**Magnetic fields and inductance**

When a length of wire is formed into a coil, it becomes a basic inductor. Current through the coil produces an electromagnetic field. The magnetic lines of force around each loop in the winding of the coil effectively add to the lines of force around the adjoining loops, forming a strong magnetic field within and around the coil. The net direction of the total magnetic field creates a north and south pole.

When there is a current through an inductor, an electromagnetic field is established. When the current changes, the electromagnetic field also changes. An increase in current expands the field and a decrease in current reduces it. Therefore a changing current produces a changing electromagnetic field around the inductor. In turn the changing electromagnetic field causes an induced voltage across the coil in a direction to oppose the change in current. This property is called self-inductance or inductance.

Inductance is symbolically denoted with a capital "L," and is measured in the unit of the Henry, abbreviated as "H." However in most practical applications mH and μH inductors are used. The schematic symbol for an inductor, like the capacitor, is quite simple, being little more than a coil symbol representing the coiled wire as seen below.

![Diagram of an inductor](image)

**Definition** – **Inductance is a measure of a coil’s ability to establish an induced voltage as a result of a change in its current, and that induced voltage is in a direction to oppose that change in current.**

**Energy storage in an inductor.**

An inductor stores energy in a magnetic field created by the current. The energy stored can be calculated using the following formula

\[ W = \frac{1}{2} LI^2 \]

As the electric current produces a concentrated magnetic field around the coil, this field flux equates to a storage of energy representing the kinetic motion of the electrons through the coil. The more current in the coil, the stronger the magnetic field will be, and the more energy the inductor will store.

![Diagram of energy storage in an inductor](image)

An obsolete name for an inductor is *choke*, so called for its common usage to block ("choke") high-frequency AC signals in radio circuits. Another name for an inductor, still used in modern times, is *reactor*, especially when used in large power applications. Both of these names will make more sense after you've studied alternating current (AC) circuit theory, and especially a principle known as *inductive reactance.*
Factors affecting inductance
There are four basic factors of inductor construction determining the amount of inductance created. These factors all dictate inductance by affecting how much magnetic field flux will develop for a given amount of magnetic field force (current through the inductor's wire coil):

NUMBER OF WIRE WRAPS, OR "TURNS" IN THE COIL: All other factors being equal, a greater number of turns of wire in the coil results in greater inductance; fewer turns of wire in the coil results in less inductance. *Explanation:* More turns of wire means that the coil will generate a greater amount of magnetic field force (measured in amp-turns!), for a given amount of coil current.

![Diagram: More turns of wire result in greater inductance.](image)

COIL AREA: All other factors being equal, greater coil area (as measured looking lengthwise through the coil, at the cross-section of the core) results in greater inductance; less coil area results in less inductance. *Explanation:* Greater coil area presents less opposition to the formation of magnetic field flux, for a given amount of field force (amp-turns).

![Diagram: Greater coil area results in greater inductance.](image)

COIL LENGTH: All other factors being equal, the longer the coil's length, the less inductance; the shorter the coil's length, the greater the inductance. *Explanation:* A longer path for the magnetic field flux to take results in more opposition to the formation of that flux for any given amount of field force (amp-turns).

![Diagram: Longer coil length results in less inductance.](image)

CORE MATERIAL: All other factors being equal, the greater the magnetic permeability of the core which the coil is wrapped around, the greater the inductance; the less the permeability of the core, the less the inductance. *Explanation:* A core material with greater magnetic permeability results in greater magnetic field flux for any given amount of field force (amp-turns). Coil cores made of ferromagnetic materials (such as soft iron) will encourage stronger field fluxes to develop with a given field force than nonmagnetic substances such as aluminum or air.

![Diagram: Soft iron core has higher permeability.](image)

An approximation of inductance for any coil of wire can be found with this formula:
\[ L = \frac{N^2 \mu A}{l} \]

**Where,**
- \( L \) = Inductance of coil in Henrys
- \( N \) = Number of turns in wire coil (straight wire = 1)
- \( \mu \) = Permeability of core material (absolute, not relative)
- \( A \) = Area of coil in square meters
- \( l \) = Average length of coil in meters

**Example 1** – Determine the inductance of a coil of length 1.5cm, diameter of 0.5cm, and 350 turns if the permeability of the core is \( 0.25 \times 10^{-3} \) H/m.

**Types of inductor**
Inductors are made in a variety of shapes and sizes. They fall into two general categories – fixed and variable. Both fixed and variable inductors can be classified according to the type of core material. The three most common types are the air core, iron core, and ferrite core. Small fixed type inductors are usually encapsulated in an insulating material that protects the fine wire in the coil, they have an appearance similar to a small resistor. The symbols for each type are shown below.

Variable inductors are usually made by providing a way to vary the number of wire turns in use at any given time or by using a screw-type adjustment to slide the core in and out of the coil.

**Series and parallel inductors**
When inductors are connected in series, the total inductance is the sum of the individual inductors' inductances. If inductors are connected together in series (thus sharing the same current, and seeing the same rate of change in current), then the total voltage dropped as the result of a change in current will be additive with each inductor, creating a greater total voltage than either of the individual inductors alone, Greater voltage for the same rate of change in current means greater inductance. Thus, the total inductance for series inductors is more than any one of the individual inductors' inductances. The formula for calculating the series total inductance is the same form as for calculating series resistances:

\[ L_{\text{total}} = L_1 + L_2 + \ldots + L_n \]

When inductors are connected in parallel, the total inductance is less than any one of the parallel inductors' inductances. Since the current through each parallel inductor will be a fraction of the total current, and the voltage across each parallel inductor will be equal, a change in total current will result in less voltage dropped across the parallel array than for any one of the inductors considered separately. In other words, there will be less voltage dropped across parallel inductors for a given rate of change in current than for any of those inductors considered separately, because total current divides among parallel branches. Less voltage for the same rate of change in current means less inductance.
Thus, the total inductance is less than any one of the individual inductors' inductances. The formula for calculating the parallel total inductance is the same form as for calculating parallel resistances:

$$L_{total} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \ldots + \frac{1}{L_n}}$$

**Example** – Determine $L_T$ in the figure below.

![Example Diagram](image)

**Inductors and calculus**

Inductors do not have a stable "resistance" as conductors do. However, there is a definite mathematical relationship between voltage and current for an inductor, as follows:

"Ohm's Law" for an inductor

$$v = L \frac{di}{dt}$$

Where,

$v =$ instantaneous voltage across the inductor  
$L =$ Inductance in Henrys  
$\frac{di}{dt} =$ instantaneous rate of current change  
(amps per second)

The form of this equation is similar to the capacitor equation. It relates one variable (in this case, inductor voltage drop) to a rate of change of another variable (in this case, inductor current). Both voltage ($v$) and rate of current change ($di/dt$) are instantaneous: that is, in relation to a specific point in time, thus the lower-case letters "v" and "i". Current rate-of-change ($di/dt$) is expressed in units of amps per second, a positive number representing an increase and a negative number representing a decrease. Like a capacitor, an inductor's behavior is rooted in the variable of time. Aside from any resistance intrinsic to an inductor's wire coil (which we will assume is zero for the sake of this section), the voltage dropped across the terminals of an inductor is purely related to how quickly its current changes over time.

**Inductors in a dc circuit**

Where there is a constant direct current in an inductor, there is no induced voltage. There is however a voltage drop due to the winding resistance of the coil. The inductance itself appears as a short to dc. Because the inductor's basic action is to develop a voltage that opposes a change in its current it follows that current cannot change instantaneously in an inductor. A certain time is required for the current to make a change from one value to another. The rate at which the current changes is determined by the RL time constant. The time constant for a series RL circuit is

$$\tau = \frac{L}{R}$$

Like the capacitor, the inductor reaches steady state after $5\tau$, and reaches 66% of its final value in $1\tau$. 
Example – Calculate the time constant for the circuit below.

The exponential formulas
The formulas for exponential current and voltage in an RL circuit are similar to those used for the RC circuit. The general formulas for voltage in RL circuits are as follows

\[ v_L = Ee^{-\frac{t}{\tau}} \quad \text{and} \quad v_R = E(1 - e^{-\frac{t}{\tau}}) \]

Example – Find the mathematical expressions for the transient behaviour of \( i_L \) and \( v_L \) and sketch the resulting curves.