Inductance

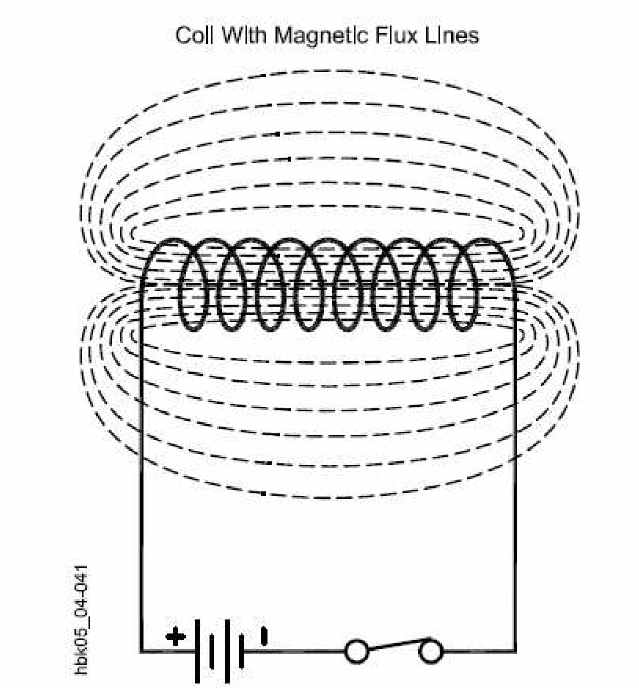
Al Penney
VO1NO

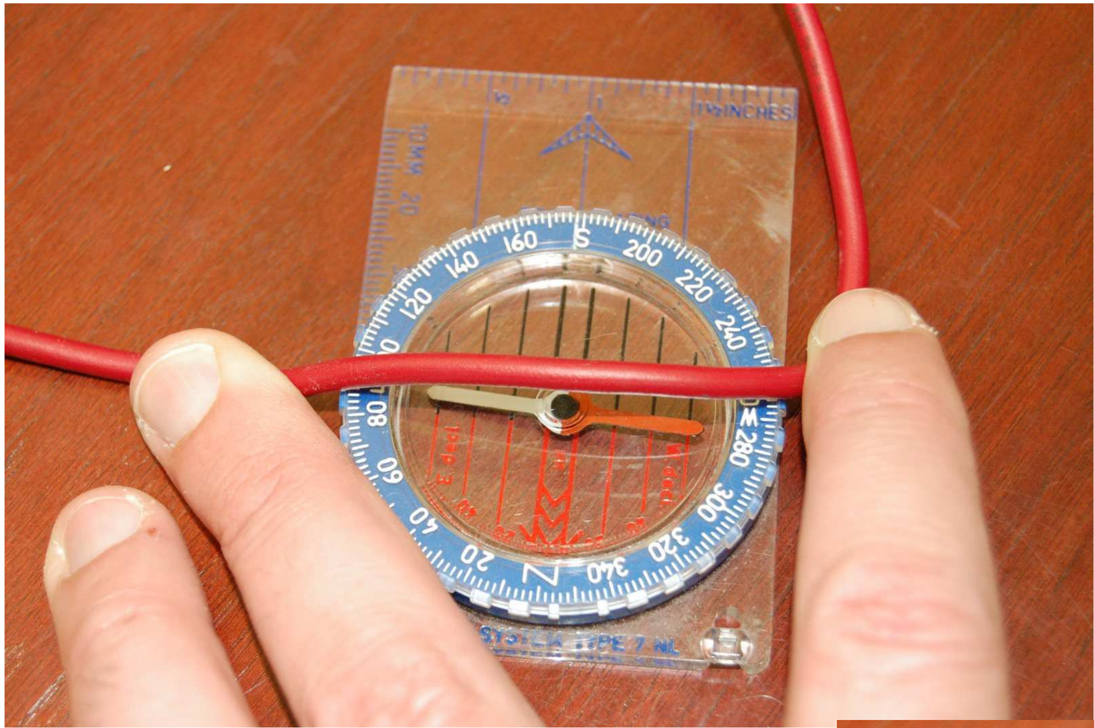
Inductance

- **Inductance** is the property of an electrical circuit that **opposes a change in current.**
- In a **DC circuit** inductance has **an effect only** when the **DC starts**, or when **attempts are made to stop it.**
- In an **AC circuit** though, the **voltage** is **constantly changing,** and **inductance** constantly **works to retard** the **change in current.**

Current Through a Wire

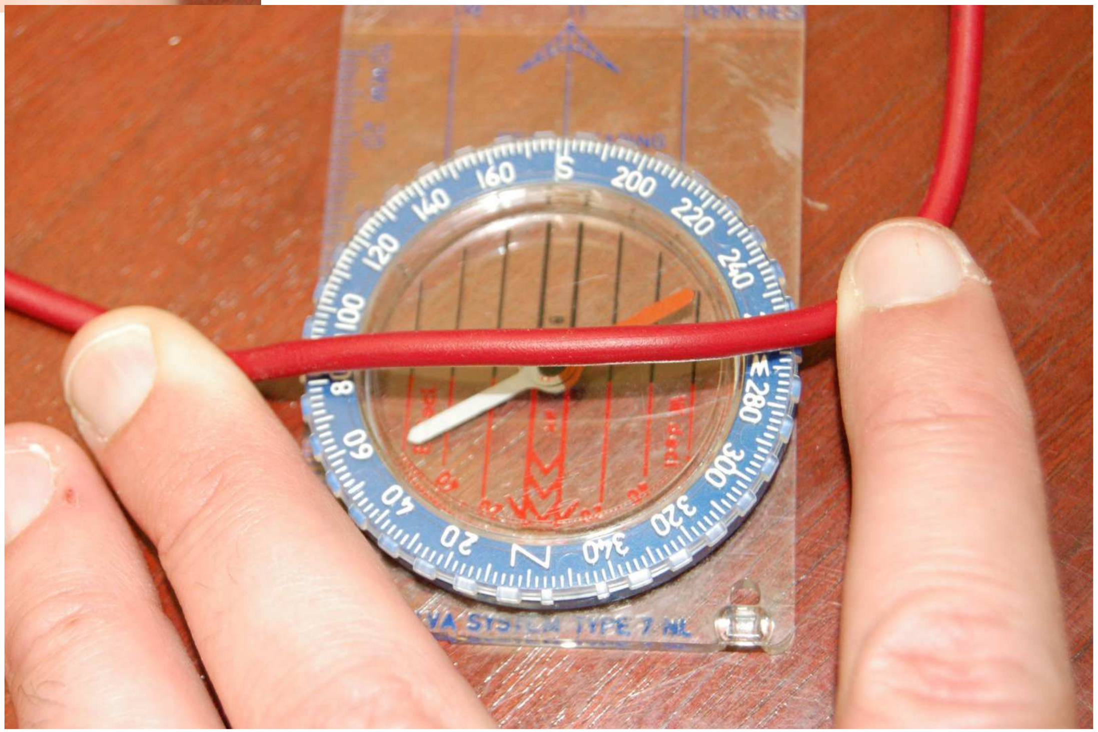
- A **current** through a **wire** will generate a **magnetic field** around that wire, as can be demonstrated by bringing a **compass** near that wire.

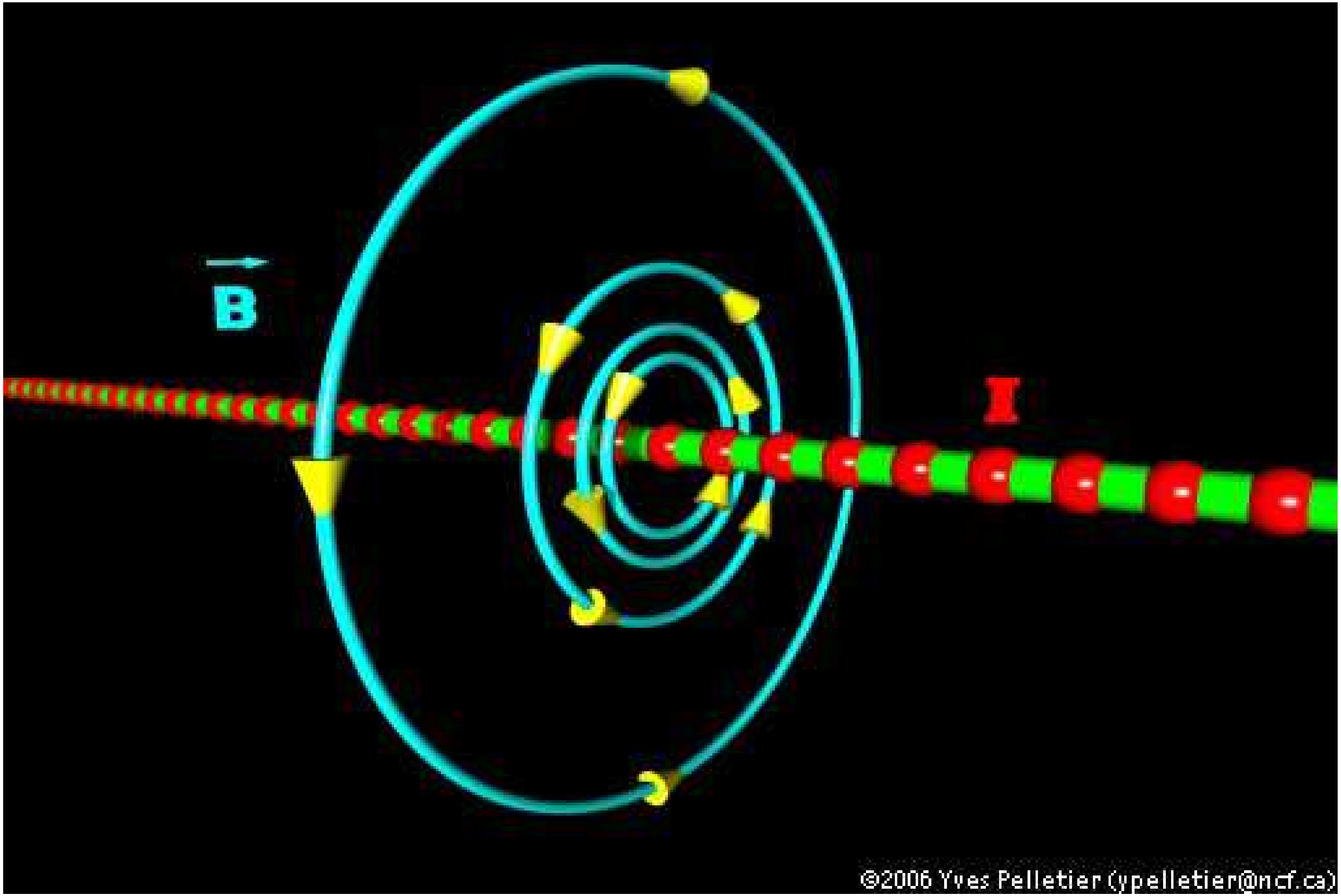




No Current

Current

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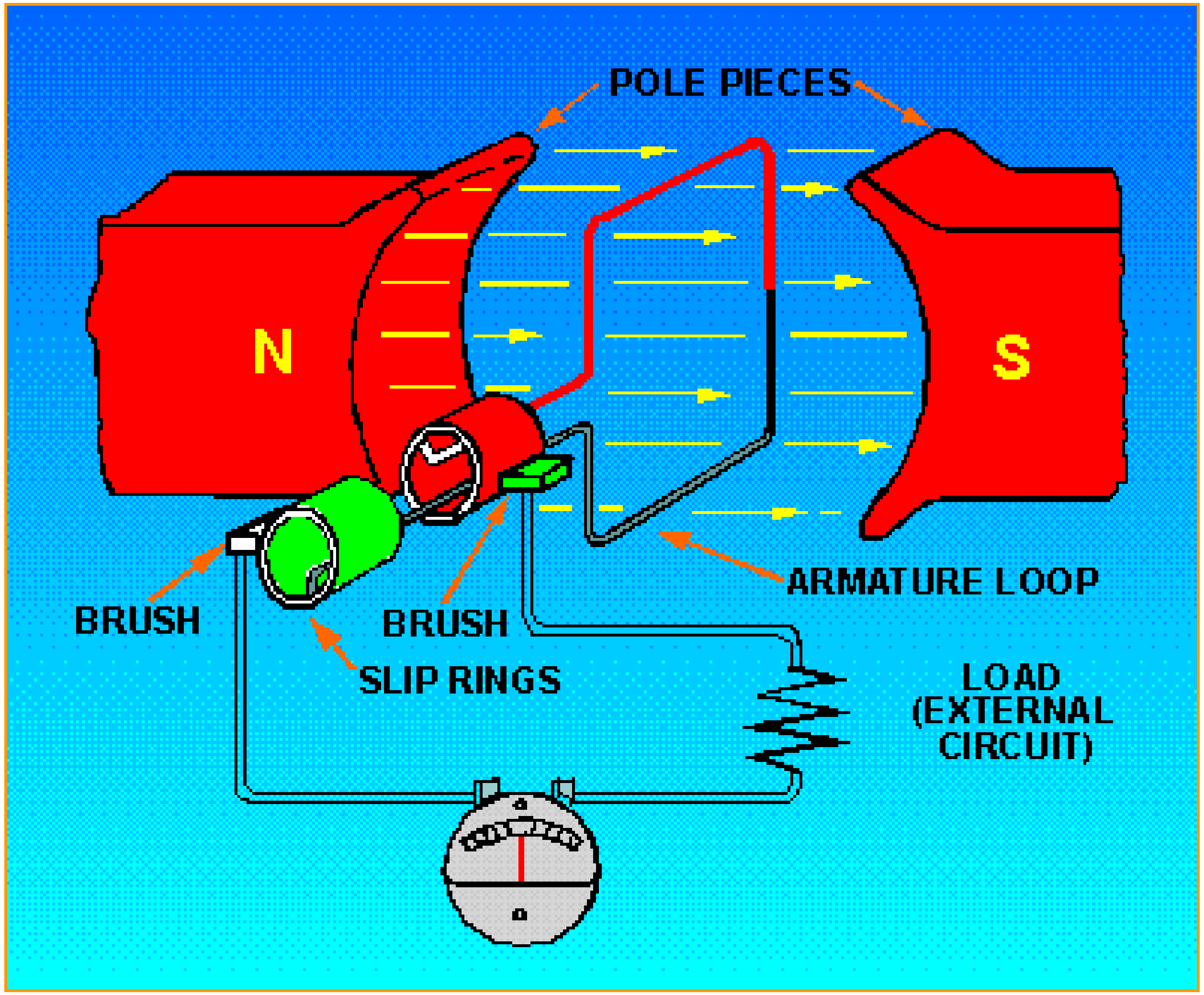
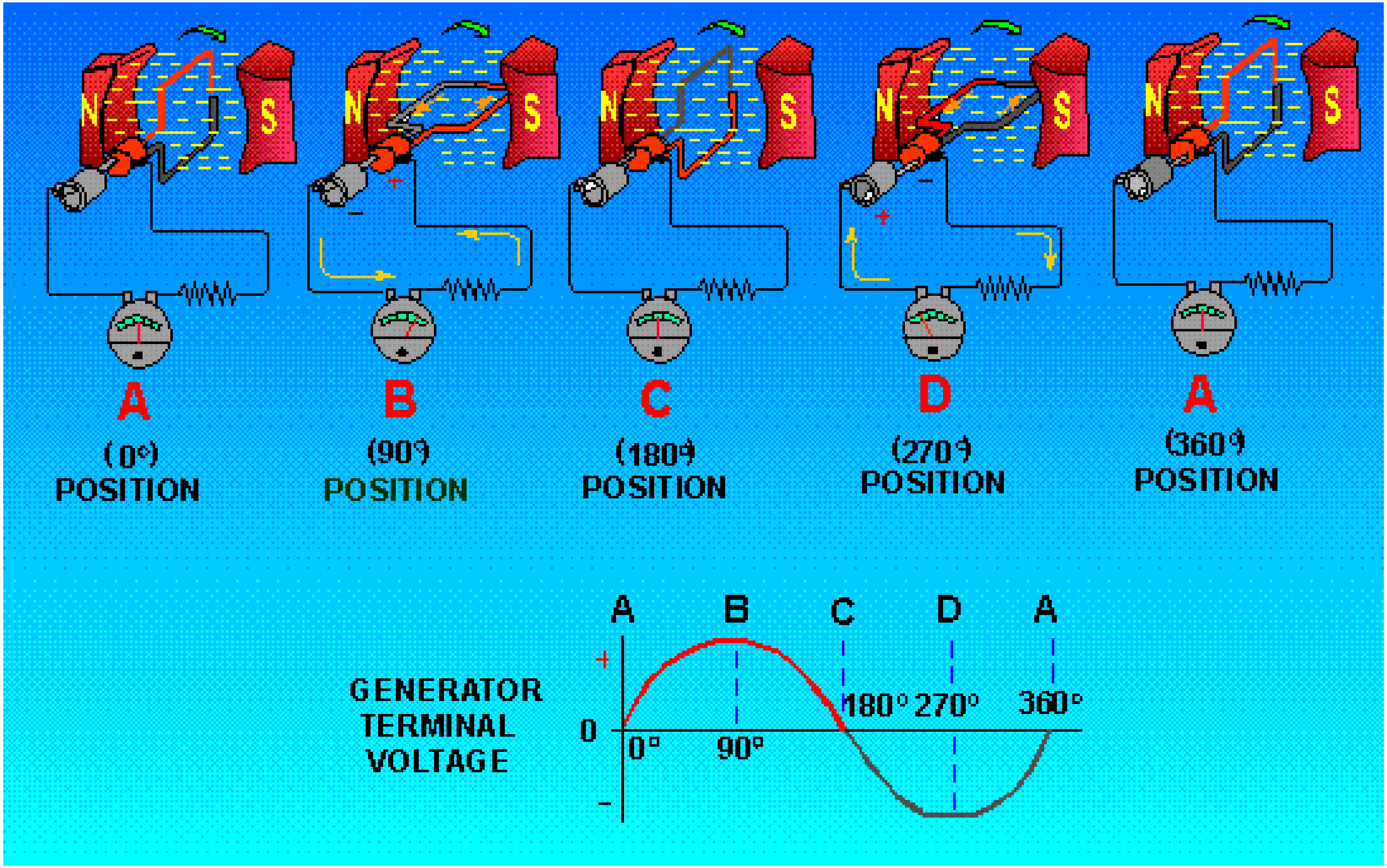
Magnetic Field Effects on a Wire

- Conversely, when magnetic **lines of flux cut** through a **wire,** a **current** will be **induced** to flow in that wire.
- This is the **basis for generators.**

Elementary Generator




N
S
A
(0°)
POSITION
B
(90°)
POSITION
C
(180°)
POSITION
D
(270°)
POSITION
A
(360°)
POSITION
GENERATOR
TERMINAL
VOLTAGE
A
B
C
D
A
+
0
-
0°
90°
180°
270°
360°

Counter EMF

- When a current **starts to flow** through a wire, it takes a **finite time** for the **magnetic field** to build up to its **final size.**
- As the magnetic field builds up, its **own lines of flux cut through the conductor.**
- This **induces** a **voltage** and **resulting current** in that wire.
- Because of Conservation of Energy reasons, that **induced current opposes the applied current.**
- This **opposing voltage** is called the **Counter** or **Back EMF (Electro Motive Force** – voltage).

Inductor in a DC Circuit

- **Counter EMF** can **only** be generated as the **magnetic field** around a conductor is **changing.**
- **After the initial current surge** in a DC circuit, the **current,** and therefore the **magnetic field, stabilize and remain steady.**
- The Counter EMF therefore **disappears.**
- Usually, **inductance** can be **ignored** in **most DC circuits,** however…

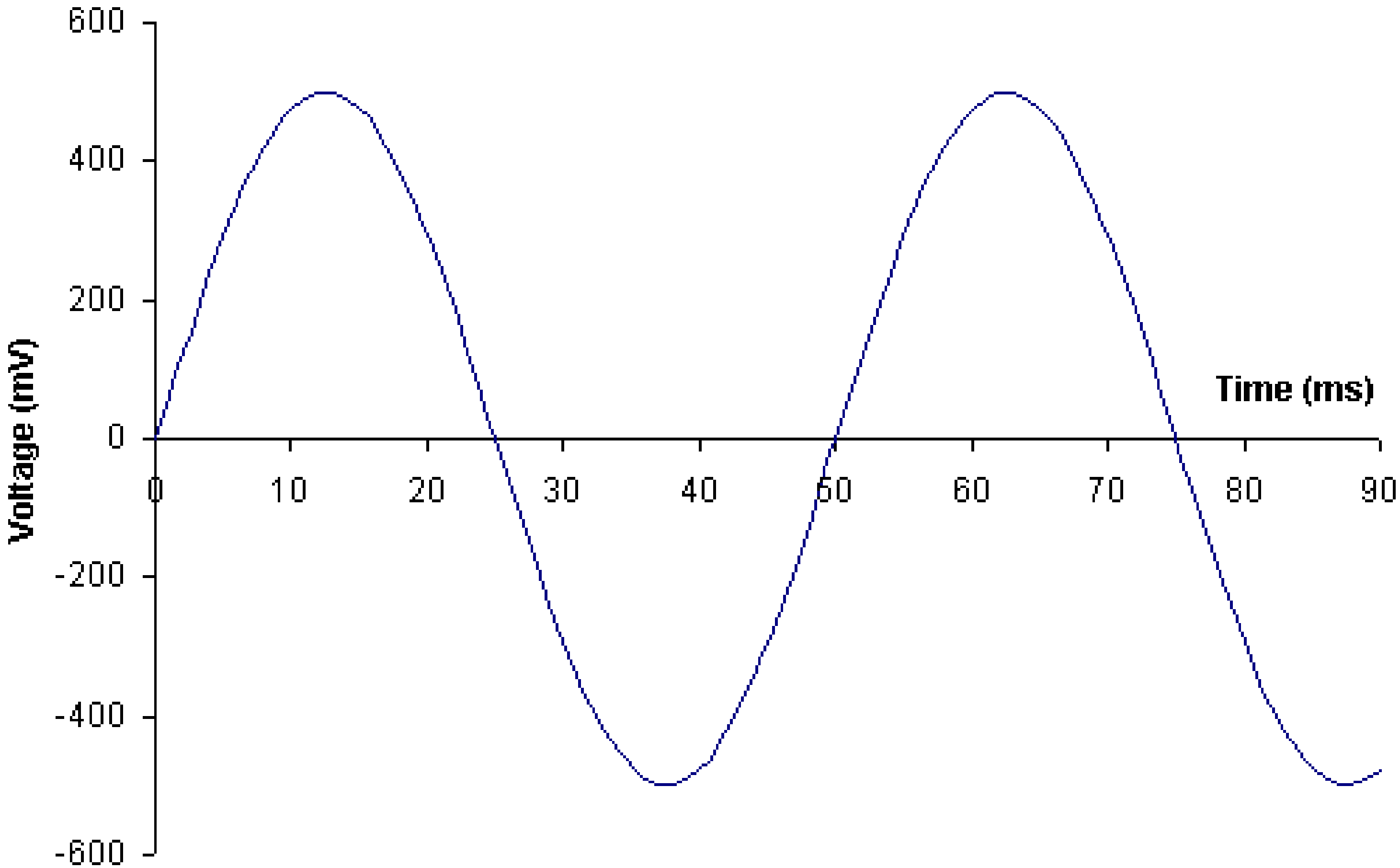
Counter EMF Backlash!

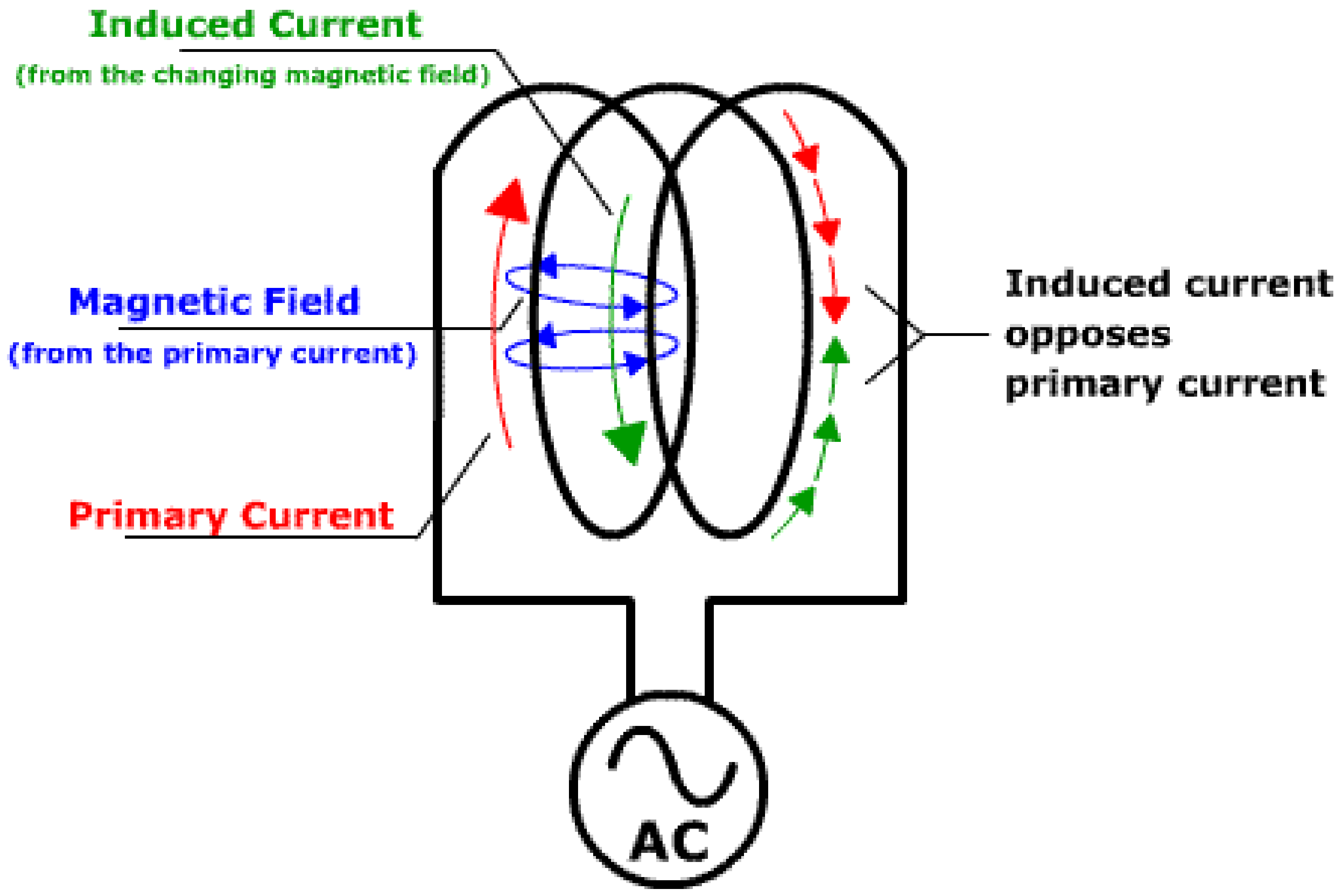
- In some devices such as **electric motors** and **relays**, the **Counter EMF** can **cause problems.**
- When the device is **turned off,** the **magnetic field collapses,** inducing a **strong Counter EMF.**
- This can be strong enough that it can cause an **arc in the switch** that controls the device.
- Sometimes it can even **weld the switch shut**, restarting the device and making it very difficult to stop.

Inductor in an AC Circuit

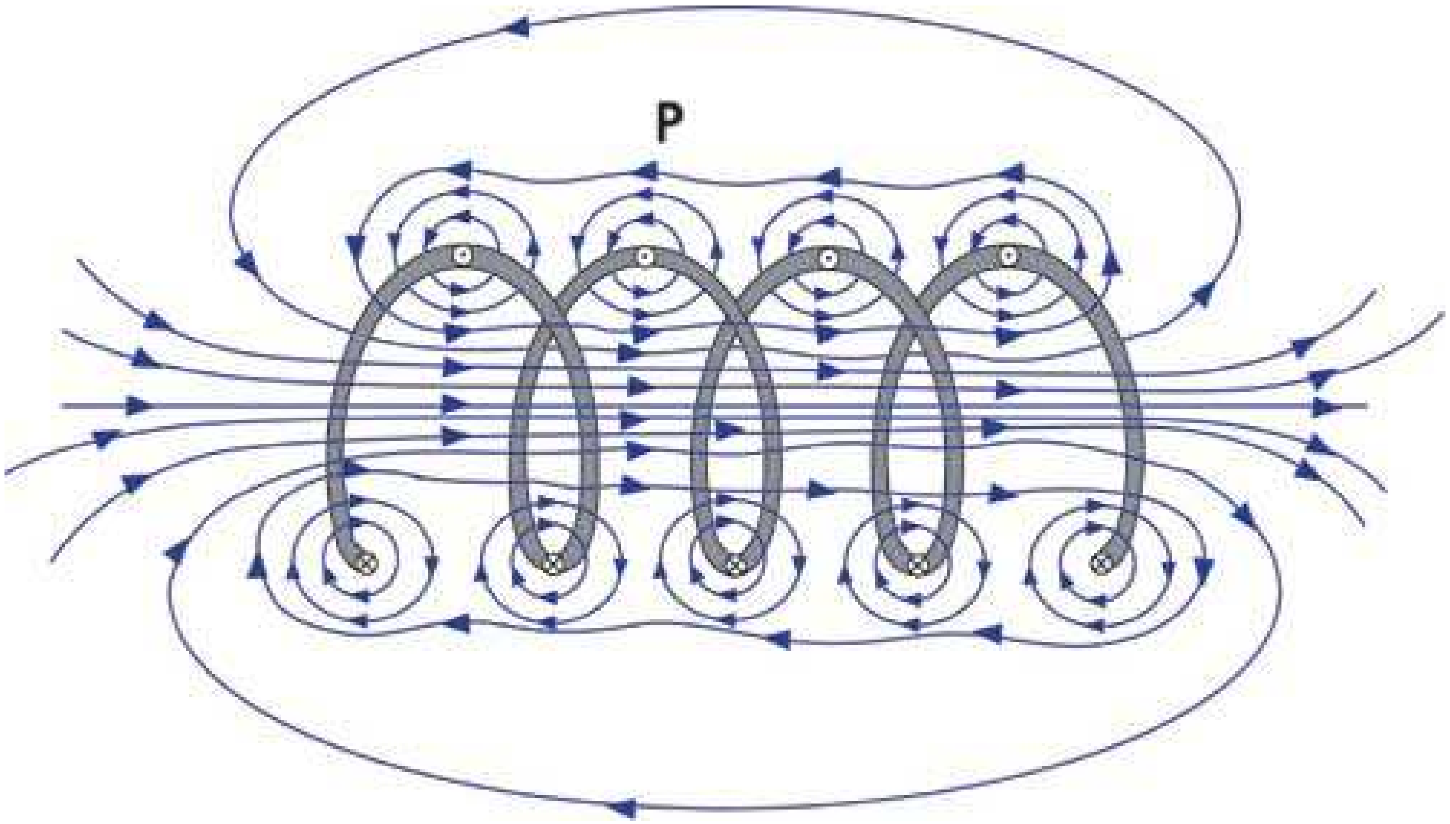
- In an **AC circuit,** the **voltage,** and therefore the **current,** is **constantly changing.**
- Because of this, the **magnetic field** around the conductor carrying the current is **constantly changing** as well.
- As the **magnetic field** alternately **expands outwards** and **collapses inwards,** the **magnetic lines of flux** are constantly **cutting** through the conductor.
- This creates a Counter EMF that constantly **acts to oppose any change in current.**

AC Circuit


600
400
200
0
-200
-400
-600
Voltage (mV)
Time (ms)
0
10
20
30
40
50
60
70
80
90


Induced Current
(from the changing magnetic field)
Magnetic Field
(from the primary current)
Primary Current
Induced current
opposes
primary current
AC

Magnetic Field Around a Coil

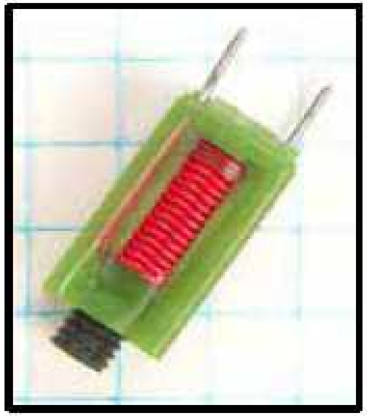


The henry

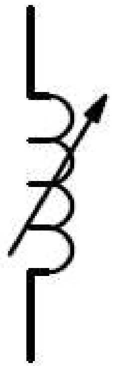
- The **unit of measurement** for inductance is the **henry,** abbreviated **"L".**
- An inductor is said to have an inductance of 1 henry if a **current** passing through it at a rate of **1 ampere per second** causes a **Counter EMF** of **1 volt** to be generated.
- This is **too large a unit** for most applications however, so **millihenrys (mh)** or **microhenrys (µh)** are more commonly encountered in electronic equipment.

Types of Inductors

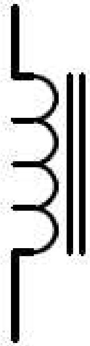
Air Core



Variable

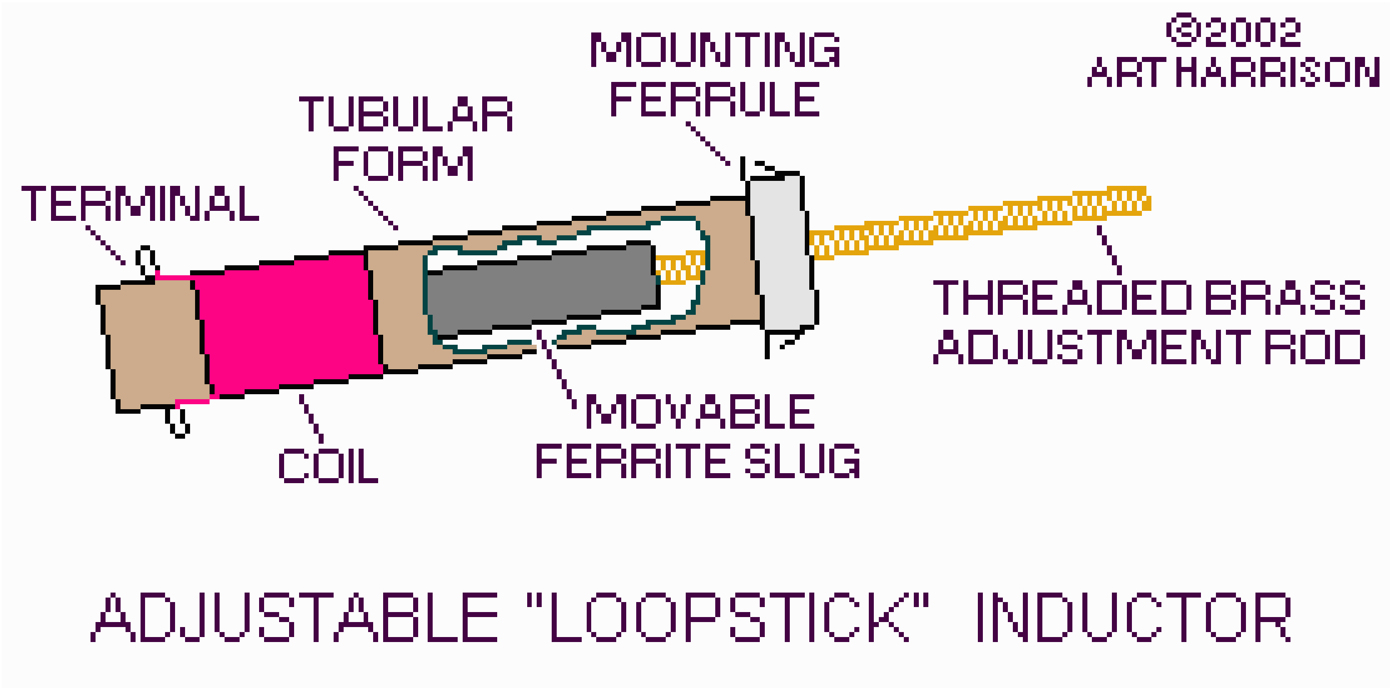


Magnetic or
Iron Core



Roller Inductor

Loopstick Inductor



Factors Affecting Inductance

- **Number of Turns:** The inductance of a coil is proportional to the **square of the number of turns.**
- A coil with **twice the number of turns** as another otherwise identical coil will have **four times the inductance.** A coil with **3 times as many turns** will have **9 times the inductance.**

Factors Affecting Inductance

- **Coil Diameter:** The **larger the diameter** of the coil, the **greater the inductance.**
- A **coil** with **twice the diameter** of an otherwise identical coil will have **twice the inductance.**

Factors Affecting Inductance

- **Changing the core:** Certain materials will **concentrate the lines of magnetic flux** better than others, and will therefore **increase the inductance** if used as a **core** for the coil.
- For example, a coil wound on an **iron core** will have much **more inductance** than one with an **air core.**

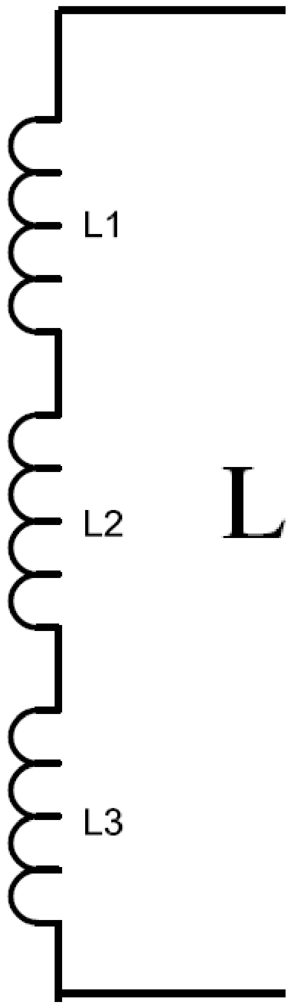
Core Materials

Properties of Some High-Permeability Materials

Material	*Approximate Percent Composition*					*Maximum Permeability*
	Fe	Ni	Co	Mo	Other	
Iron	99.91	—	—	—	—	5000
Purified Iron	99.95	—	—	—	—	180000
4% silicon-iron	96	—	—	—	4 Si	7000
45 Permalloy	54.7	45	—	—	0.3 Mn	25000
Hipernik	50	50	—	—	—	70000
78 Permalloy	21.2	78.5	—	—	0.3 Mn	100000
4-79 Permalloy	16.7	79	—	—	0.3 Mn	100000
Supermalloy	15.7	79	—	5	0.3 Mn	800000
Permendur	49.7	—	50	—	0.3 Mn	5000
2V Permendur	49	—	49	—	2 V	4500
Hiperco	64	—	34	—	2 Cr	10000
2-81 Permalloy*	17	81	—	2	—	130
Carbonyl iron*	99.9	—	—	—	—	132
Ferroxcube III**	($MnFe_2O_4$ + $ZnFe_2O_4$)				1500	

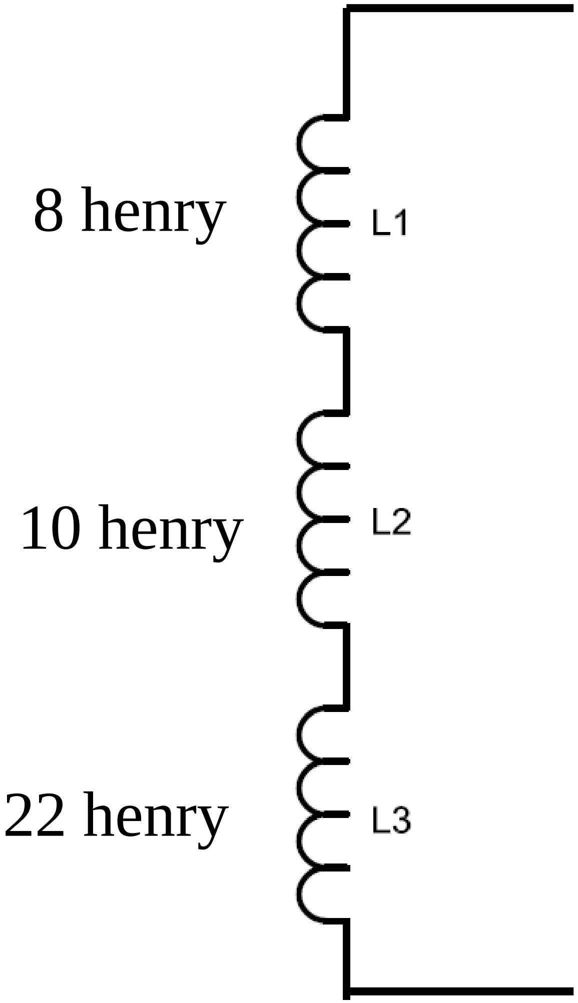
Note: all materials in sheet form except * (insulated powder) and ** (sintered powder).
(Reference: L. Ridenour, ed., *Modern Physics for the Engineer*, p 119.)

Inductors in Series



$$L_{total} = L1 + L2 + L3 \ldots + L_n$$

Example - Inductors in Series



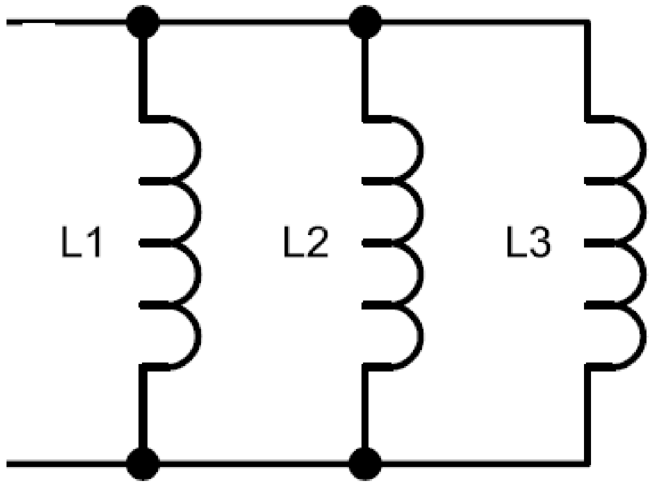
$$L_{total} = L1 + L2 + L3$$

$$L_{total} = 8H + 10H + 22H$$

$$L_{total} = 40\ H$$

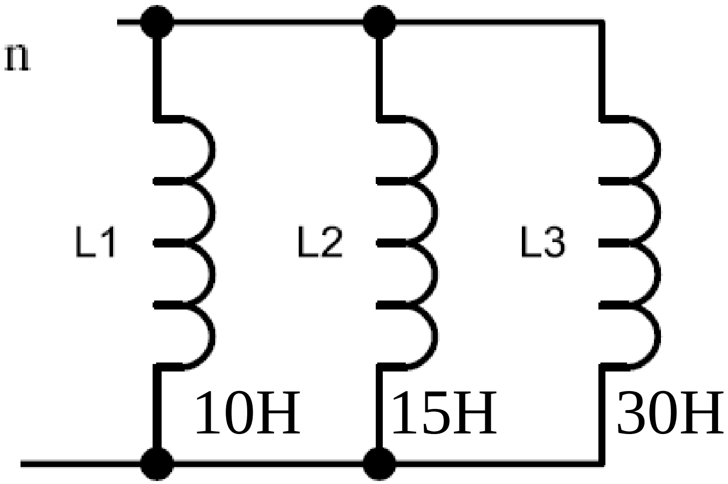
Inductors in Parallel

$$L_{total} = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} + ... + \frac{1}{L_n}}$$



Example - Inductors in Parallel

$$L_{total} = \frac{1}{\frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3} + \ldots + \frac{1}{L_n}}$$



$$L_{total} = \frac{1}{\frac{1}{10} + \frac{1}{15} + \frac{1}{30}}$$

$$L_{total} = \frac{1}{\frac{3}{30} + \frac{2}{30} + \frac{1}{30}} = \frac{1}{6/30} = 5H$$

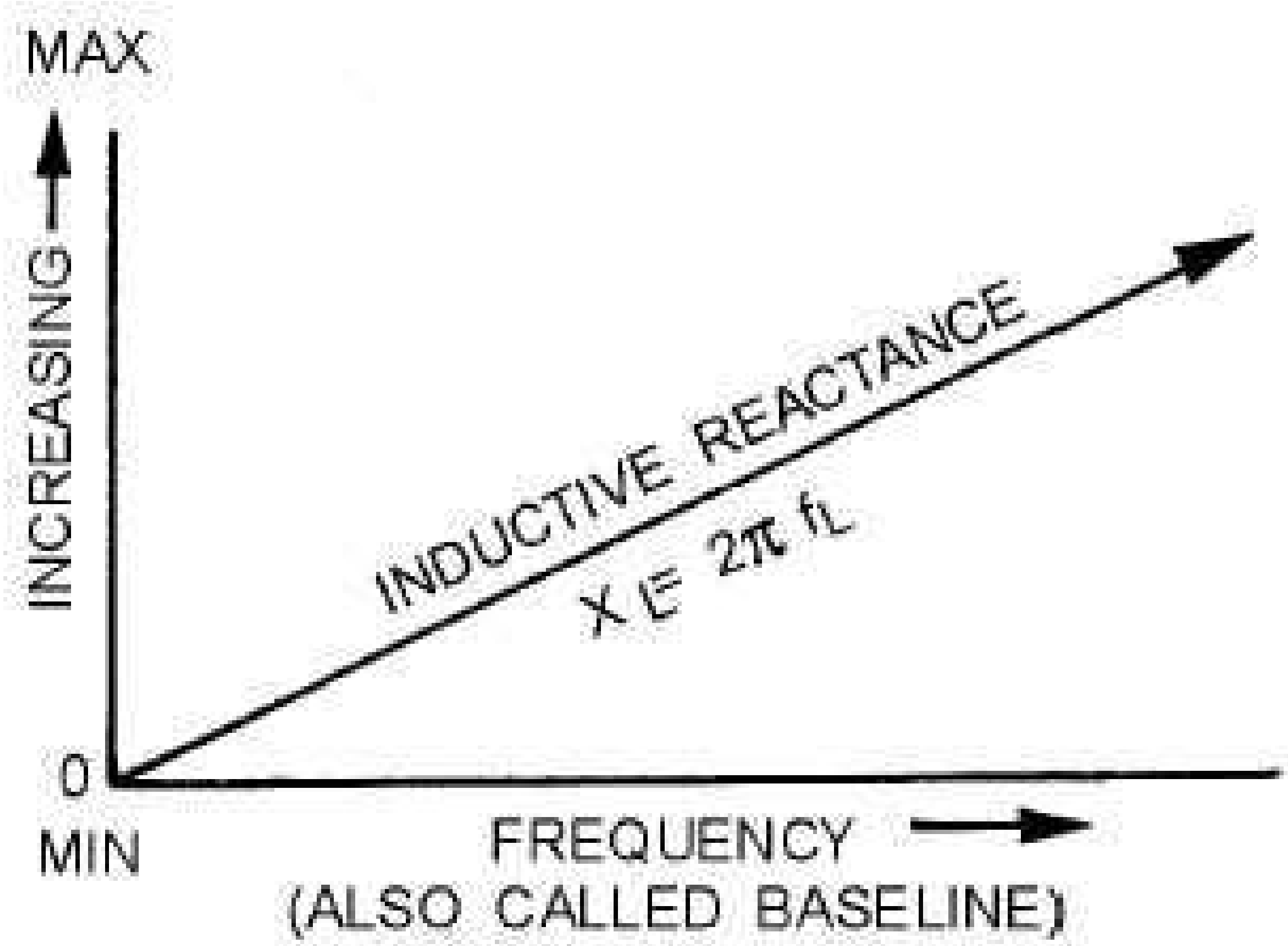
Reactance

- **Reactance** is the **opposition** to the **flow of Alternating Current (AC).**
- **Reactance** has **no effect** on the flow of **Direct Current (DC).**

Inductive Reactance

- **Inductive Reactance** is the **opposition** to the **flow of current** in an **AC circuit** caused by an **inductor.**
- As the **frequency increases,** Inductive Reactance **also increases.**
- The **symbol** for **Inductive Reactance** is $\mathbf{X_L}$**.**
- Even though it is expressed in ohms, **power is not dissipated by Reactance!** Energy **stored in an inductor's magnetic field** during **one part of the AC cycle** is simply **returned to the circuit** during the **next part of the cycle!**

Inductive Reactance



Inductive Reactance

$$X_L = 2\pi f L$$

- Where:

  f = frequency in Hertz

  L = inductance in henrys

  π = 3.14

Inductive Reactance Example 1

- What is the reactance of a coil having an inductance of 8.00 henrys at a frequency of 120 Hertz?

$$X_L = 2\pi f L$$

$$\mathbf{X_L = 2 \times 3.14 \times 120\ Hertz \times 8.00H}$$

$$\mathbf{X_L = 6030\ Ohms}$$

Inductive Reactance Example 2

- What is the reactance of that same coil having an inductance of 8.00 henrys at a frequency of 2 kHz?

$$X_L = 2 \pi f L$$

Remember that **2 kHz = 2000 Hz**

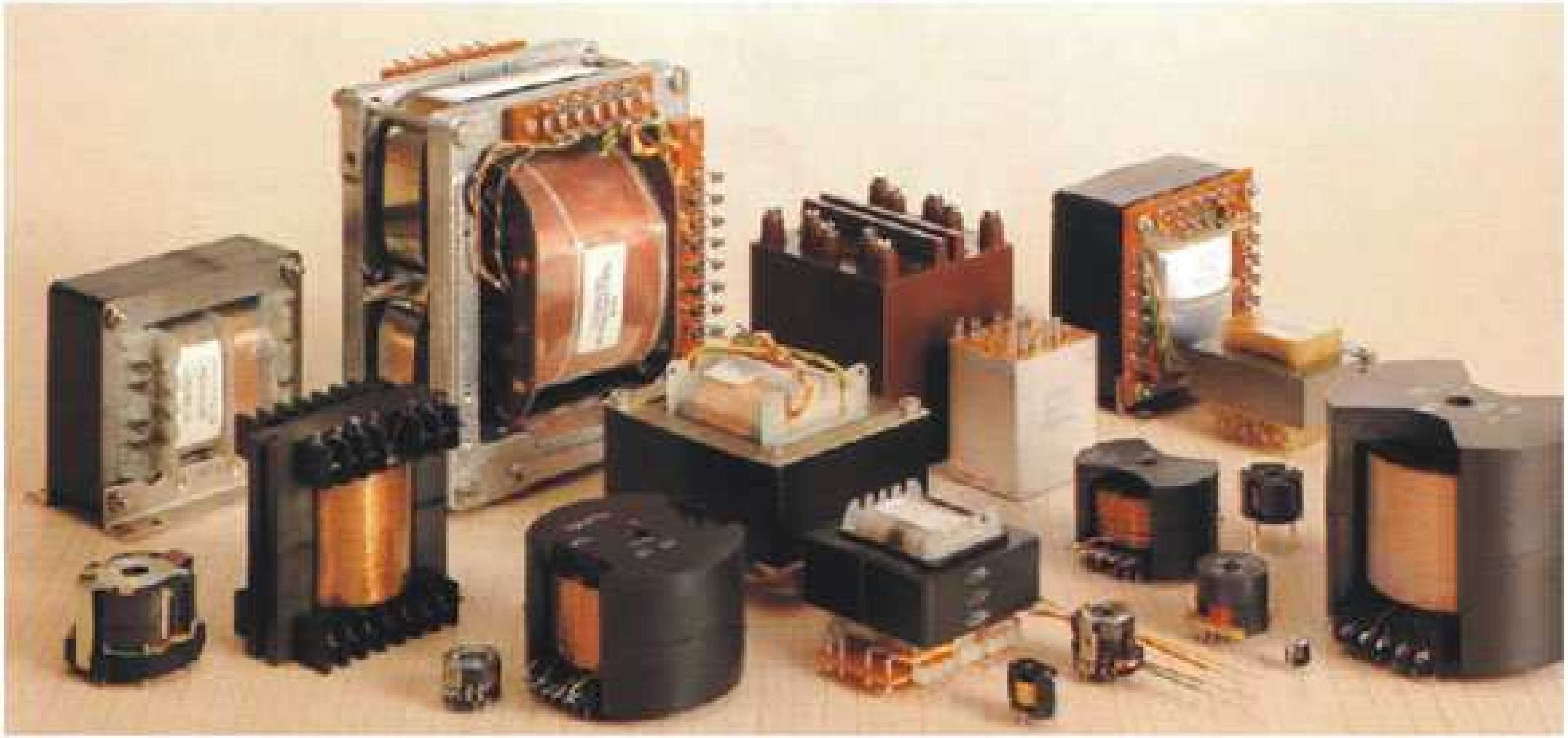
$$\mathbf{X_L = 2 \times 3.14 \times 2000\ Hertz \times 8.00H}$$

$$\mathbf{X_L = 100{,}480\ Ohms}$$

Inductive Reactance Examples

- Note that as the **frequency increased** from 120 Hz to 2000 Hz, the **Inductive Reactance increased** from 6030 ohms to 100,480 ohms.
- **Remember:**
  - **Inductors allow DC to pass, but hinder AC;**
  - Inductors **store energy** as a magnetic field; and
  - As the **frequency increases, inductive reactance increases (and vice versa!).**

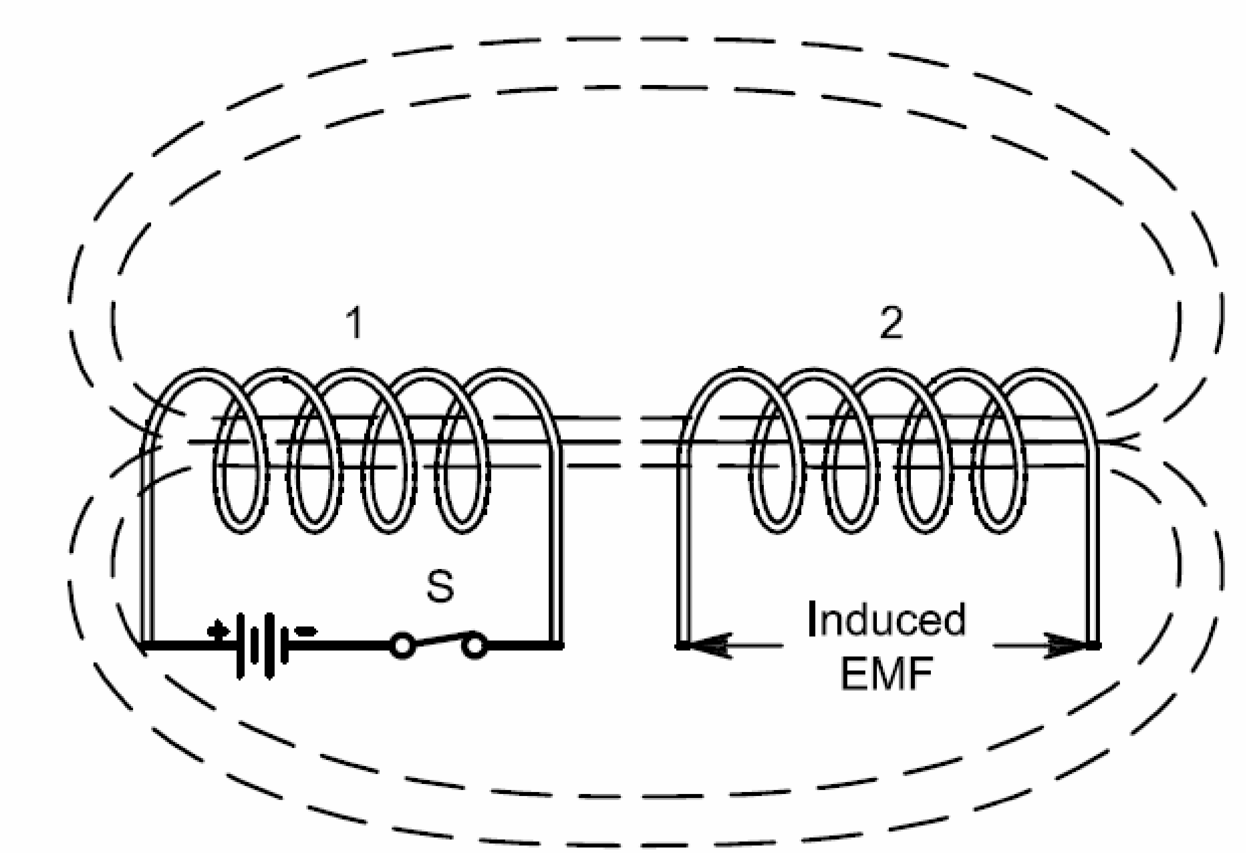
Transformers

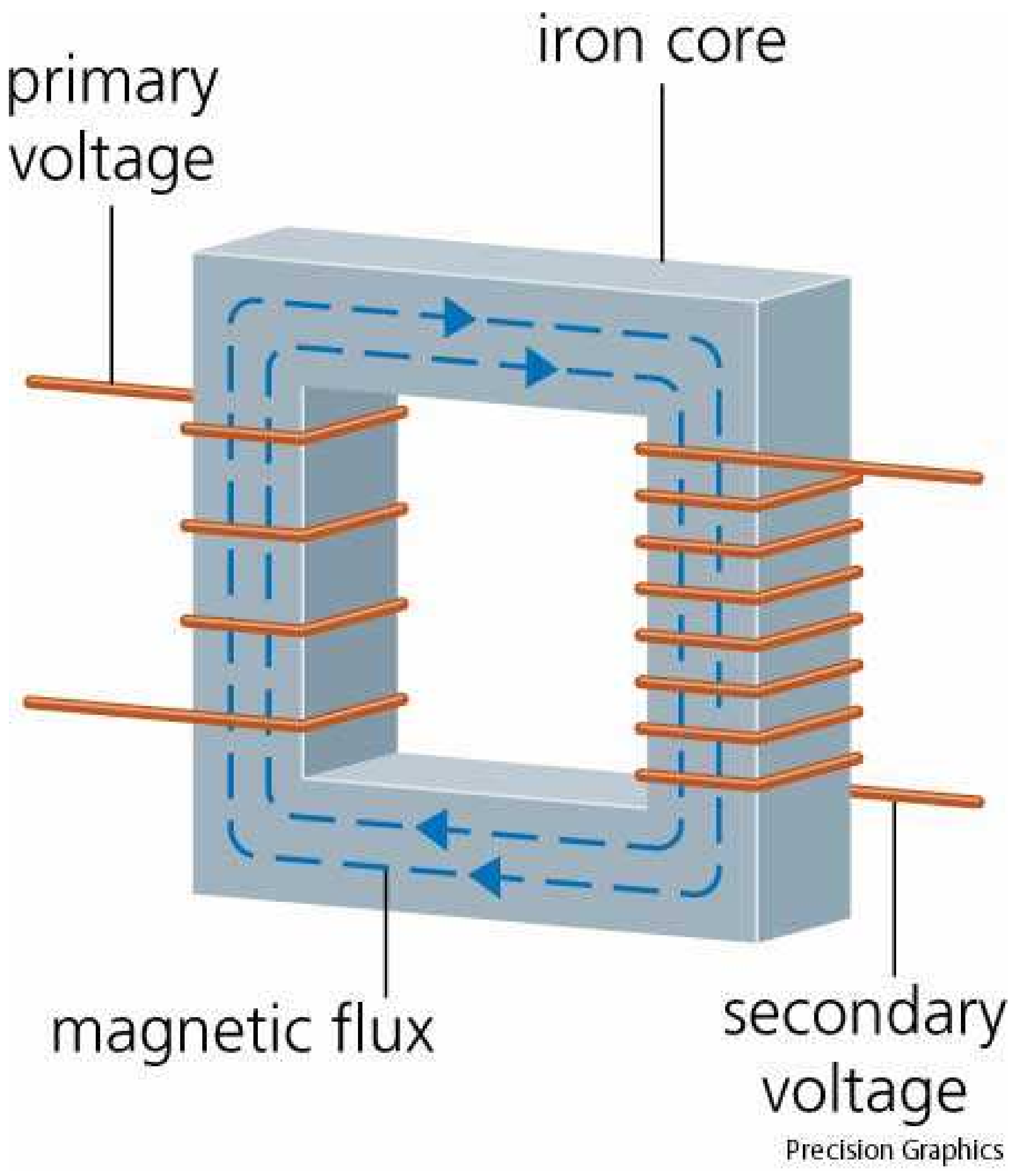


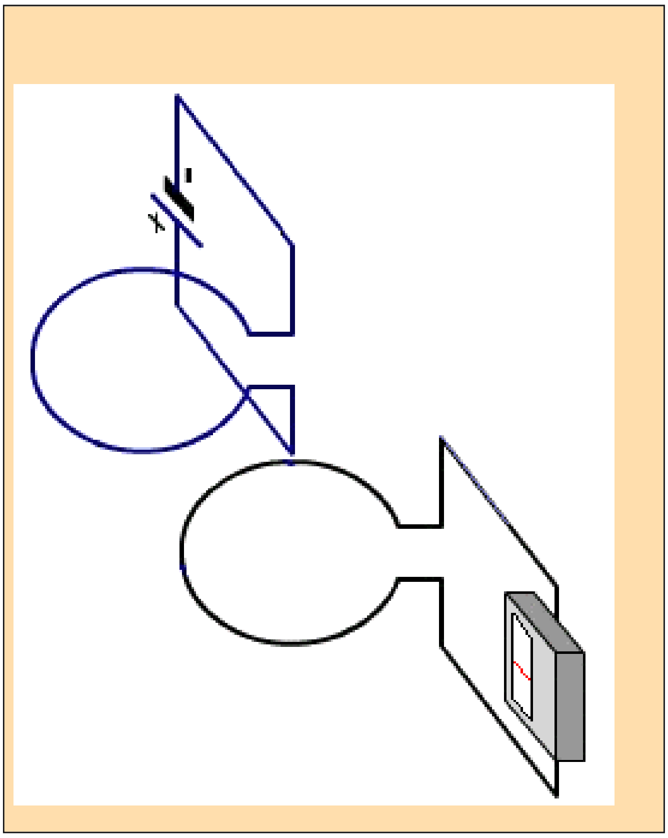
Transformers

- Any device that **transfers power** from **one voltage-current level** to **another voltage-current level** is called a **transformer.**
- Transformers work on the principle of **changing current** in **one inductor** inducing a **current** in **another inductor.**

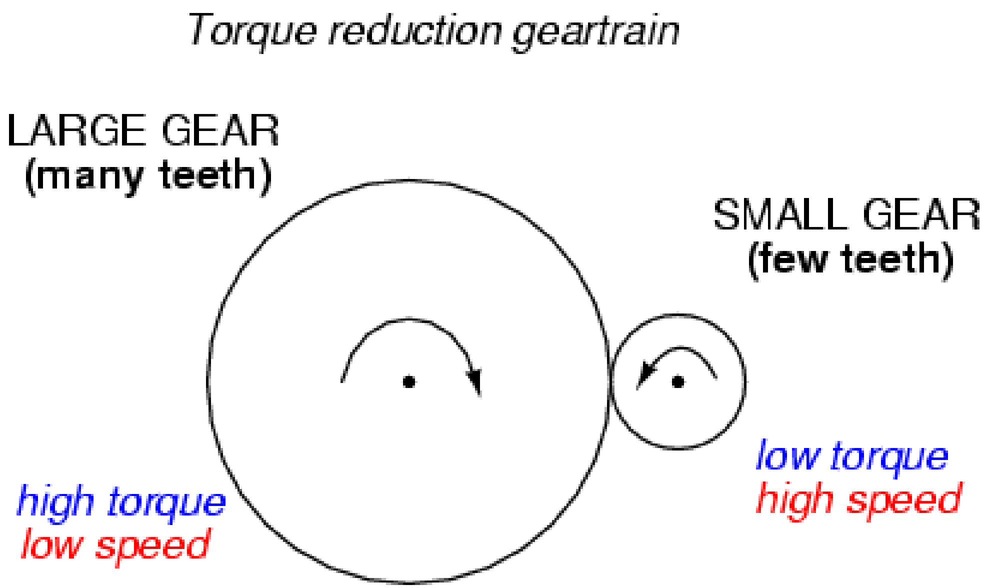
Induced EMF




iron core
primary voltage
magnetic flux
secondary voltage
Precision Graphics



Transformer Mechanical Equivalent

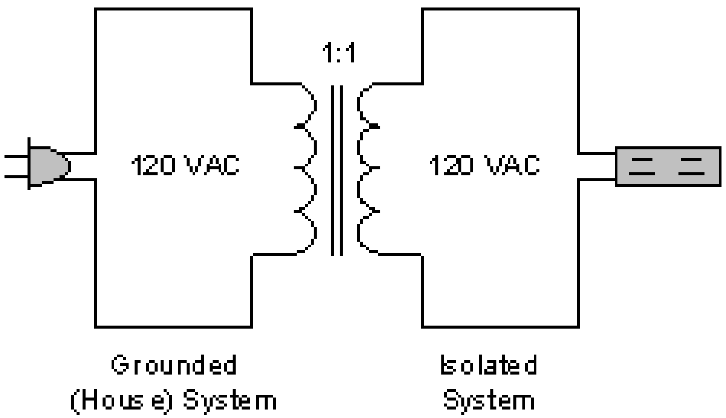


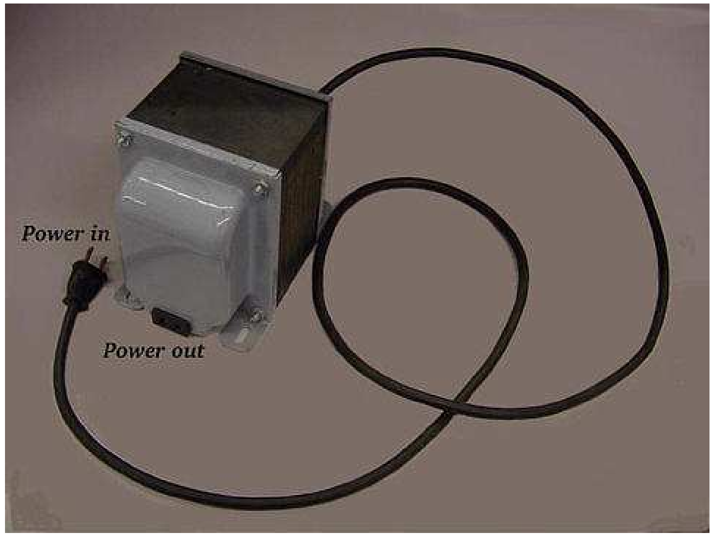
Transformer Applications

- Transformers have **3 primary applications:**
  - **Isolating** one part of a circuit from another (**magnetic** linkage only, versus **conductive** linkage);
  - **Stepping voltages up or down**; and
  - **Impedance matching.**

Isolation Transformer

- Many uses for isolation transformers in electronic circuits.
- Also used in power circuits, using transformers that have a 1:1 turns ratio.





Changing the Voltage

- A **transformer** can be used to **step the voltage up or down.**
- The **ratio of turns** in the primary and secondary windings determine the **amount of voltage change:**

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

Example

- *Input voltage is 120 VAC. You require an output voltage of 24 VAC. The Primary winding has 240 turns. How many turns does the Secondary winding need?*

Example (2)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

Example (3)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

- $120 / 24 = 240 / T_{sec}$

- $T_{sec} =$

Example (4)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

- $120 / 24 = 240 / T_{sec}$
- $T_{sec} = 240 \times 24 / 120$

Example (5)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

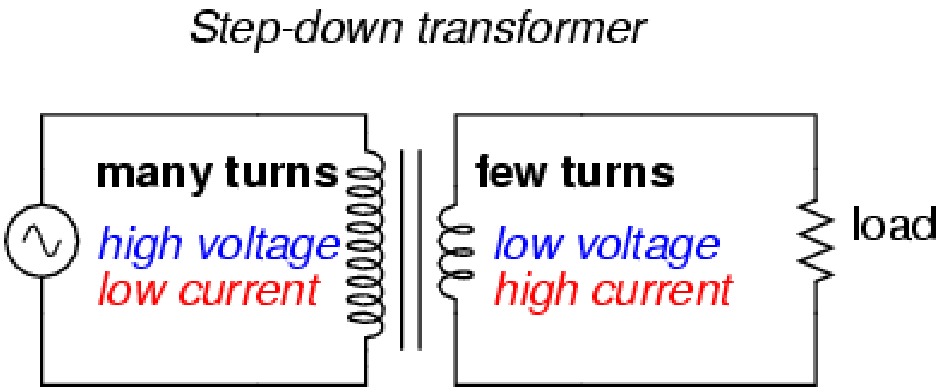
- $120 / 24 = 240 / T_{sec}$
- $T_{sec} = 240 \text{ x } 24 / 120$
- $T_{sec} =$

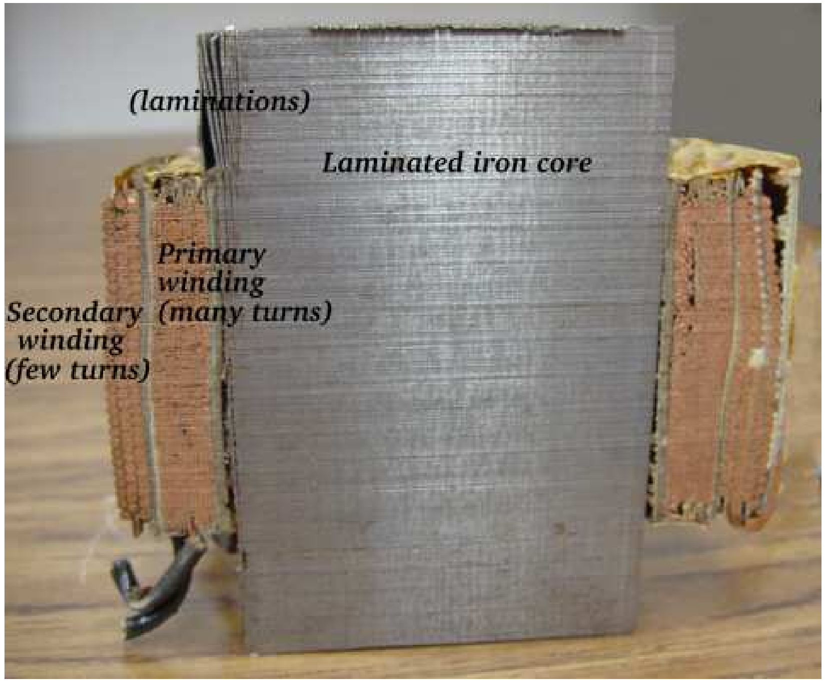
Example (6)

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{\# Turns Primary winding}}{\text{\# Turns Secondary winding}}$$

- $120 / 24 = 240 / T_{sec}$
- $T_{sec} = 240 \times 24 / 120$
- $T_{sec} = 48$ turns

Step Down Transformer



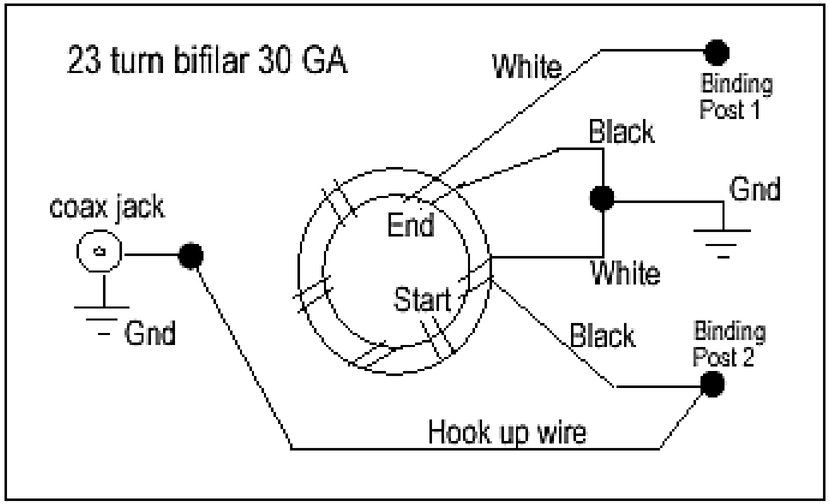


Impedance Matching

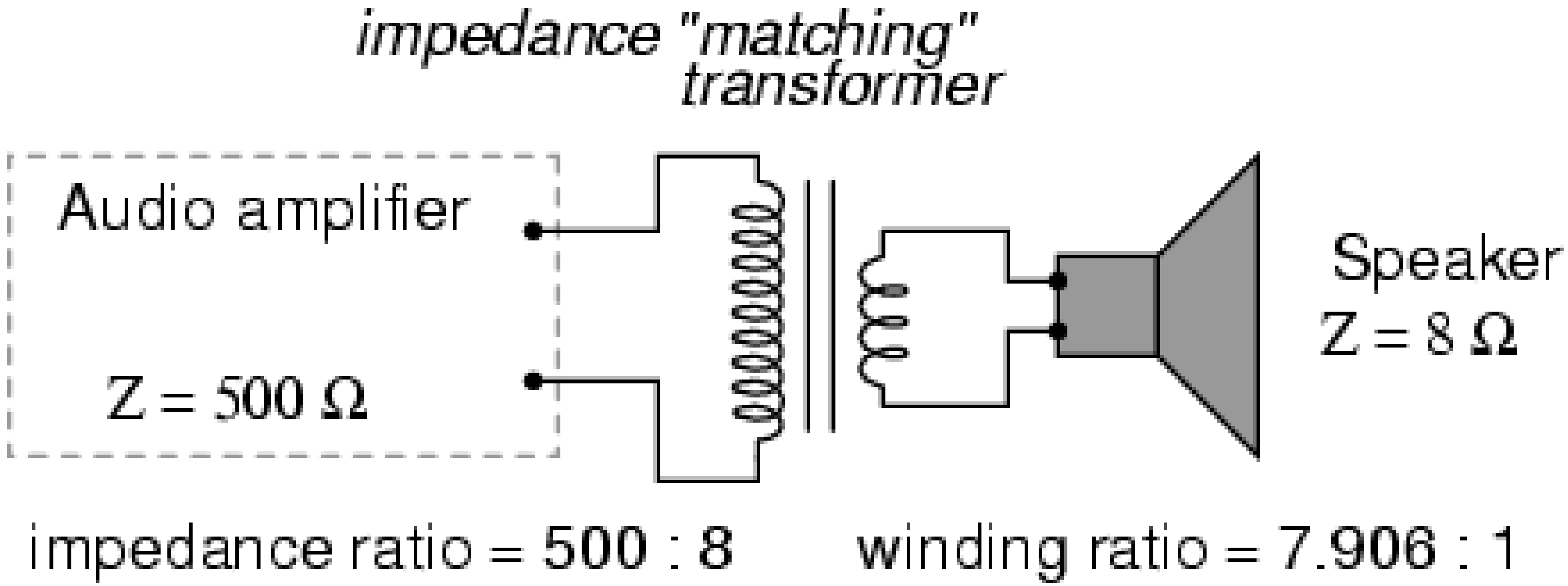
- Transformers are used to **match differing impedances** in RF and AF circuits.
- The **turns ratio** determines the **degree of impedance change.**

Antenna Impedance Matching

- Transformers are often used to **match impedances** in **antenna systems.**
- The most frequently encountered are **1:1** and **4:1,** but other impedance transformations are available.



Audio Impedance Matching



Power Rating of the Transformer

- Determined by the **size of the core** and the **diameter of the wire.**
- Power rating usually **stamped on the side** of the transformer, and is **expressed in Volt-Amperes** (abbreviated **VA**).
- **Power = Voltage x Current**
- Calculate power requirements of the equipment using the transformer and compare it with the Power rating of the transformer.

Power

- Power = Voltage x Current **(P = EI)**
- If transformer is **100% efficient,** then Power in the **primary** winding equals Power in the **secondary** winding **($P_P = P_S$).**
- Therefore **E_P x I_P = E_S x I_S.**
- In a **Step Up** transformer, the **current available** from the **secondary** winding is necessarily **less than** in the **primary** winding.
- The **opposite is true** for a **Step Down** transformer.

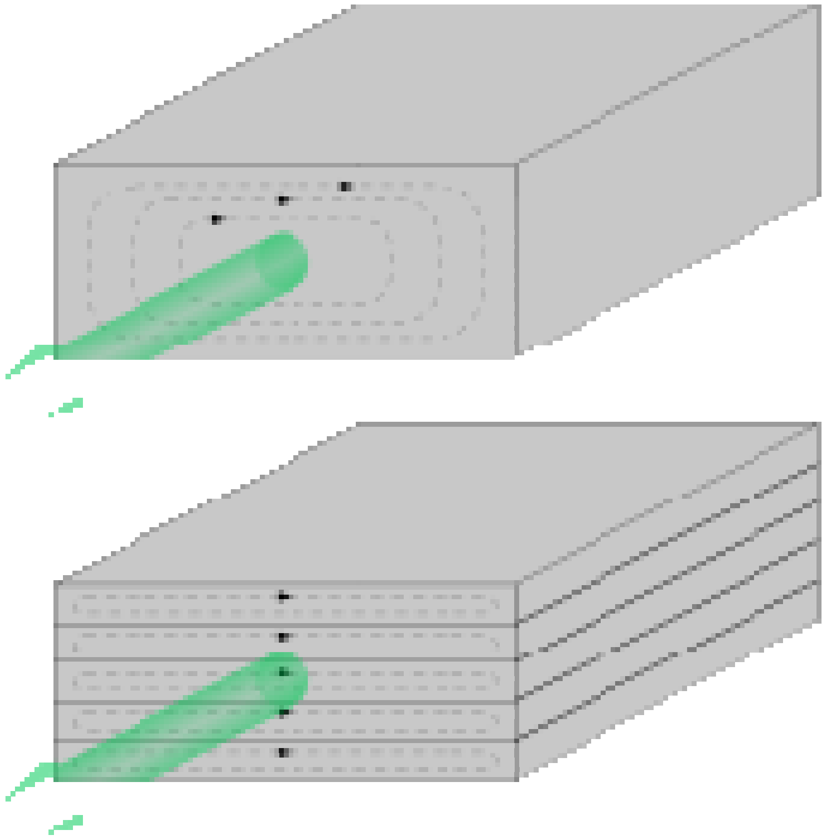
Energy Losses in Transformers

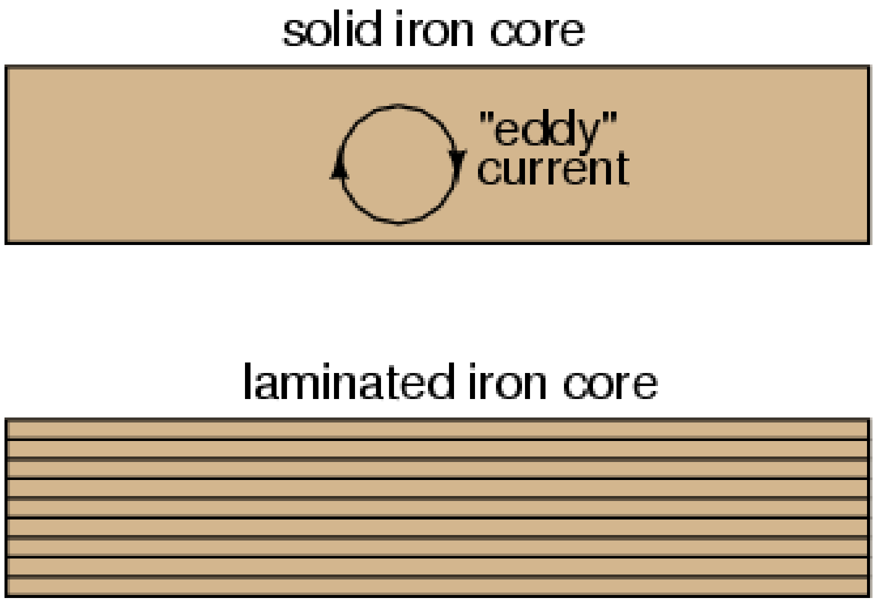
- No transformer is 100% efficient however – some **energy is always lost.** Heating of a transformer is proof of this.
- There are **4 primary energy losses:**
  - **Eddy Currents;**
  - **Winding Resistance;**
  - **Magnetic leakage; and**
  - **Hysteresis.**

Eddy Currents

- The changing **magnetic fields generate electric current** called **Eddy Currents** in the **core** of the transformer.
- These currents **divert energy** away from the transformer's actual purpose.
- To prevent eddy currents, we use **thin layers of insulated metal** to make up the core, instead of a solid piece of metal.
- At higher frequencies (RF) **powdered metal** with a **ceramic** or **plastic filler** is used instead.

Eddy Currents





Winding Resistance

- There is always some **loss** caused by the **resistance of the wire** in the windings.
- This loss appears as **heating of the transformer.**
- It is sometimes called **Copper Loss.**
- Transformers that must carry large currents use **larger wire.**

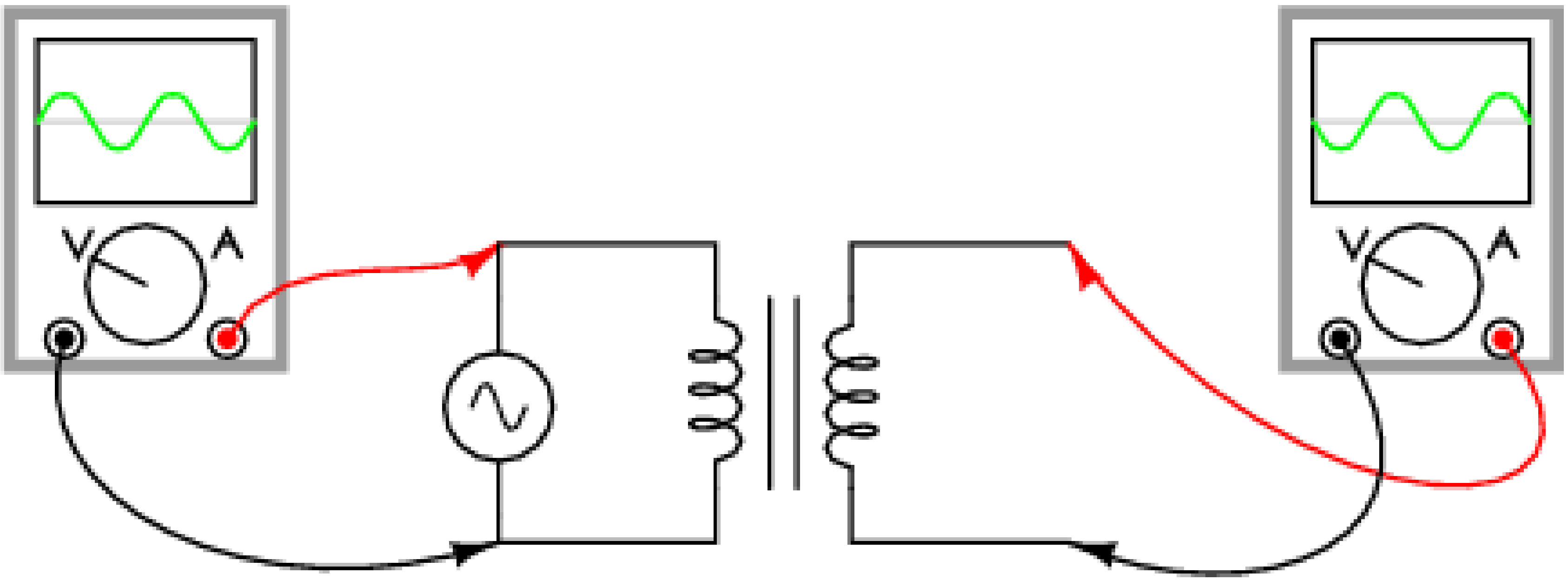
Magnetic Leakage

- **Not every magnetic flux line** produced by the primary winding **can cut through** the secondary winding.
- This inefficiency is called **Magnetic Leakage.**
- **Proper core design** can minimize these losses.

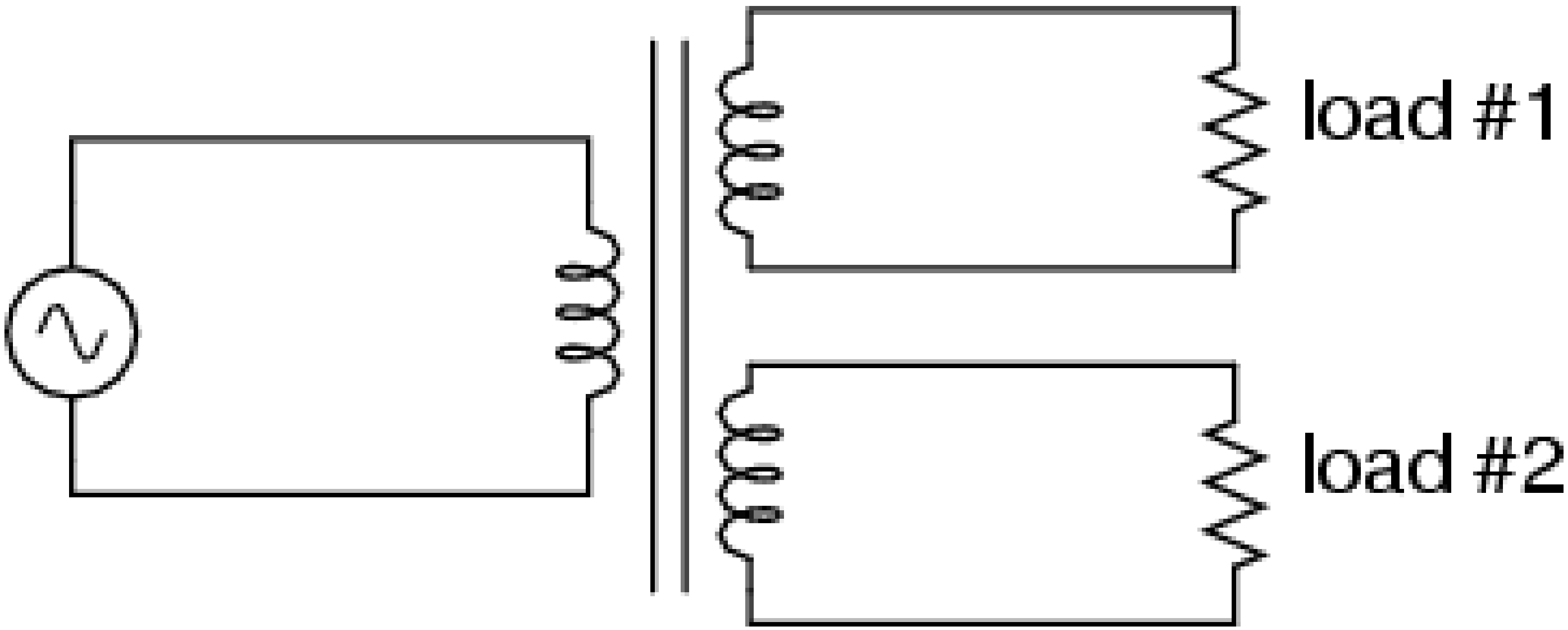
Hysteresis

- The transformer core must become **magnetized** and **de-magnetized** during **every AC cycle.**
- This **requires energy,** diverting it away from the transformer's purpose.
- This inefficiency is called **Hysteresis Loss.**

Phase Relationship

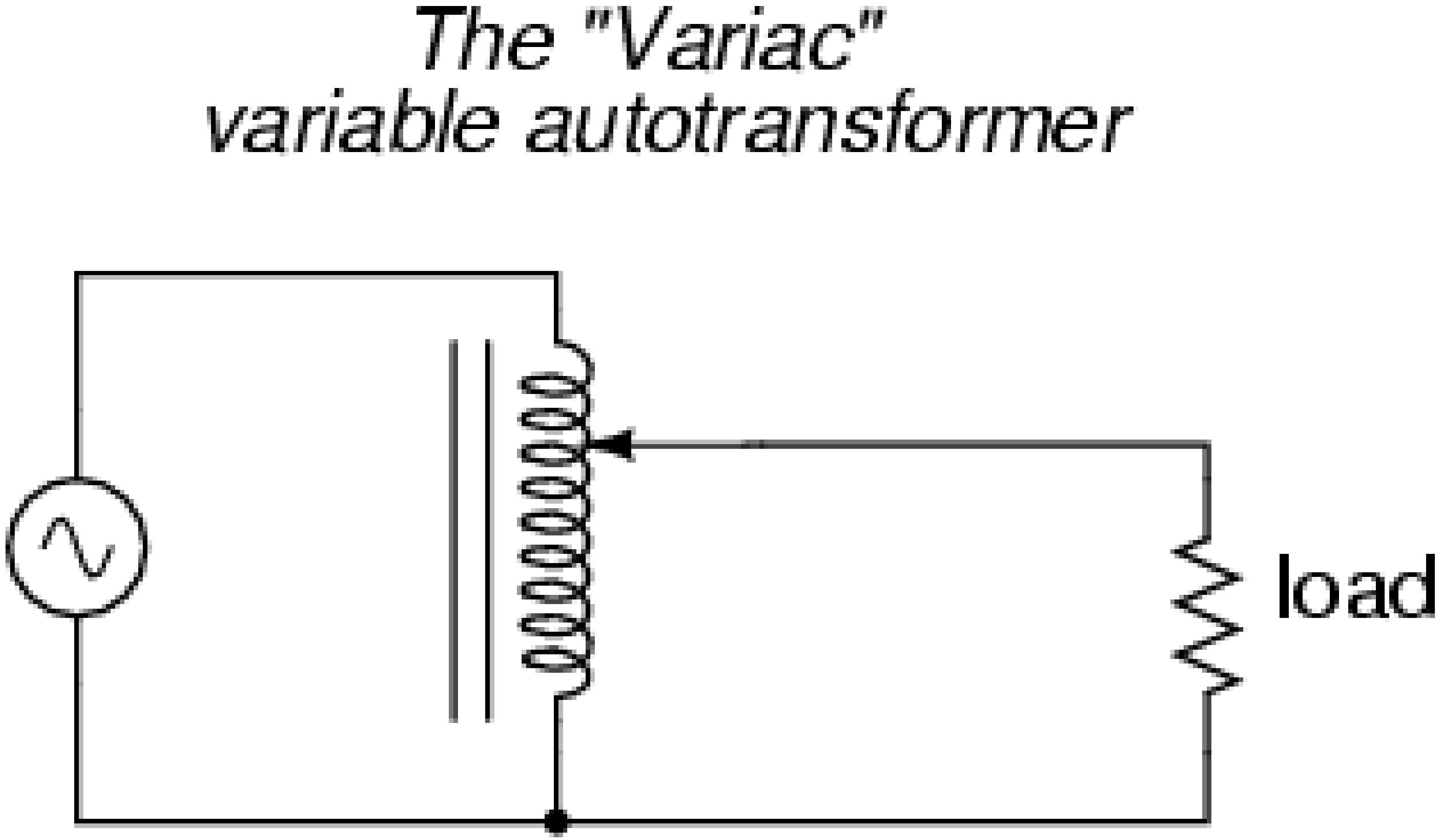


Multiple Windings



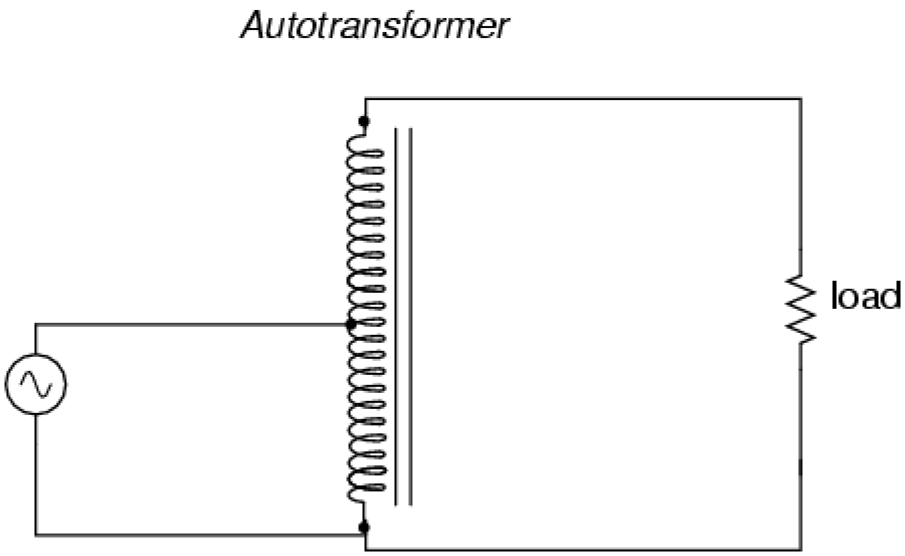
Multiple Windings

Variac – Variable Transformer



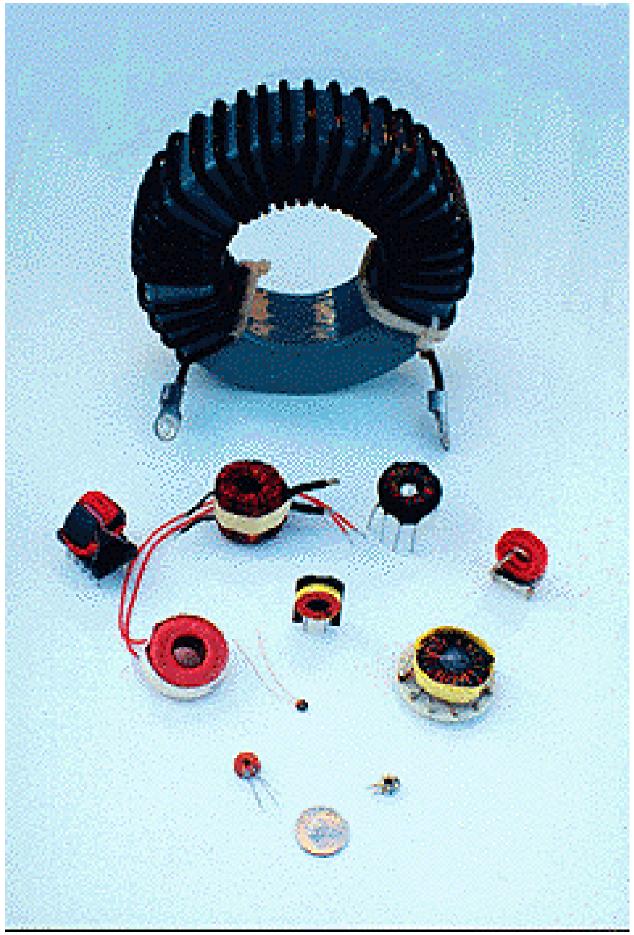
Auto Transformer

- Transformer that utilizes a **single winding.**
- Often used to **adjust** a line voltage that is consistently **too low or high.**



Toroids

- **Doughnut-shaped cores** (usually) made of a ferrite material used to wind transformers and inductors.
- **Entire magnetic field** is contained **within** the toroid.



Questions?