Inductors

An INtroDUCTiOn to the Application of Inductors

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Inductors - Overview

- Along with Resistors and Capacitors, Inductors have been one of the main building blocks of the Electronic Age, and are likely to be utilized even more in the future.
- Some prominent applications include:
  - Motors and Generators
  - Transformers and autotransformers
  - Electric Heating elements – Induction heating
  - Wireless Charging
  - Electric Meter movements
  - Core Memory in early computer circuits

Inductors – Overview (cont’d)

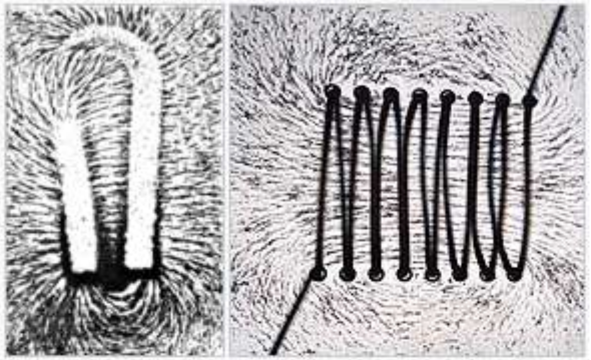
- In Vintage Radio applications we find them used in:
  - Antennas
  - Chokes and Filters in Power Supplies and RF Circuits
  - Radio Frequency Tuning Circuits
  - Interstage coupling
  - Neutralization
  - Transformer Audio Output stages
  - Headphones and Loudspeakers
  - Meters
  - Motor Drive Tuning
  - Slug Tuned Circuits

Inductors – Magnetic Fields

- A **magnet** is a material or object that produces a magnetic field. This magnetic field is invisible but is responsible for the most notable property of a magnet: a force that pulls on other ferromagnetic materials, such as iron, steel, nickel, cobalt, etc. and attracts or repels other magnets [Wikipedia]
- A **permanent magnet** is an object made from a material that is magnetized and creates its own persistent magnetic field. Materials that can be magnetized, which are also the ones that are strongly attracted to a magnet, are called ferromagnetic.
- An **electromagnet**, or **solenoid** can be produced by a coil of wire with an electric current passing through it.

Inductors – Magnetic Field (Cont'd)

- While the magnetic field itself is invisible, the effects can be demonstrated by scattering iron filings in the vicinity of the magnet and seeing how they line up.



A permanent magnet, a piece of magnetized metal alloy

A solenoid (electromagnet), a coil of wire with an electric current through it

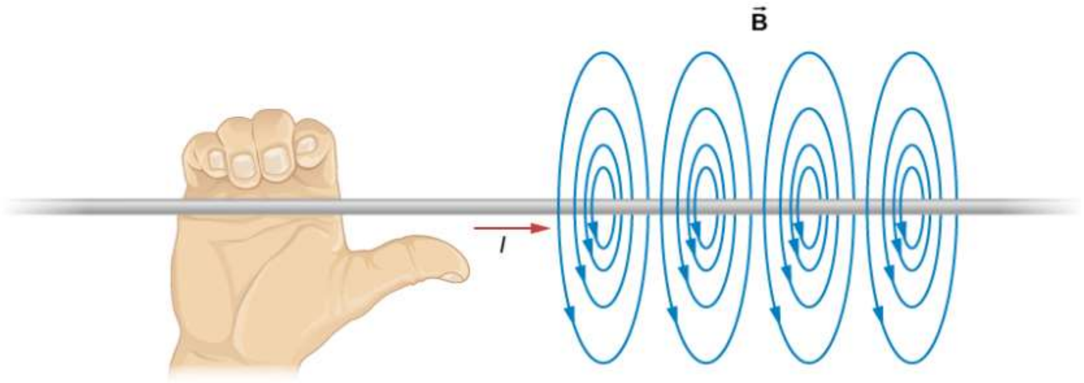
The shape of the magnetic fields of a permanent magnet and an electromagnet are revealed by the orientation of iron filings sprinkled on pieces of paper

Inductors- Magnetism cont’d

- Magnets have poles, correlating to the earth itself being a natural magnet, with a North and South Pole.
- Individual magnets will line up with the Earth’s poles if freely suspended. One end is called the north-seeking-pole and the other the south-seeking-pole, i.e North and South poles of the magnet.
- Magnetic forces between magnets result in ***Unlike Poles Attract***ing while ***Like Poles Repel***.

Inductors - Electromagnetism

- The key physical property of an inductor is that of electromagnetism, that a magnetic field surrounds a wire when an electric current is passed through it.
- The magnetic field (B) around a straight wire is quite weak, with the

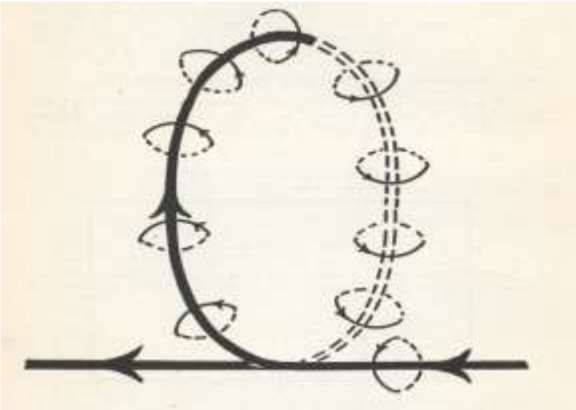


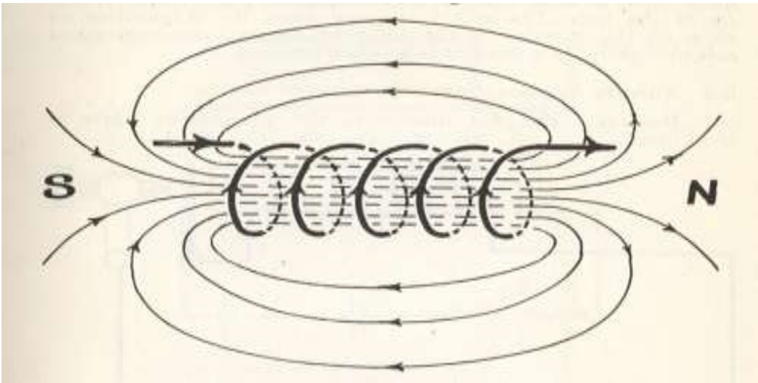
$$B = \frac{\mu_0 I}{2\pi R}$$

Where: $\mu_0 = 4\pi \times 10^{-7}$ [Tesla] permeability of free space

Inductors – Electromagnets

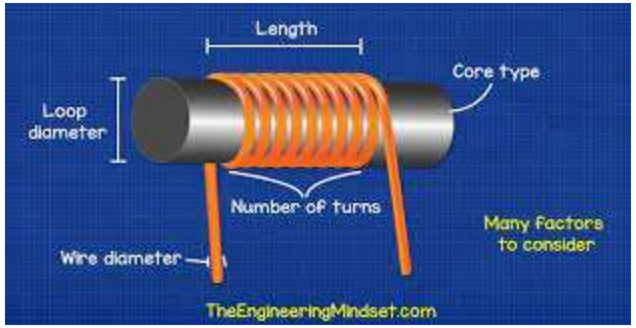
- The magnetic field in a straight wire is directly proportional to the current [I], and inversely proportional to the distance from the centre of the wire [R]
- The effect of magnetism can be concentrated by configuring the straight wire into a loop, and then adding more turns to the loop.





Inductors - Solenoids

- This is where the inductor becomes classified as a Solenoid.
- The magnetic field associated with the solenoid can be further enhanced by utilizing a magnetic core.

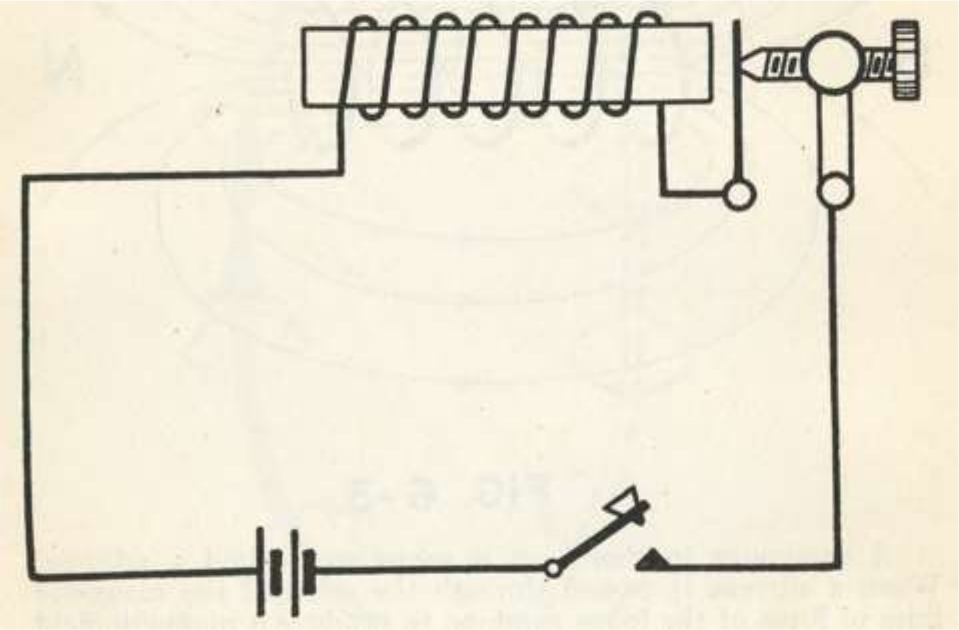


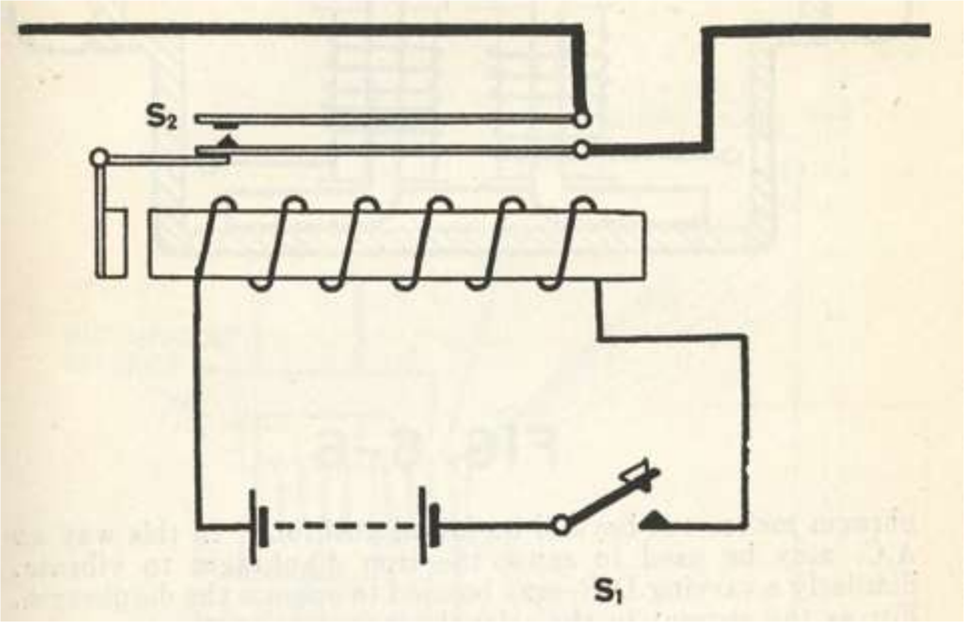
Substance	Type	Relative Permeability
Bismuth	Diamagnetic	0.99983
Air	Paramagnetic	1.0000004
Aluminum	Paramagnetic	1.00002
Ferroxcube 3 (Mn-Zn-ferrite powder)	Ferrimagnetic	1500
Mild Steel (0.2 C)	Ferromagnetic	2000
Iron (0.2 impurity)	Ferromagnetic	5000
Purified iron (0.05 impurity)	Ferromagnetic	200000

The magnetic field in a solenoid of length L around an iron core with N turns is given by: $B=\mu NIL$.

Examples of Solenoids at Work

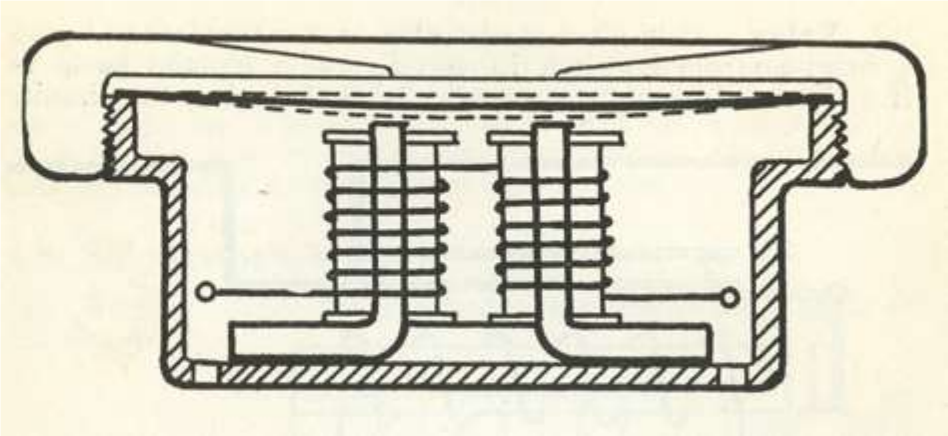
- The magnetic field exhibits a force on ferrous materials and can then do work. Examples show a Buzzer and a Relay

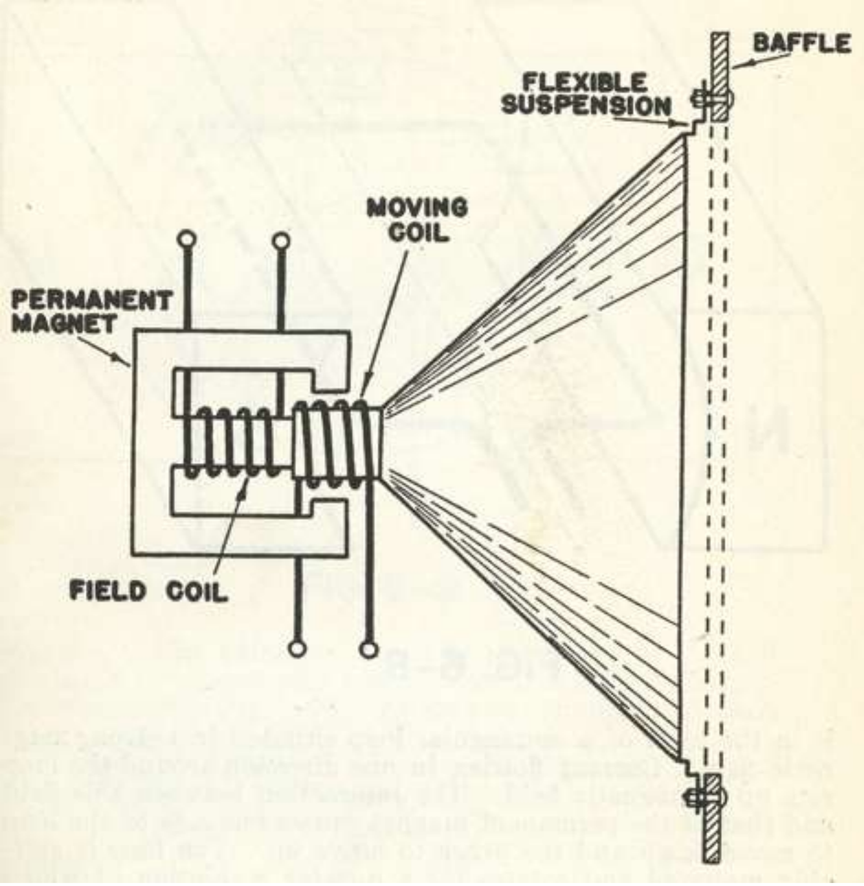




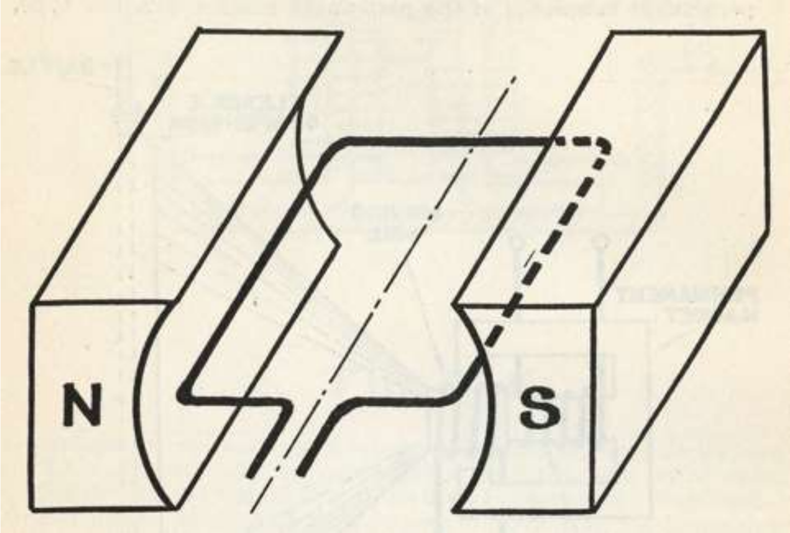
Electromechanical Examples – Audio Transducers

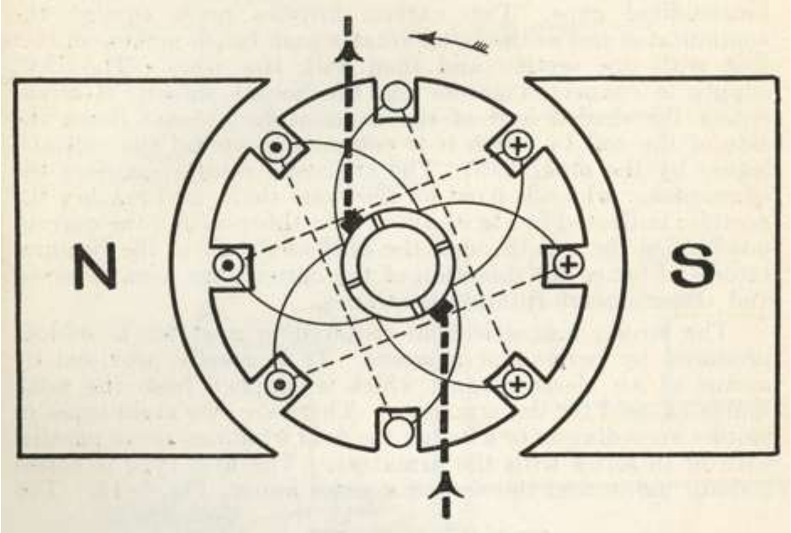
- Audio examples for a headset and an Electrodyamic Loudspeaker

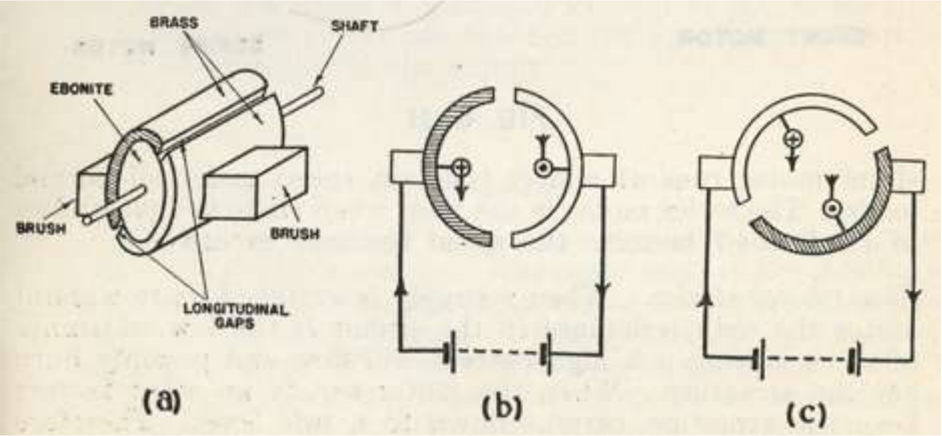




Electromechanical Examples – Motors (and Generators)

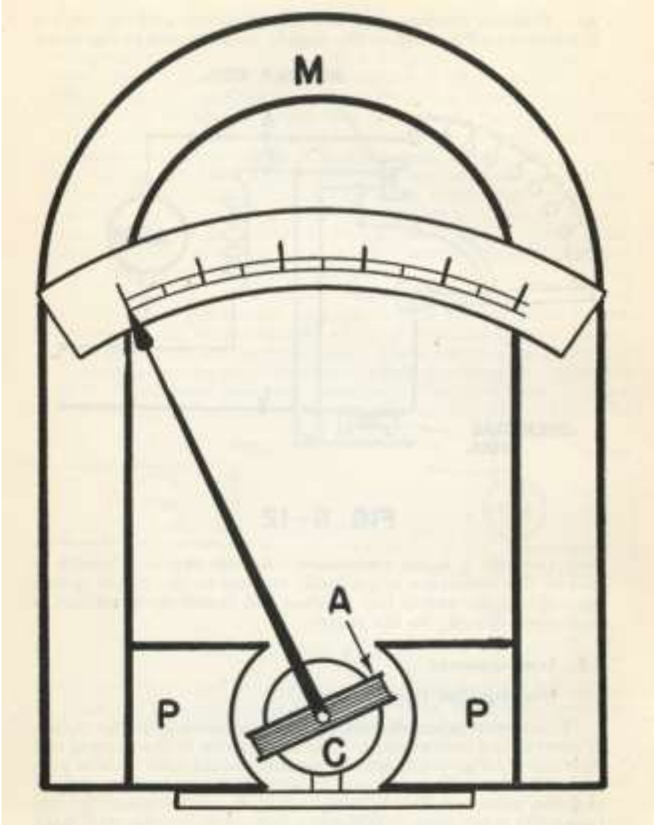


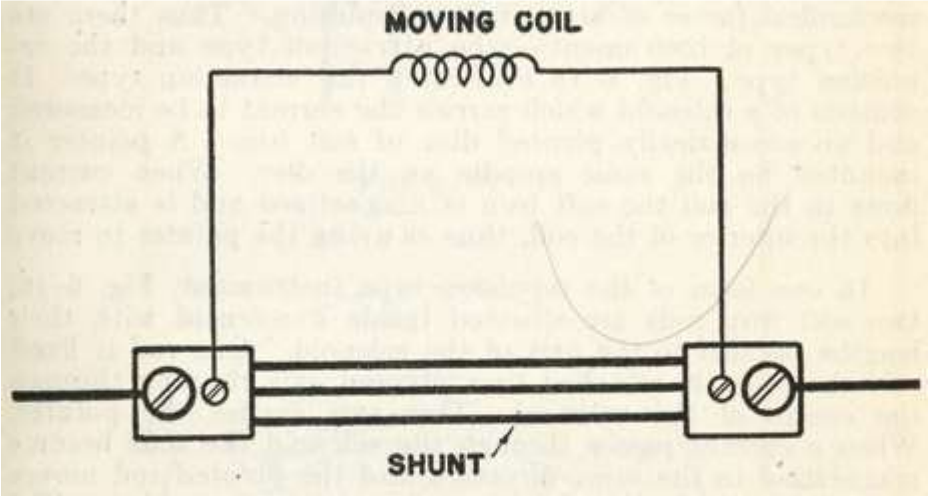




Electromechanical Examples - Meters

- Example showing moving coil Meter Movement and application as an Ammeter with Shunt Resistance





Inductors – Electromagnetic Induction

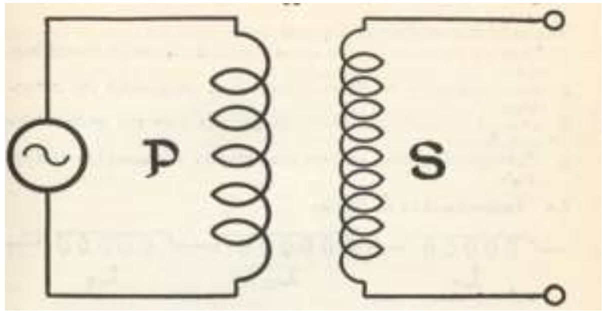
- **Faraday's law of induction** (or simply **Faraday's law**) is a law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (emf). This phenomenon, known as electromagnetic induction, is the fundamental operating principle of transformers, inductors, and many types of electric motors, generators and solenoids.[2][3] [Wikipedia]
- Electromagnetic induction was discovered independently by Michael Faraday in 1831 and Joseph Henry in 1832.[4] Faraday was the first to publish the results of his experiments.

Electromagnetic Induction - Basics

- Whenever there is a change in the number of magnetic lines of force cutting a conductor, an E.M.F. (energy per unit electric charge – measured in volts) is ***induced*** in the conductor. If the conductor forms part of a complete circuit, an ***induced current*** flows. The changing magnetic flux can be produced by:
  - A permanent magnet whose position relative to the conductor is changing
  - An electromagnet carrying a D.C. current whose position relative to the conductor is changing
  - An electromagnet carrying either an A.C or a varying D.C. current placed near the conductor
  - A changing current in the conductor itself

- The conductor is usually a coil to optimize the magnetic coupling.
- A coil in which an induced effect is produced is called an Inductor.
- ***Faraday's First Law***: When the magnetic flux linked with a circuit changes, an EMF is induced into the circuit
- ***Faraday's Second Law***: The value of the induced EMF is proportional to the rate of change of flux linkage
- ***Lenz's Law***: The induced EMF acts in such a direction as to oppose the change producing it.

Mutual Induction



- A ***changing current in coil P*** produces a ***changing magnetic field*** which interlinking with coil S, ***induces an EMF*** in it. The process is termed mutual induction and consists essentially of ***a transfer of energy from the first circuit to the second***.
- The direction of the induced EMF in S depends on the relative windings of the two coils. The size of the EMF depends on:
  - The ***level and rate of change (frequency) of current*** in coil P
  - The relative position and physical constructions of the coils
- The mutual inductance between the coils depends upon the **permeability of the magnetic core joining the two coils**, **the number of turns in each coil** and the **cross-sectional area of the core**.

Self Induction

- When an EMF is induced in a circuit by a changing current in the circuit itself, the process is called self induction. If the current in a circuit is increasing , the magnetic field increases and the flux linkage (between the coils) increases.
  - Faraday’s First Law states that an EMF is induced in the circuit
  - Lenz’s Law shows that the EMF acts in opposition to the increasing current which caused the induction
    - An increasing current causes a back EMF of self induction, and conversely
    - A decreasing current causes a forward EMF which tends to maintain the current
    - The value of the EMF, whether back or forward depends on:
      - The rate of change of current in the circuit
      - The construction of the circuit
  - The tendency of a coil to resist changes in current in itself

Inductance dependencies

- The unit of inductance is the henry [H].
  - A circuit has an inductance of l H if a current changing at the rate of 1 A per second in it induces an EMF of 1 V
- The inductance of a coil depends on:
  1. Number of turns – the more turns the greater the inductance
  2. Axial length – the shorter the length the greater the inductance
  3. Area of cross-section – the larger the area the greater the inductance
  4. Material of core – an iron core greatly increases the inductance
- An inductance calculator from All About Circuits is shown on the next page.

Online Inductance Calculator–

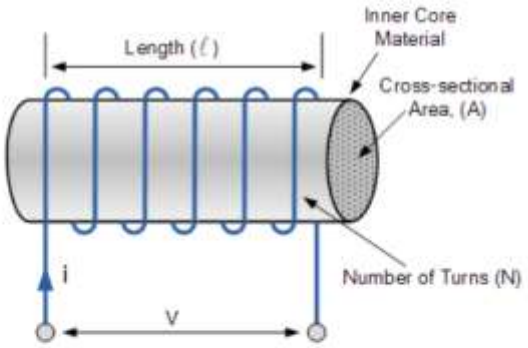
https://www.allaboutcircuits.com/tools/coil-inductance-calculator/

Inputs

Coil Radius	Coil Radius	cm
Area (cross-section)	0.00e+0	cm^2
Solenoid Length	Solenoid Length	cm
Number of Turns	Number of Turns	
Permeability of Air	1.26e-6	H/m
Relative Permeability	Relative Permeability	
	Calculate	

Output

Inductance:	Inductance	H



Equation

$$L_{coil} = \frac{\mu_r \mu_0 N^2 A}{l} = \frac{\mu_r \mu_0 N^2 \pi r^2}{l}$$

Where:

L_{coil} = inductance of the coil in henries (H)

μ_r = relative permeability of the core (dimensionless)

μ_0 = permeability of free space = $4\pi \times 10^{-7}$ (H/m)

N = number of turns

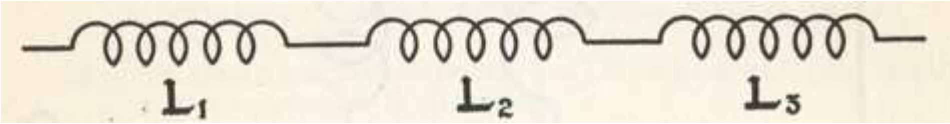
A = coil area (m^2)

r = coil radius (m)

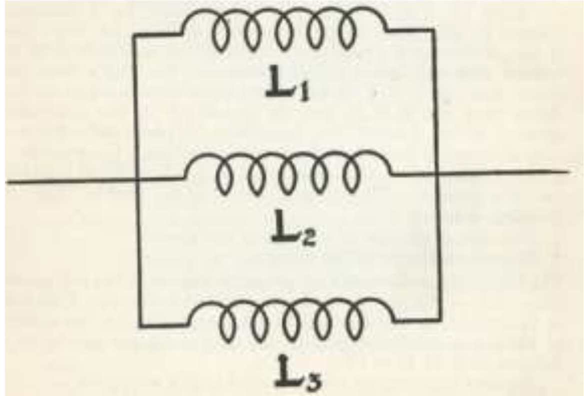
l = coil length (m)

Inductors in Series and Parallel

- Inductances in Series and Parallel behave as Resistors in Series and Parallel.
- Inductors in Series
  - $L = L_1 + L_2 + L_3$



- Inductors in Parallel
  - $1/L = 1/L_1 + 1/L_2 + 1/L_3$



Methods of Varying the Value of Inductance

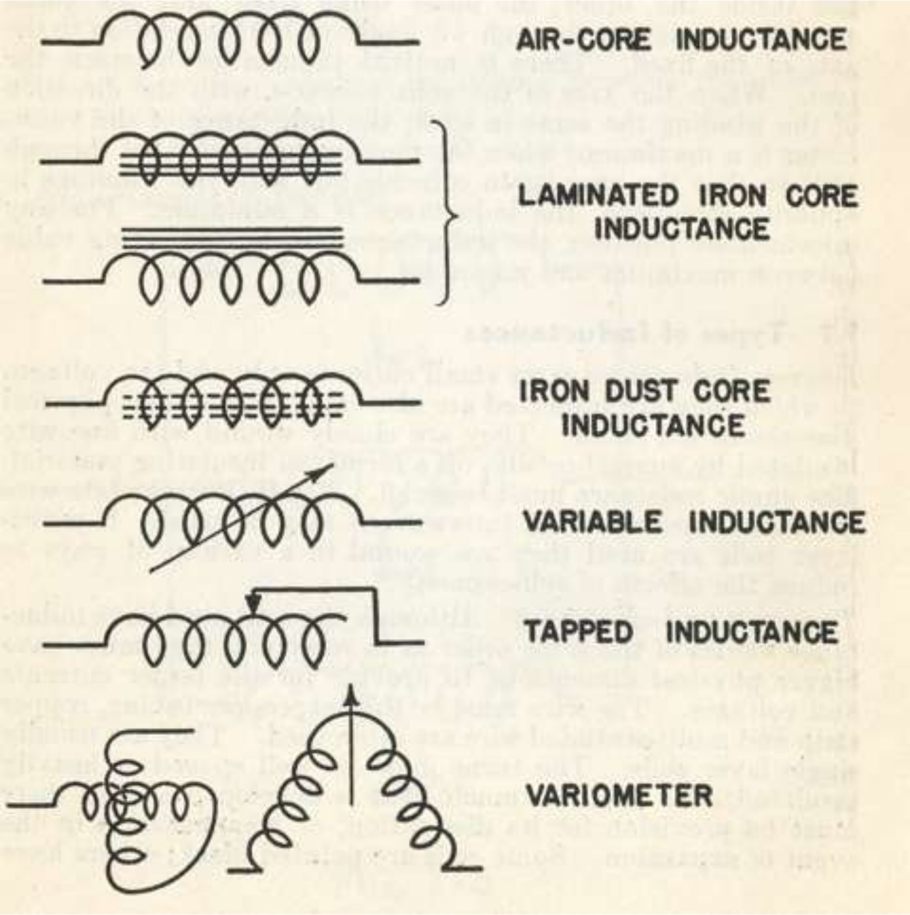
- A sliding contact, varying the inductance by whole turns

- A revolving contact on a screw, varying the inductance by any fraction of a turn
- Tapping contacts, leaving all the unused turns at one end
- Sets of Plug in Coils
- Built-in coils capable of being switched into use
- An iron coil (usually powdered iron) capable of being screwed into or out of the coil

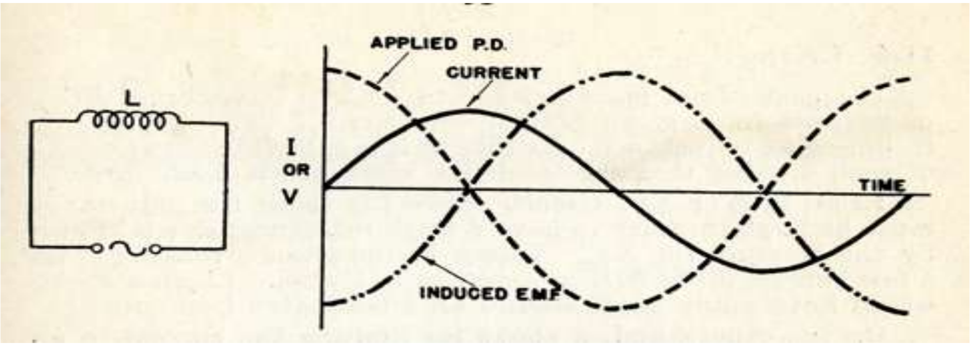
Variometer

- Consists of two inductances in series, one inside the other, the outer being fixed and the inner capable of rotation through 180^0 in relation to the axis of the fixed. There is mutual inductance between the two . When the axes of the coils coincide, with the direction of the winding the same in each, the inductance of the variometer is a maximum; when the windings are in opposite directions the inductance is at a minimum. For any intermediate position, the inductance is a corresponding value between maximum and minimum.

Inductor Circuit Symbols



Inductors in AC Circuits – Inductive Reactance (X_l)

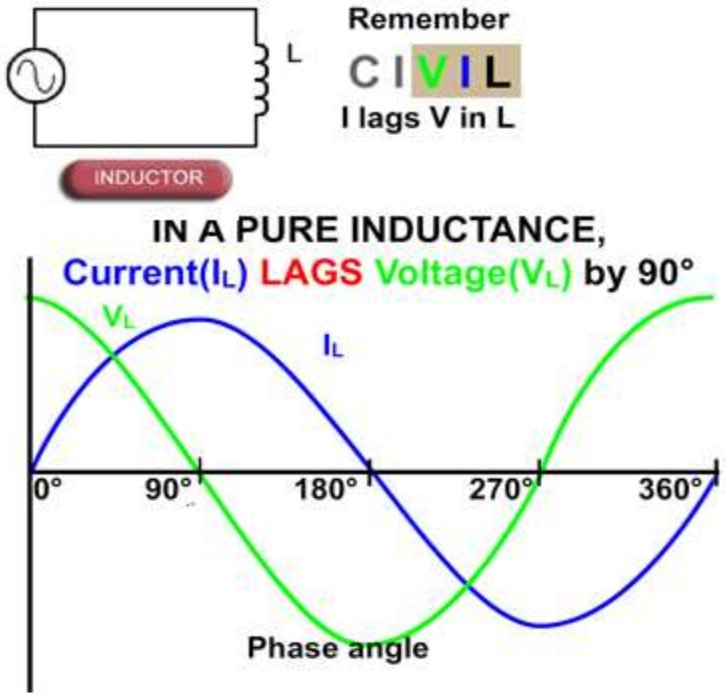


- Inductive reactance is the opposition that an inductor offers to alternating current due to its phase-shifted storage and release of energy in its magnetic field. Reactance is symbolized by the capital letter "X" and is measured in ohms just like resistance (R).
- Inductance reduces circuit current in the circuit. Note that the energy switches between the circuit and the magnetic field.
- $X_L = 2\pi fL$

Factors affecting X_L

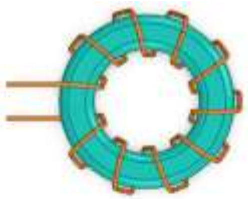
- Inductive reactance is due to the EMF of self induction and so depends on:
  - The amount of inductance in the circuit – the larger the inductance the larger the reactance [L in Henries]
  - The frequency of the rate of change of current [2πf in Hertz]
  - X_L is measured in ohms

Relative Phases of Voltage and Current in an Inductor



Equivalent Circuits for a Real Inductor

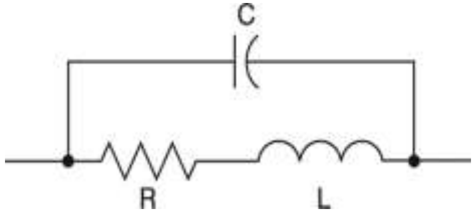
- Including the resistance of the wire making up the coil



(a)

(b)

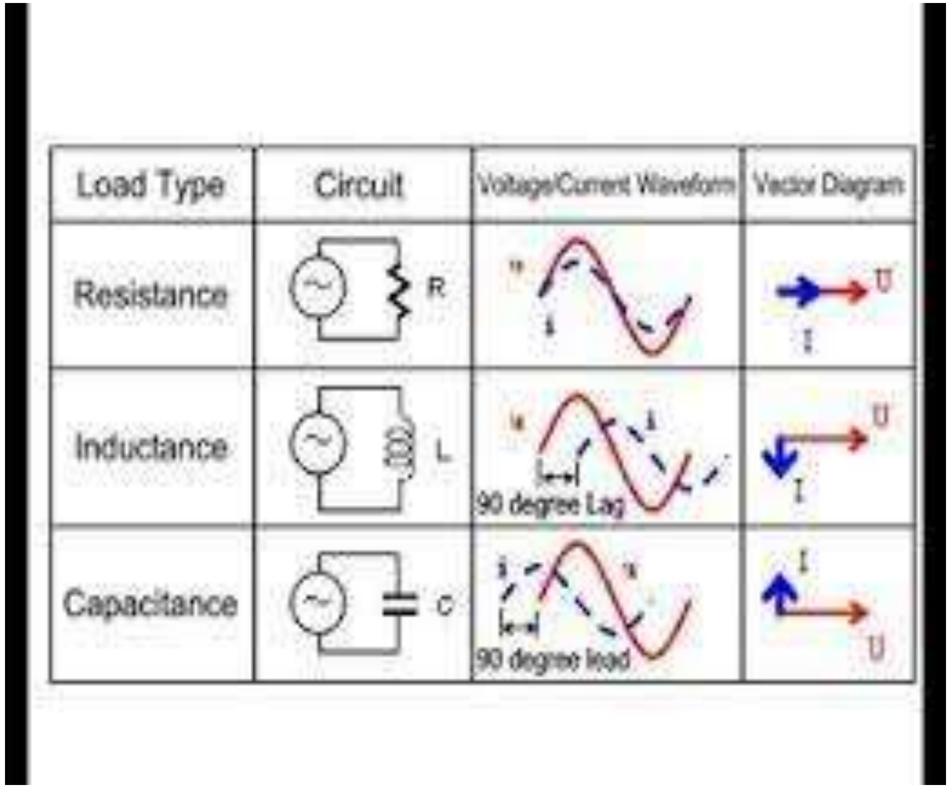
- Including Parasitic Capacitance between the coil segments



Comparisons Between Resistors Inductors and Capacitors

Elements Symbol	RESISTOR	CAPACITOR	INDUCTOR
Denoted by	R	C	L
Equation	$R = \frac{V}{I}$	$C = \frac{Q}{V}$	$L = \frac{V_L}{(di/dt)}$
Series	$R_T = R_1 + R_2$	$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}$	$L_T = L_1 + L_2$
Parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$	$C_T = C_1 + C_2$	$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2}$

www.electricaltechnology.org



Comparisons Between RLC

- Inductive reactance: $X_L = 2\pi f L = \omega L$
- Capacitive reactance: $X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}$
- When $X_L > X_C$ the circuit is Inductive
- When $X_C > X_L$ the circuit is Capacitive
- Total circuit reactance = $X_T = X_L - X_C$ or $X_C - X_L$
- Total circuit impedance = $Z = \sqrt{R^2 + X_T^2} = R + jX$

Measuring Inductance

- There are numerous devices which measure LRC ranging from the very inexpensive multifunction testers to instruments from the mainline manufacturers
- A variation on the Wheatstone Bridge called the Maxwell or Anderson Bridge is used to measure the self-inductance of an Inductor.
- The GenRad DigiBridge has in the past been a reliable tool for measuring LCR components.
- If measuring with Test Leads, best to get an instrument with a 4-wire Kelvin setup to avoid including lead inductance in the measurements

Measruring Inductance - Instruments

AideTek ESR01 LCR Tester Capacitance Equivalent Resistance Meter with test leads

Brand New

$11.27

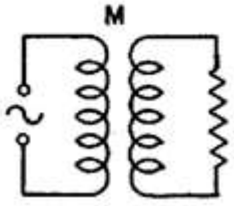
Save up to 15% when you buy more

Was: ~~$11.99~~ 6% off

or Best Offer

Free shipping

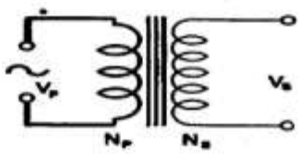
Transformers



- Transformers transfer energy from one circuit to another by means of mutual inductive coupling
- The supply voltage is applied across one coil called the ***primary***, and ***energy is induced*** into the second core called the ***secondary***
- In order to make the coupling tight the coils are wound on a laminated soft-iron yoke with a typical 1940s era shape being shown on the next page.

Transformer

- The ratio of the output voltage to the input is given by the turns ratio [N_s /Np] of the primary and secondaries
- $$V_s /V_p = N_s /N_p$$
- If $V_s > V_p$ it is a step-up transformer
- If $V_s < V_p$ it is a step-down transformer
- Note that a step-up in voltage results in a step-down in current and vice-versa



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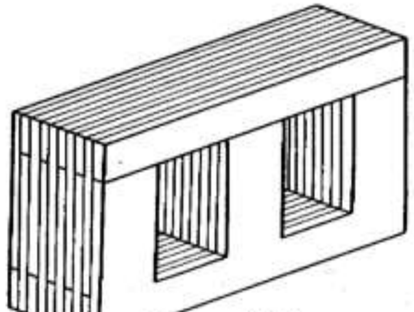
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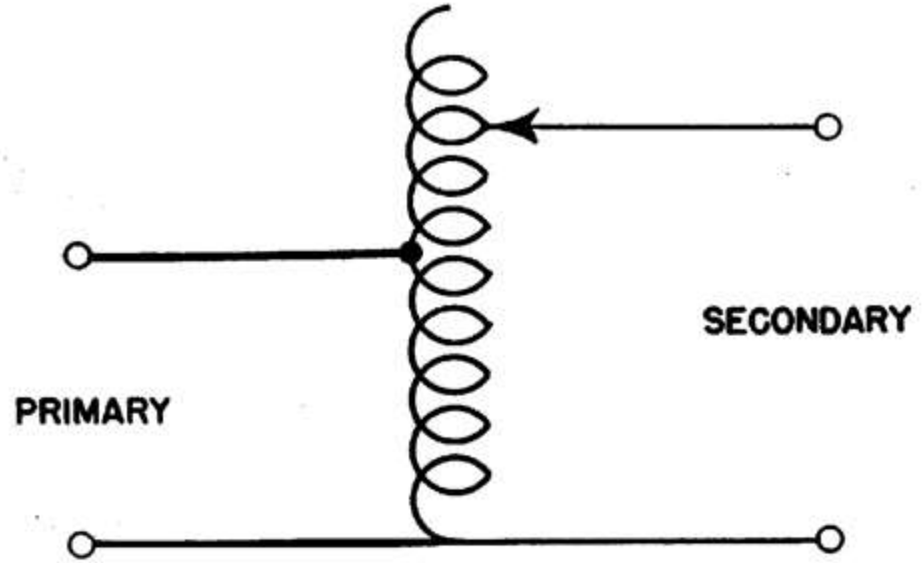
Types of Transformers

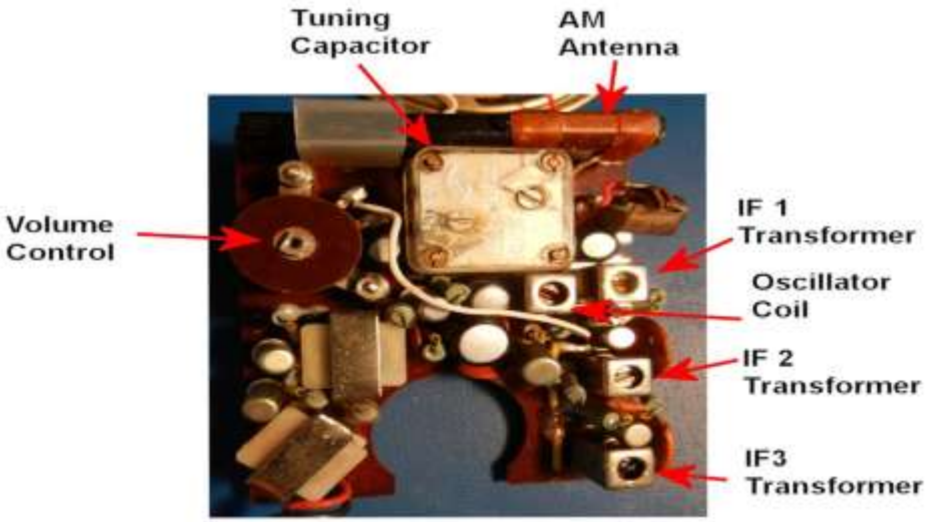
- Power transformers typically convert the mains voltage to the secondary voltages required by the radio, B+, and include a winding for heater current
- Autotransformers (Variacs) used to set voltages



Interstage Transformers

- Intermediate Frequency (IF) and Radio Frequency (RF) transformers are used in the IF and RF stages of receivers. These transformers typically have air cores for high frequency +
- RF work because of the losses which would occur in an iron core. As either or both of the coils are tuned, the tuning capacitors are often incorporated in the transformer construction. IF transformers may have ferrite cores capable of screwdriver adjustment. The entire unit is enclosed in a metal can for shielding.

Examples of IF Transformers



Summary

- This has been more of an Introduction than an in-depth analysis of Inductors, however is probably better suited for a presentation.
- There is more information which can be found on the www, including videos.
- Further useful subjects would be Resonance and Alignment with bench top examples
- This presentation was heavily based on the "Radio Theory Notes" textbook for the Royal Canadian Navy's Radio Articifer Course presented at H.M.C. Signal School, St. Hyacinthe Que, 1943-1945.