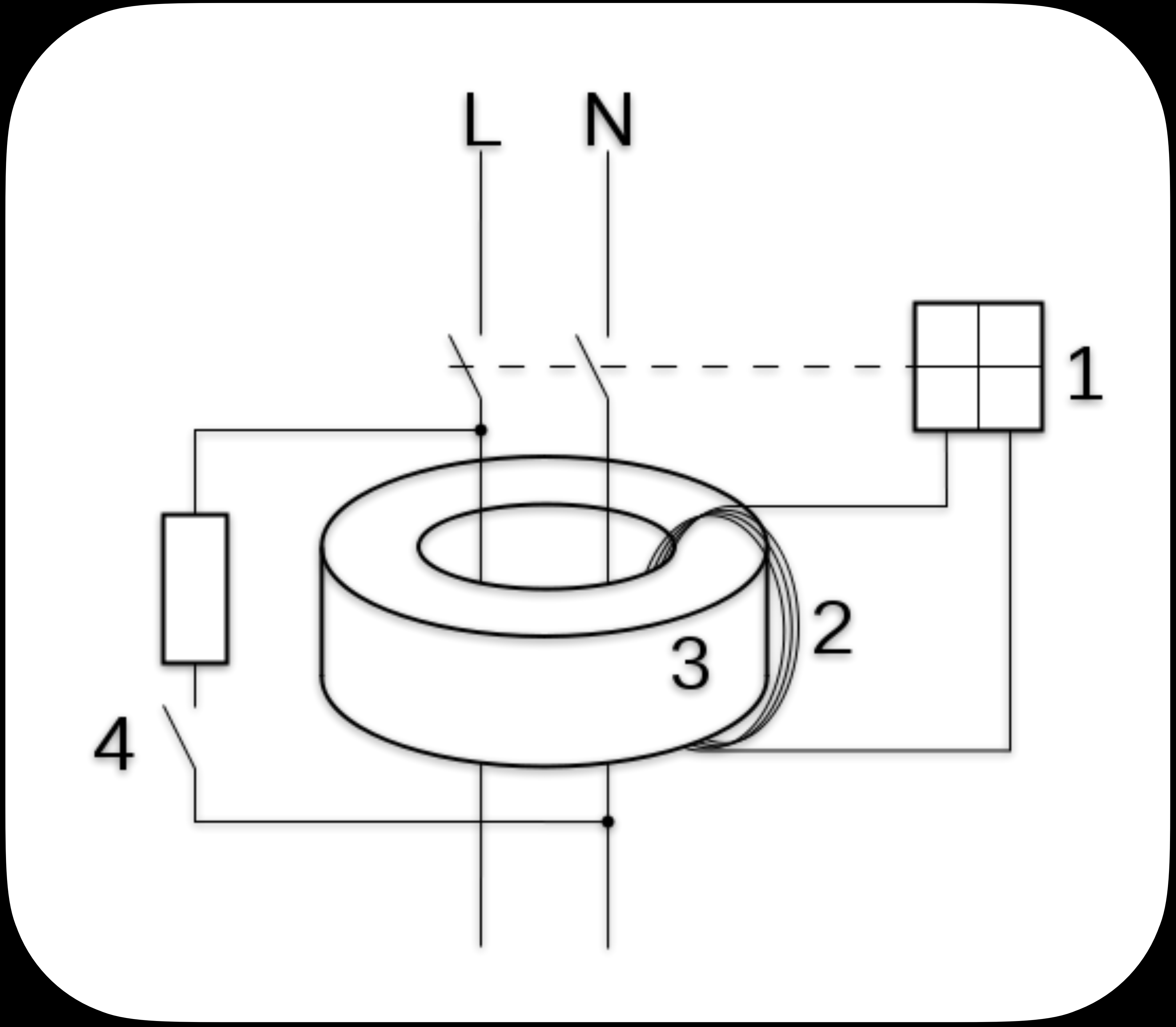
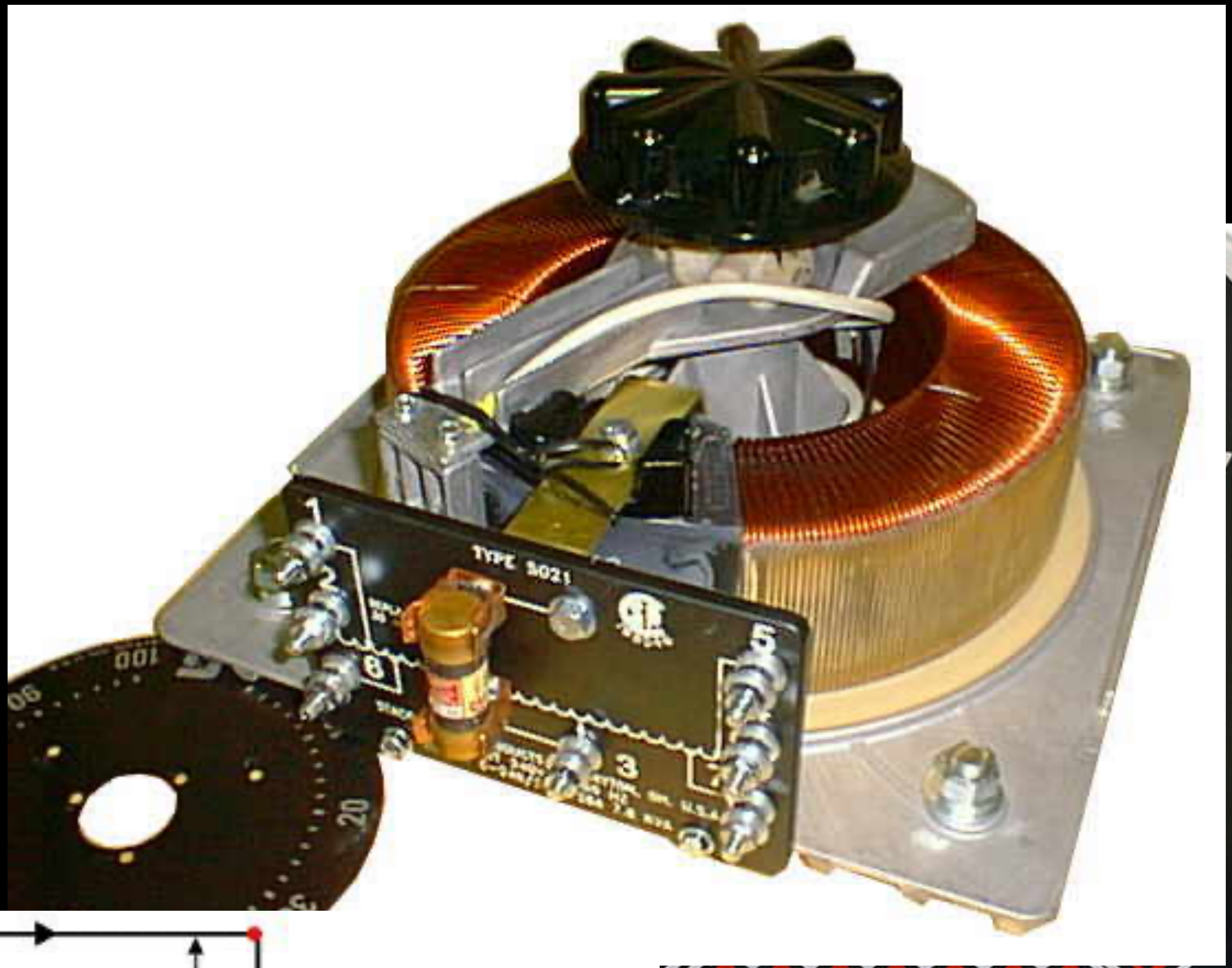
Ground Fault Interruptor

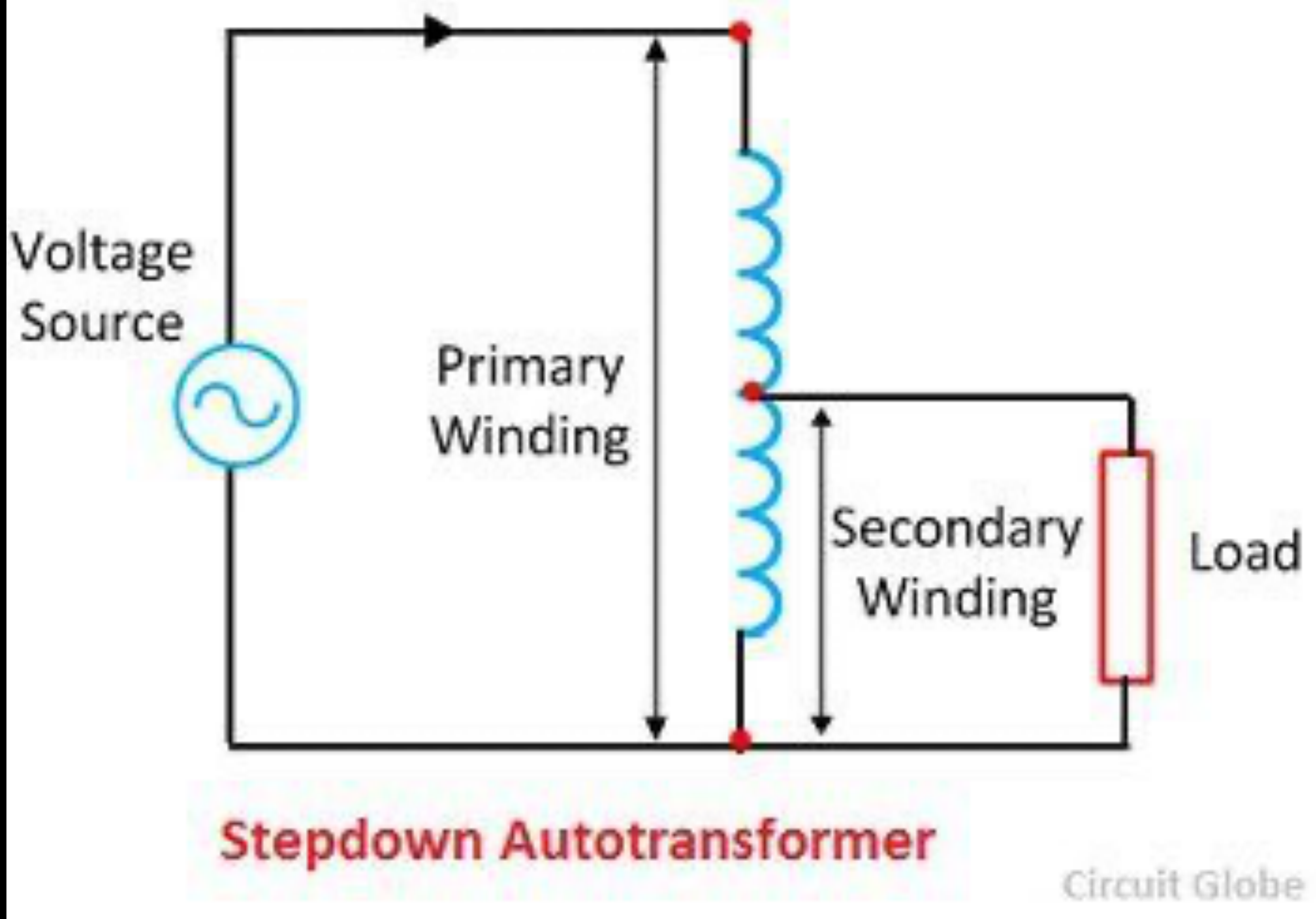


- Clever device
- L + N -> net magnetic flux
  - equal & opposite = 0
  - not equal -> flux
- Sense flux with secondary winding
- Trigger the breaker if voltage present

Variac (autotransformer)

- Primary and secondary common
- Wiper taps the secondary
  - called autotransformer
- Step down and up
- Most care about voltage
  - but V, I tradeoff still there
  - depends on wire and core



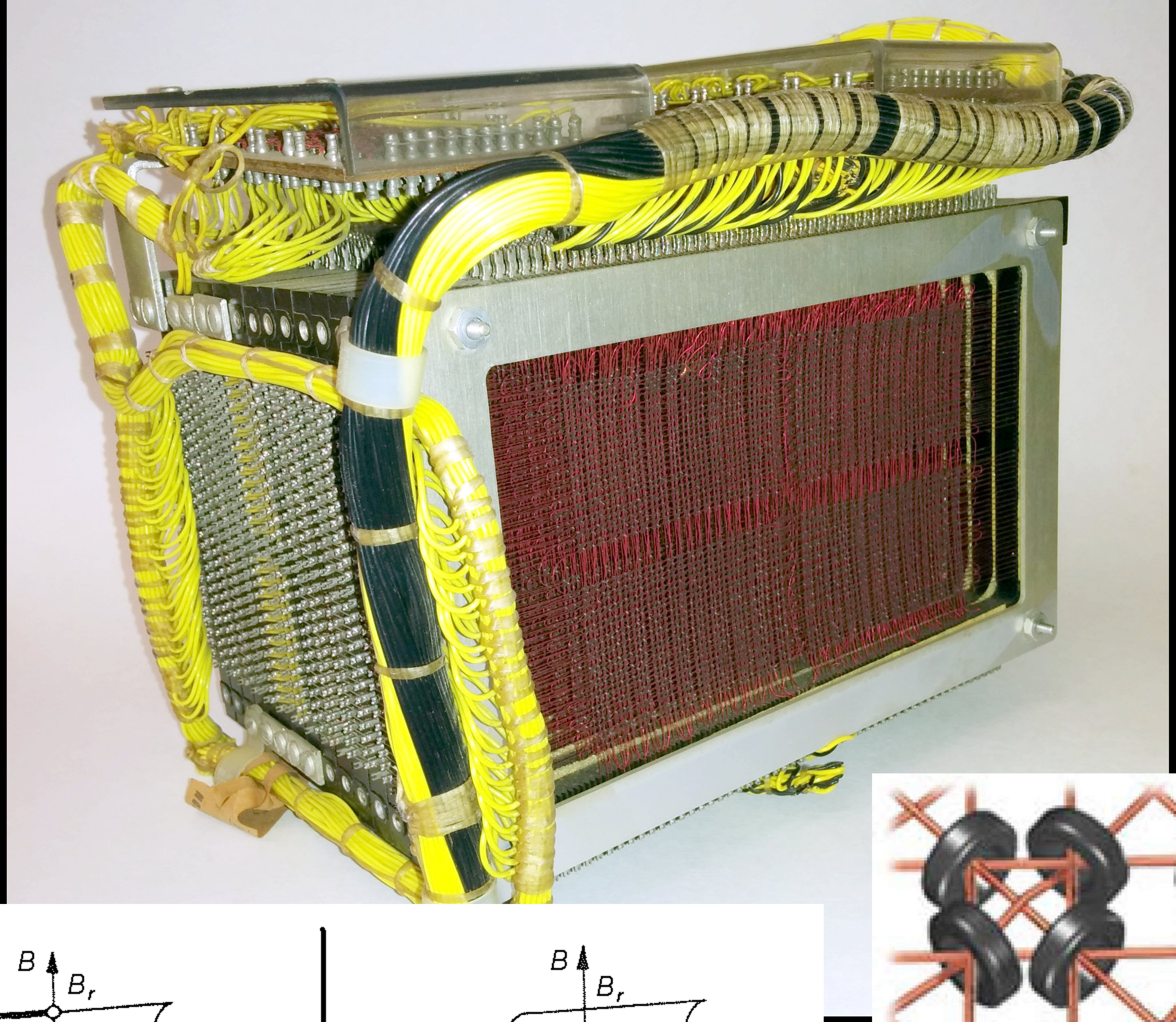


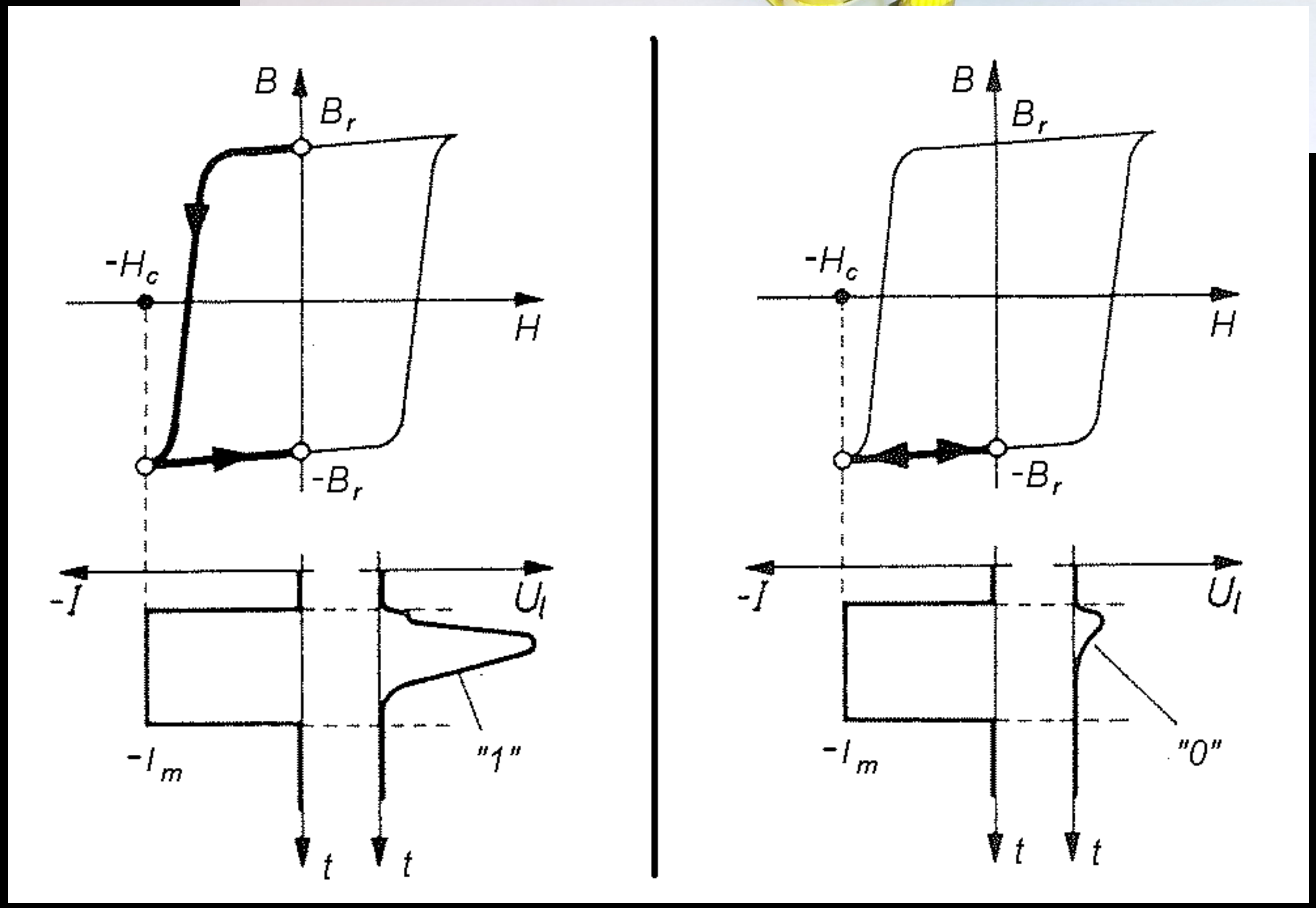
Ferroresonant

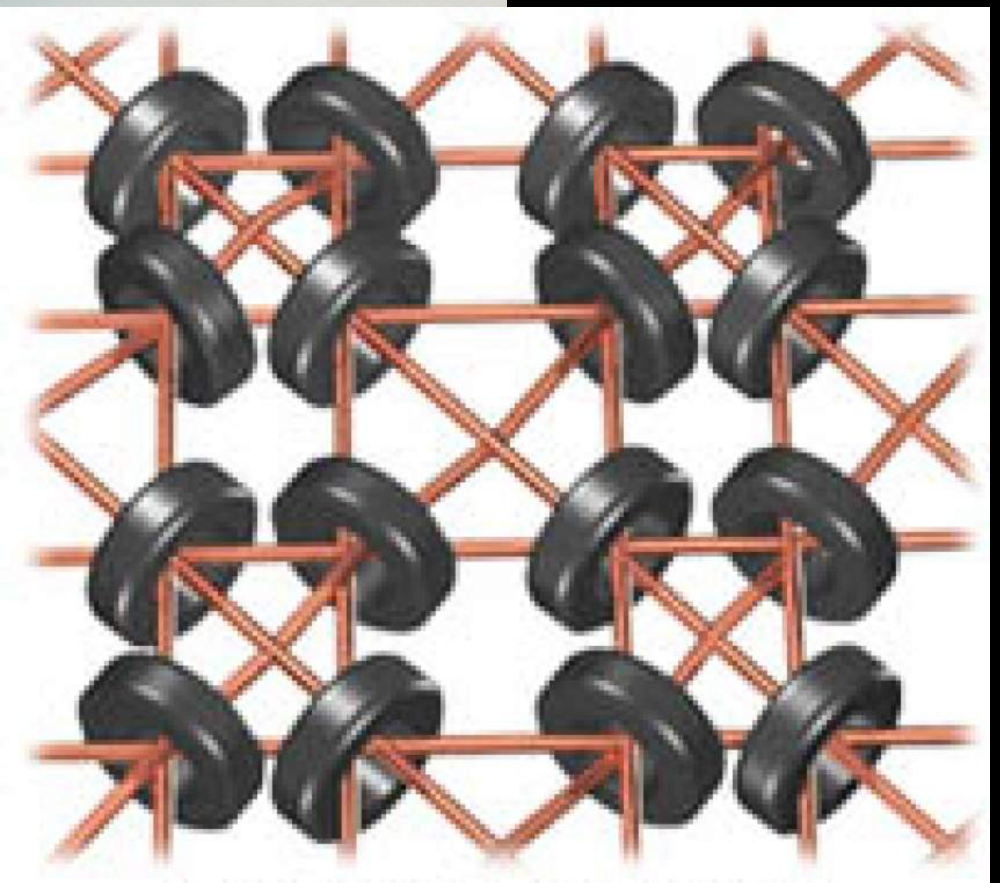
- Look about the same
- Iron core partially saturated at no load
  - in nonlinear region
- Sometimes resonated with a capacitor
- Output much less sensitive to input variations
- Lovely buzzing sound!
  - lots of harmonics
  - can lead to EM interference

Core Memory

- Ferrite beads (toroids)
- High coercivity
  - push to magnetization
- Delayed transformer effect
- Travel the hysteresis curve
  - writes go one way
  - reads the other





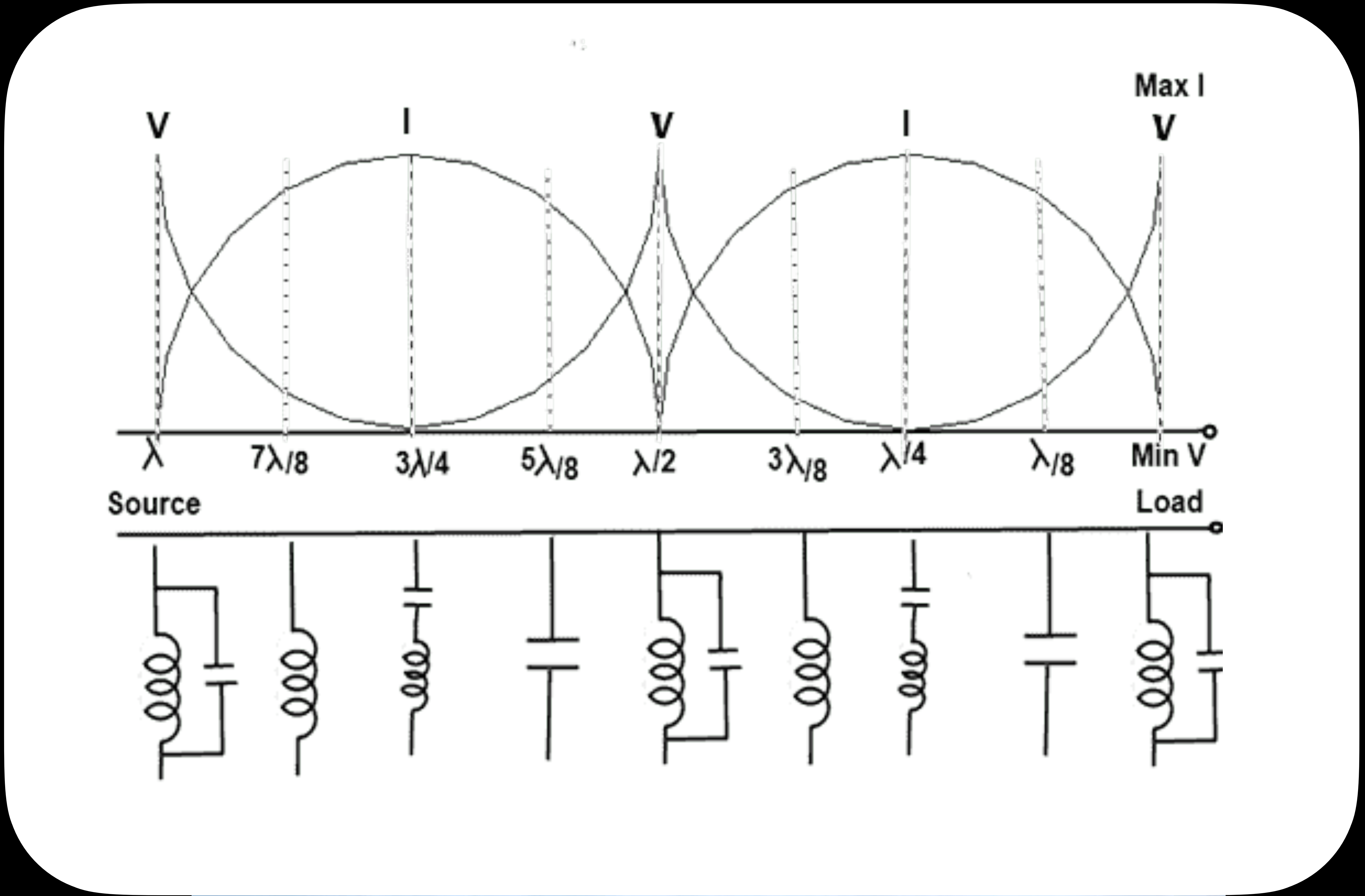


By Wdwdderivative work: User:ArnoldReinhold - Ringkernspeicher_hysteresekurven.PNG, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16154290

Transmission Line

A different take

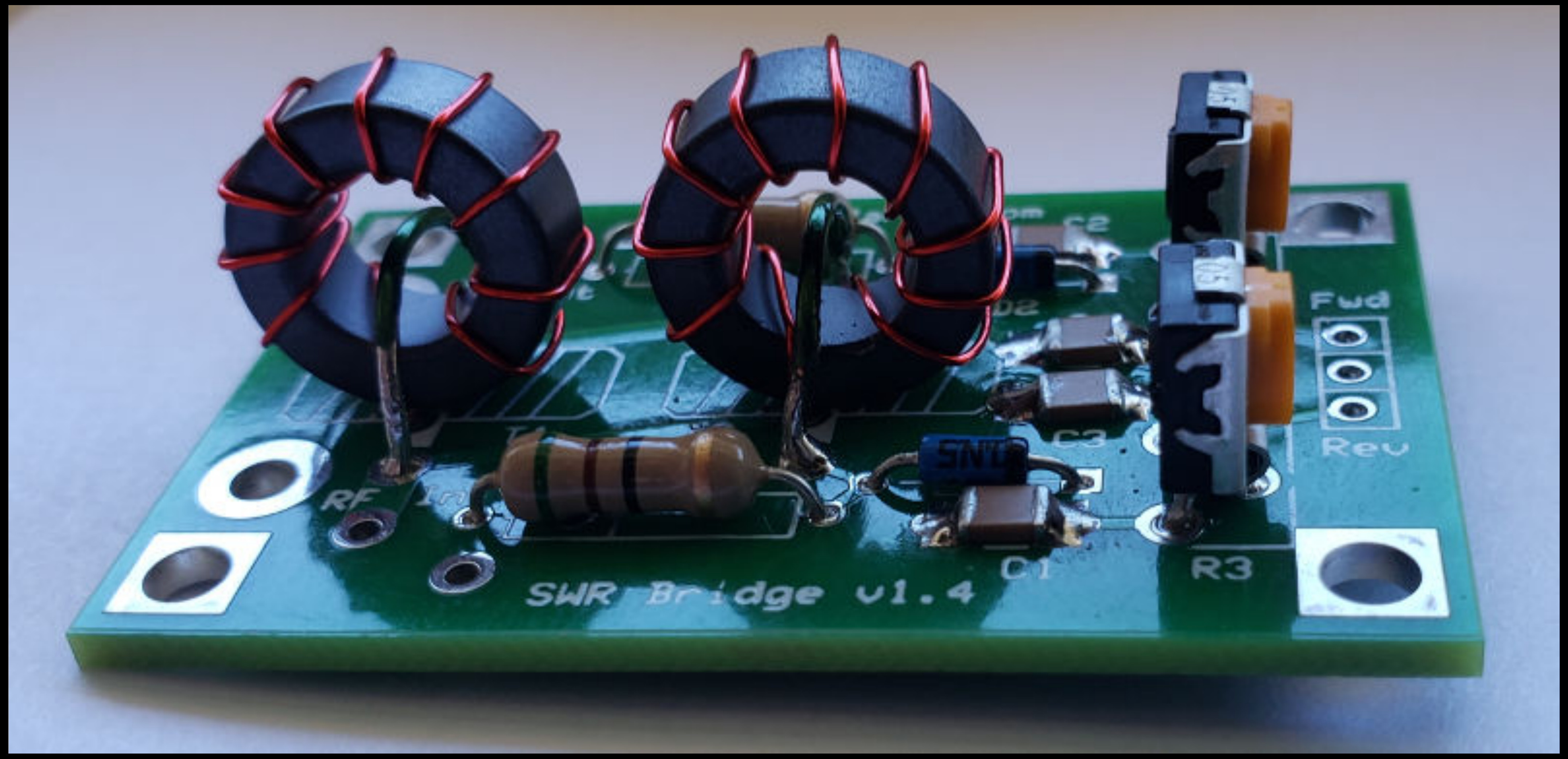
- A kind of transformer
  - but rather different
- Doesn't use flux linkage
  - uses transmission line characteristics
- Wavelength dependent
- Confusing terminology again
  - TLT is balun / unun?

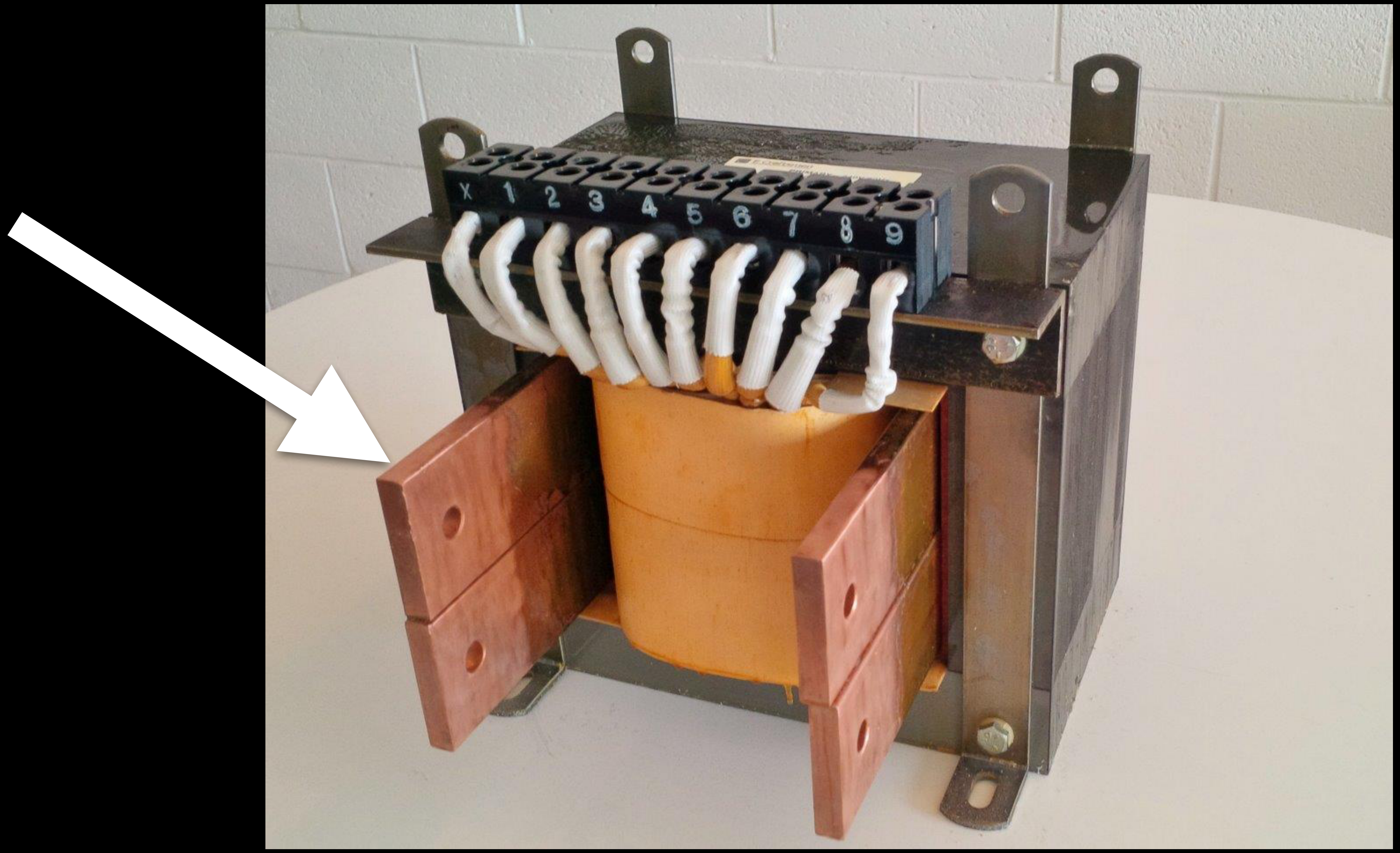


Single winding

SWR Meter

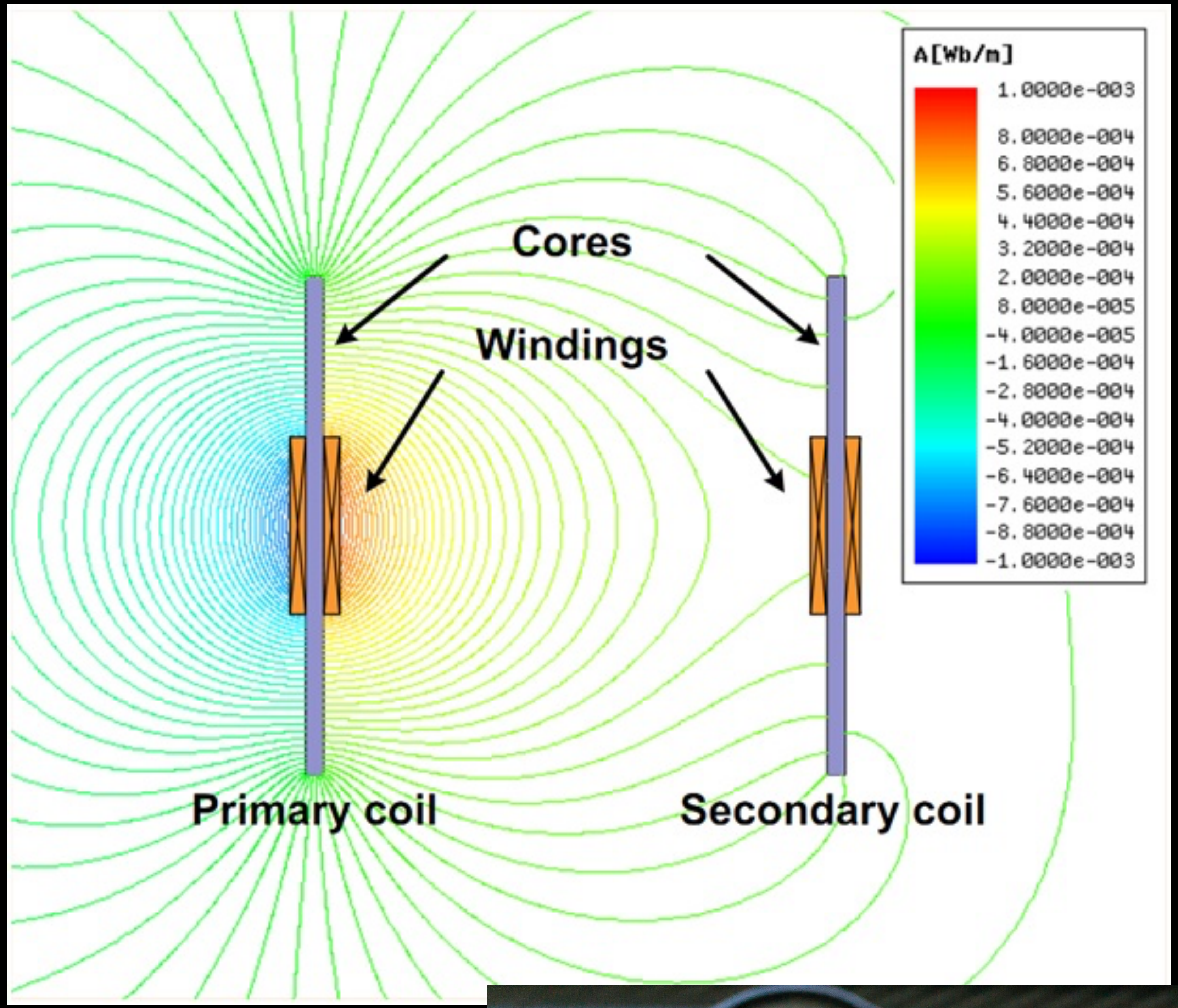
- Just need one loop to get flux
- Like the 'current transformer'
    - but for RF
- A winding is a winding
    - as long as it passes through the center
- Voltage set with turns ratio

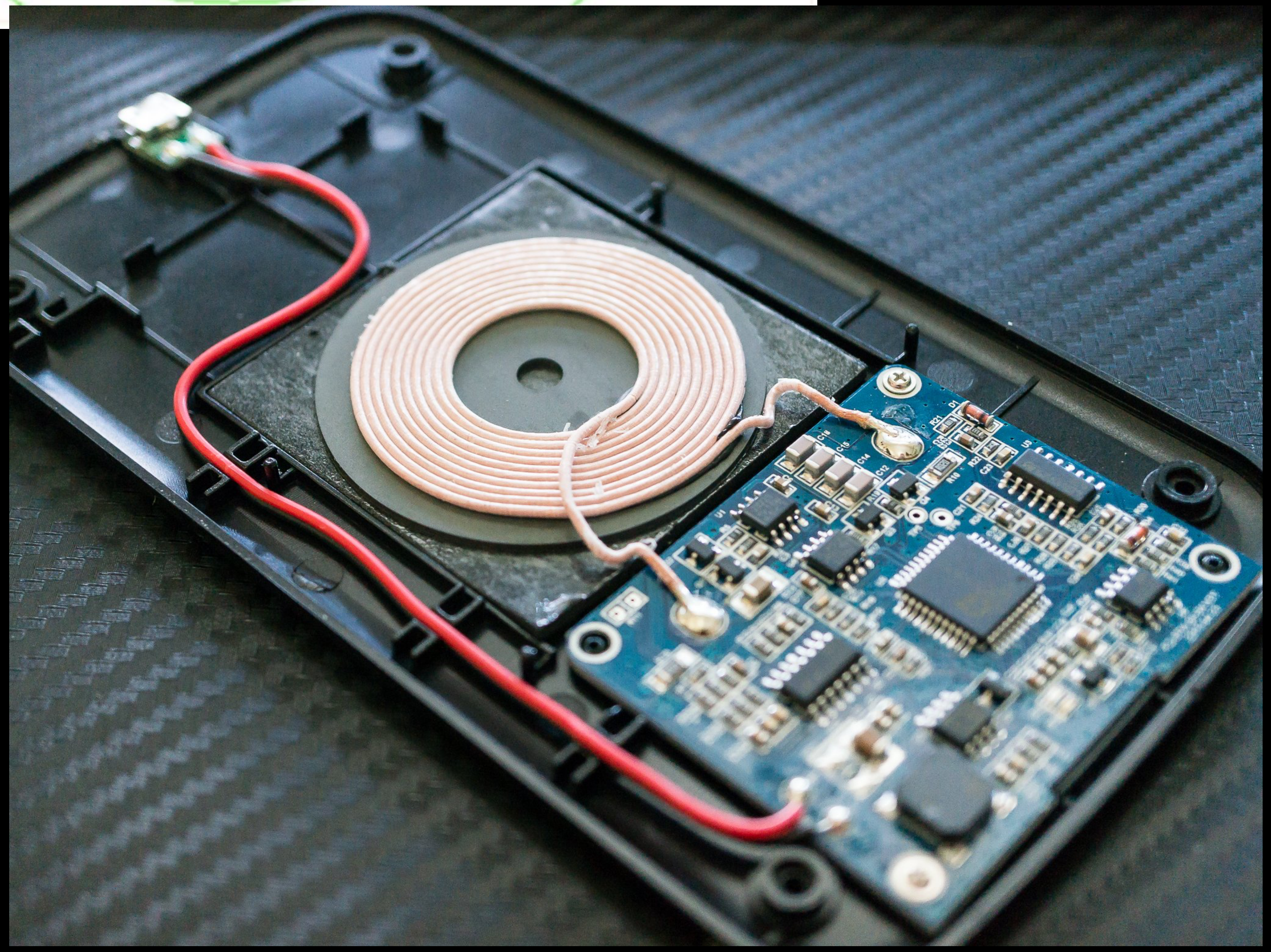




Wireless Power Transfer

- All the rage right now
- Inefficient
    - why?
    - flux leakage
    - ohmic losses
- Qi hunts for best coupling freq
    - looks for resonance





What have we learned?

- Transformers are interesting
  - understood with Maxwell
- Transformers are fun
  - you can transform V, I, Z
- Transformers are fair
  - energy is conserved
- Transformers are useful
  - they’re everywhere in electronics

Questions?

Thank you!