ELECTRICAL ENGINEERING FUNDAMENTALS

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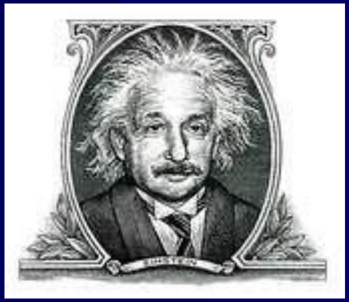
Science and Engineering

"Scientists investigate that which already is;

Engineers create that which has never been"

(Albert Einstein)



INTRODUCTION

Engineering practice is " ***…the ..process of creating, developing, integrating, sharing and applying knowledge …for the benefit of humanity and the profession***“

(*from IEEE Mission Statement*)

Electrical quantities and SI units

- The International System of Units (SI) will be used throughout this course;
- The basic quantities and their SI units are:
  - Length, L, l .... meter, m
  - Mass, M, m .... kilogram, kg
  - Time, T, t .... second, s
  - Current, I, i .... Ampere, A
  - Temperature, T .... degrees Kelvin, K
  - Amount of substance …………. moles mol
  - Luminous intensity ……………. candelas, Cd

- Two supplementary quantities are:
  - Plane angle (phase angle) ……. radian, rad
  - Solid angle …………………….. steradian, sr

All other units may be derived from the seven basic units.

Electrical quantities and SI units

- The electrical quantities and their symbols commonly used in electrical circuit analysis are:

  - Electric charge, Q, q .... Coulomb, C
  - Electric potential, V, v .... Volt, V
  - Resistance, R .... Ohm, Ω
  - Conductance, G .... Siemens, S
  - Inductance, L .... Henry, H
  - Capacitance, C ……………………….…… Farad, F
  - Frequency, f ……………………………….. Hertz, Hz
  - Force, F ………………………….………… Newton, N
  - Energy, work, W, w ………………..……… Joule, J
  - Power, P, p ………………………………... Watt, W
  - Magnetic flux, Φ …………………………… Weber, Wb
  - Magnetic flux density, **B** ………………….. Tesla, T
  - Electric field intensity, **E** .... Volt/meter, V/m

Electrical quantities and SI units

- The decimal multiples and submultiples of SI units, which act as multipliers on the basic unit, are:

Prefix	Factor	Symbol	Prefix	Factor	Symbol
yocto	10^{-24}	y	deca	10	da
zepto	10^{-21}	z	hecto	10^{2}	h
atto	10^{-18}	a	Kilo	10^{3}	K
femto	10^{-15}	f	Mega	10^{6}	M
pico	10^{-12}	p	Giga	10^{9}	G
nano	10^{-9}	n	Terra	10^{12}	T
micro	10^{-6}	µ	Peta	10^{15}	P
mili	10^{-3}	m	Exa	10^{18}	E
centi	10^{-2}	c	Zetta	10^{21}	Z
deci	10^{-1}	d	Yotta	10^{24}	Y

Electric Charge and Current

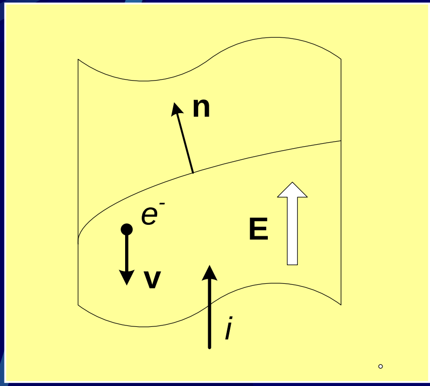
- All maters is made up of fundamental building blocks known as *atoms*.
- Atoms are composed of smaller components known as particles.
- The three fundamental particles comprising atoms are called *protons*, *neutrons*, and *electrons.*
- The protons and neutrons are very tightly bound together (because of a force called the *strong nuclear force* which has effect only under very short distances), forming the *nucleus* of the atom, while the electrons have more freedom to move around the nucleus.
- The tight binding of protons in the nucleus is responsible for the stable identity of chemical elements.
- If neutrons are added or gained, the atom will still retain the same chemical identity, but its mass will change slightly and it may acquire strange *nuclear* properties such as radioactivity.
- Because of the attraction/repulsion behavior between individual particles, electrons and protons are said to have opposite electric charges. That is, each electron has a negative charge, and each proton a positive charge. Neutron has no electric charge.

Electric Charge and Current

- Normally, the number of protons is equal with the number of electrons, we say the net electric charge of atom is balanced.
- The process of electrons arriving or leaving is exactly what happens when certain combinations of materials are rubbed together: electrons from the atoms of one material are forced by the rubbing to leave their respective atoms and transfer over to the atoms of the other material; the atom's net electric charge becomes unbalanced and we say that the material becomes charged.
- The result of the imbalance of this electrons between objects is called *static electricity*.
- Electron is the smallest known carrier of electric charge, is defined as the *elementary charge*.
- $e^- = 1.602 \ 10^{-19}$ C quantum of the electric charge
- A charge of negative one Coulomb (1C) consist of accumulated charge of about $6.24 \ 10^{18}$ e^-.

Electric Charge and Current

- Electric charges in motion constitute a *current*.
- Electrical charges could be: electrons in conductors, ions in liquids and "free" electrons and positive charges in semiconductors.



- The current is defined as the ratio between the total charge ΔQ that penetrate the surface in a time Δt when the time shrink to zero, $\Delta t \rightarrow 0$
- The current represents the rate at which the charges flow changes with time:

$$i = \frac{dQ}{dt} \quad [A] \equiv \frac{[C]}{[s]}$$

- For the reference direction of the current adopted in fig., the current is positive when:
  - positive charges cross the plane surface S in the same direction with the current;
  - negative charges cross the plane surface S in the opposite direction with the current.

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Andre-Marie Ampere (1775–1836), a French mathematician and physicist, laid the foundation of electrodynamics. He defined the electric current and developed a way to measure it in the 1820s.

Born in Lyons, France, Ampere at age 12 mastered Latin in a few weeks, as he was intensely interested in mathematics and many of the best mathematical works were in Latin. He was a brilliant scientist and a prolific writer. He formulated the laws of electromagnetics. He invented the electromagnet and the ammeter. The unit of electric current, the ampere, was named after him.

Electric Potential. Voltage

- In the neighborhood of an electric charge a force will be exerted when another charge is introduced. Such a region of influence is called *electric field*.
- The electric field is defined at a point as the force per unit-positive charge. That is, the electric field at any point is the force, in magnitude and direction, which would act on a unit-positive charge at that point, **E=F**/Q. Contribution to the total field at any point are made by all the charges that are close enough to have any influence.
- The measure for the electric field is the *electric field intensity*, **E**.
- *Potential difference* or *voltage*, U, is defined as the work per unit-positive charge in moving a charge between two points in the field; V=W/Q.
- The SI unit for the voltage is *Volt*, [V].
- Potential difference can exist regardless of whether current is flowing:
  - If a conducting path exists between two points with a potential difference, than charge will flow, resulting in a electric current;
  - If there is no such path, the potential difference will continue to exist even in the absence of current flow.

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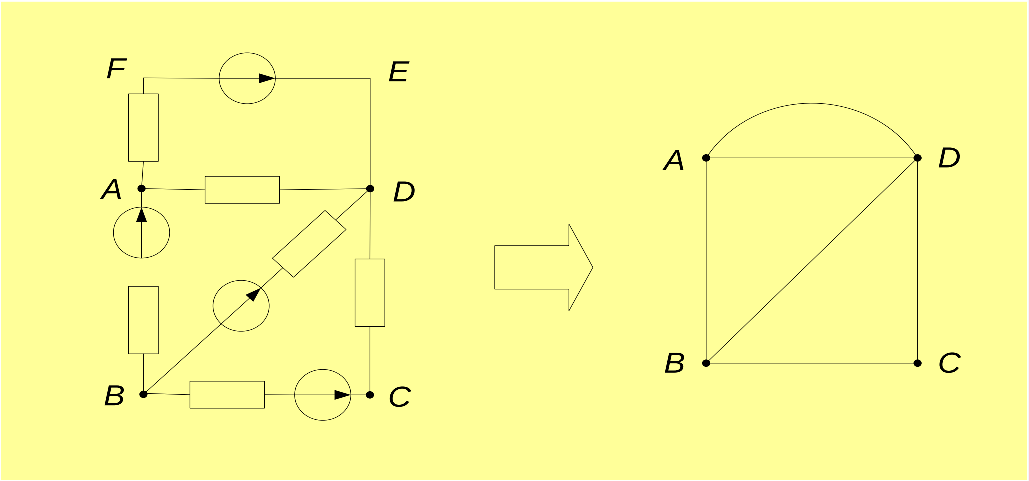
Alessandro Antonio Volta (1745–1827), an Italian physicist, invented the electric battery—which provided the first continuous flow of electricity—and the capacitor.

Born into a noble family in Como, Italy, Volta was performing electrical experiments at age 18. His invention of the battery in 1796 revolutionized the use of electricity. The publication of his work in 1800 marked the beginning of electric circuit theory. Volta received many honors during his lifetime. The unit of voltage or potential difference, the volt, was named in his honor.

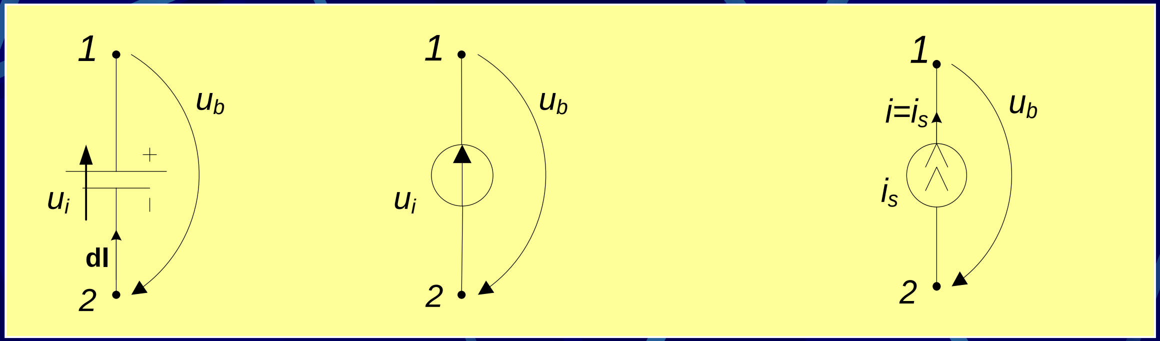
Basic Circuit Concepts

- *Circuit element* is an object to which two wires (assuming to be ideal conductors), called *leads*, are connected.
- *Circuit* is a collection of elements in which each lead of the given element is connected to a lead of at least one other element.
- *Branch* – a portion of the circuit between two nodes.
- *Node* – a place in the circuit where at least three branches converges.
- *Sub-circuit* – a part of a circuit connecting to the rest of the circuit by two terminals.
- *Path* – described as an ordered sequence of elements, each two successive elements of which share a common node; a path has a direction from the initial node to the finale node shown by an arrow.
- *Loop, mesh* – a branches sequence that follow a closed path.



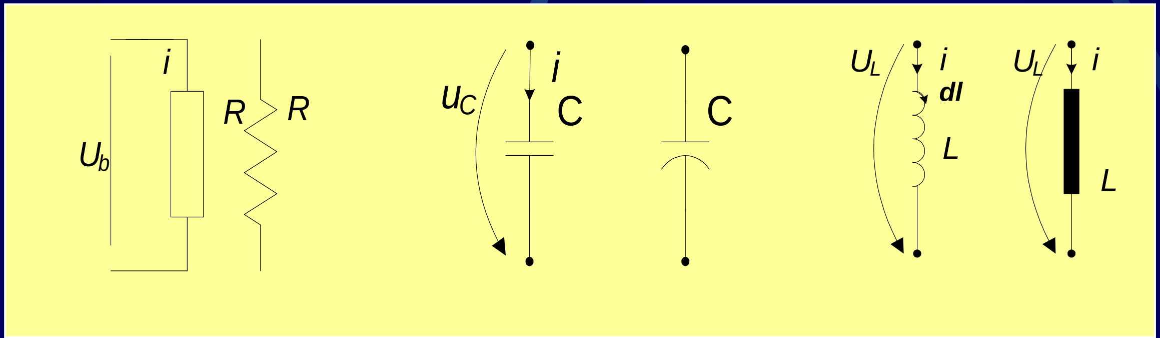
Basic Circuit Concepts

- *Active elements* are voltage or current sources which are able to supply energy to the network.



symbols for voltage sources symbol for current sources

- *Passive elements* – *Resistors*, *Inductors*, *Capacitors* - take energy from the sources and either convert it to another form or store it in an electric or magnetic field.

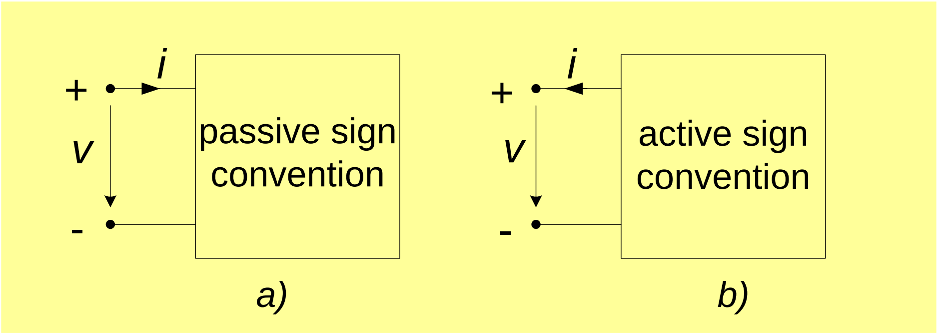


symbols for resistors symbols for capacitors symbols for inductors

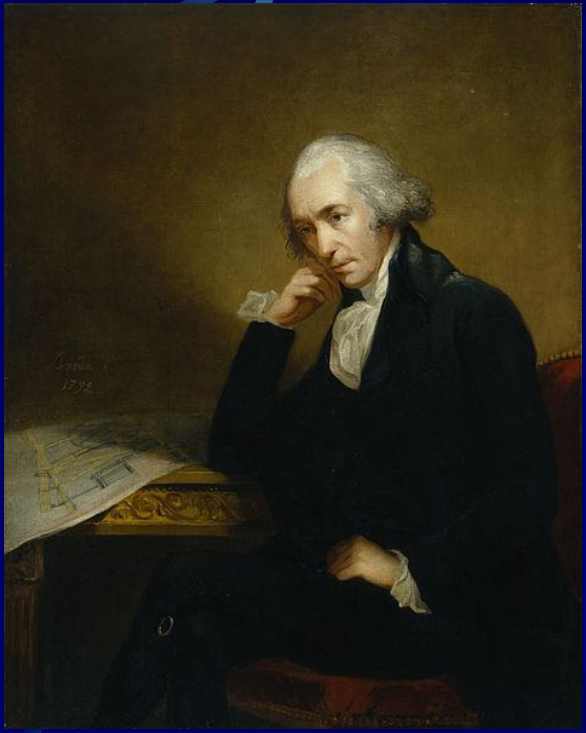
Power and Energy

- The power in an electrical circuit is: $$P = U \cdot I \quad [W] \equiv [V][A]$$

- Consider a two-terminal sub-circuit with a voltage *v* defined across its terminals and a current *i* into one of these terminals.
- In the fig.a) is defined the positive current reference going into the terminal which has the positive voltage reference. This choice is called the *passive sign convention*. The sub-circuit *absorbs power (removes power)*.
- In the fig.b) is defined the positive current reference coming out of the terminal which has the positive voltage reference. This choice is called the *active sign convention*. The sub-circuit *generates power (delivers power)*.



James Watt, (19 January 1736 – 25 August 1819) was a Scottish inventor and mechanical engineer whose improvements to the Newcomen steam engine were fundamental to the changes brought by the Industrial Revolution in both his native Great Britain and the rest of the world.

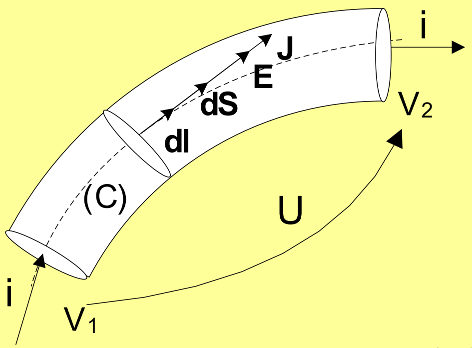


While working as an instrument maker at the University of Glasgow, Watt became interested in the technology of steam engines. He realized that contemporary engine designs wasted a great deal of energy by repeatedly cooling and re-heating the cylinder. Watt introduced a design enhancement, the separate condenser, which avoided this waste of energy and radically improved the power, efficiency, and cost-effectiveness of steam engines. Eventually he adapted his engine to produce rotary motion, greatly broadening its use beyond pumping water.

He died in 1819 at the age of 83. Watt has been described as one of the most influential figures in human history.

He developed the concept of horsepower and the SI unit of power, the watt, was named after him.

Ohm's Law



$$i = \int_{\Delta S} \mathbf{J} \cdot \mathbf{dS} = J \, \Delta S \qquad \Rightarrow J = \frac{i}{\Delta S}$$

$\mathbf{J} = \sigma \mathbf{E}$ local conduction law

σ- conductivity [S/m]

σ- represents the relative mobility of electrons within a material

$\rho = \frac{1}{\sigma}$ resistivity [Ωm]

$$U = V_1 - V_2 = \int_C \mathrm{E} \cdot \mathrm{dl} = \int_C \frac{\mathrm{J}}{\sigma} \cdot \mathrm{dl} = i \int_C \frac{dl}{\sigma \Delta S} = i R$$

$R = \int_C \frac{dl}{\sigma \Delta S}$ resistance [Ω] $\qquad R = \frac{l}{\sigma \Delta S} = \frac{\rho l}{\Delta S}$

$G = \frac{1}{R}$ conductance [S] $\qquad \boxed{U = i R}$

Georg Simon Ohm (1787–1854), a German physicist, in 1826 experimentally determined the most basic law relating voltage and current for a resistor. Ohm's work was initially denied by critics.

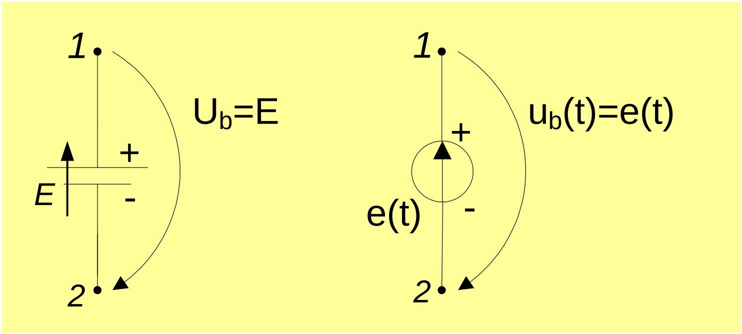
Born of humble beginnings in Erlangen, Bavaria, Ohm threw himself into electrical research. His efforts resulted in his famous law. He was awarded the Copley Medal in 1841 by the Royal Society of London. In 1849, he was given the Professor of Physics chair by the University of Munich. To honor him, the unit of resistance was named the ohm.

Active and Passive Circuit Elements

1 Active Circuit Elements

- The circuit elements capable to supply energy in circuit are called sources.
- Independent sources produce a voltage or a current waveform which is unaffected by the circuit to which it is connected.

The Independent Voltage Source

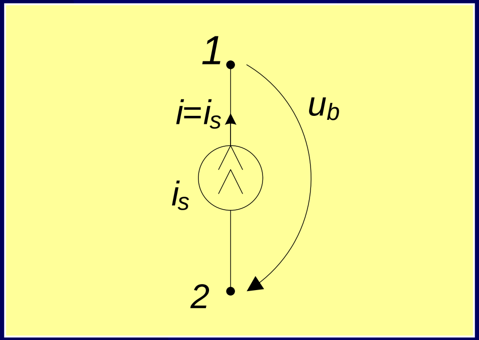


- There is not possible a parallel connection of voltage sources of different values.
- There is not possible to put in short circuit a voltage source.

- The voltage drop from 1 to 2, $u_b(t)$, is independent of the load that may be connected to the source and is determined exclusively by the function e(t).
- When a load is connected by the source terminals, a current exists in the source in the direction of the voltage rise. A current direction from – to + signifies the source is delivering energy to the load. It is also possible for the current in the source to exist in the direction of the voltage drop. In this situation the voltage source is extracting energy from the system as is the case when a battery is charged.

- The voltage $u_b(t)$ is always equal to $e(t)$, no matter what the value of the current $i(t)$ pass true the voltage source. The current depends upon the circuit into which the voltage source is connected.
- If the voltage $u(t)$ does not change in time, we write U (that is, we use an uppercase letter). If we simply write $u(t)$, we mean that the voltage can change with time or can be constant. We call constant voltages and currents *dc quantities*. This is short for *direct current*, and is used for both currents and voltages.

The Independent Current Source



There is not possible a series connection of current sources of different values.
There is not possible to put in open circuit a current source.

- The arrows in the current symbol point in the direction of positive current.
- The current is independent of the voltage. The current source does not constrain the voltage u_b. The voltage is determined by the circuit into which the current source is connected.

- An ideal current source is characterized by a current which is independent of load connected at its terminals.
- When supplying power to a load, the source current is in the direction of the voltage rise. The value of the voltage rise varies with the power requirements of the load.

- *For the two sources, the values e(t) and $i_s(t)$ are not affected by the loads connected to them or by the electrical conditions that exist elsewhere in the systems in which they are employed. For this reason, the ideal voltage and current sources are referred to as* independent sources.

2 Passive Circuit Elements

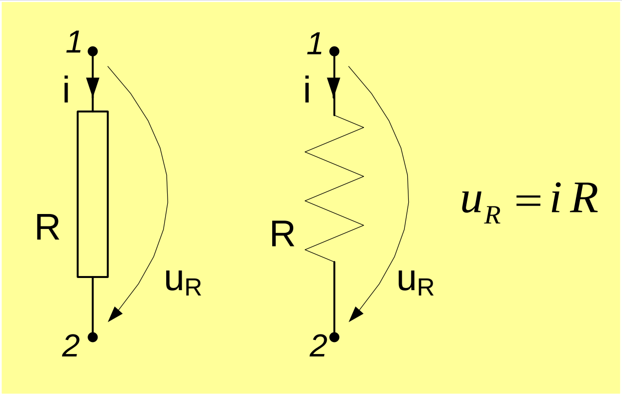
- The circuit elements capable of removing energy from the system by storage in a field or by dissipation are called passive circuit elements.
- Usually, for the passive circuit elements, is assumed the passive sign convention, i.e. the positive current reference going into the terminal which has the positive voltage reference.

Resistance

- The circuit element used to represent energy dissipation is most commonly described by requiring the voltage across the element be directly proportional to the current through it. The constant of proportionality R is the resistance of the element and is measured in ohms [Ω].

$$u_R = i\,R$$

- The voltage-current relation expressed is known as Ohm's law.



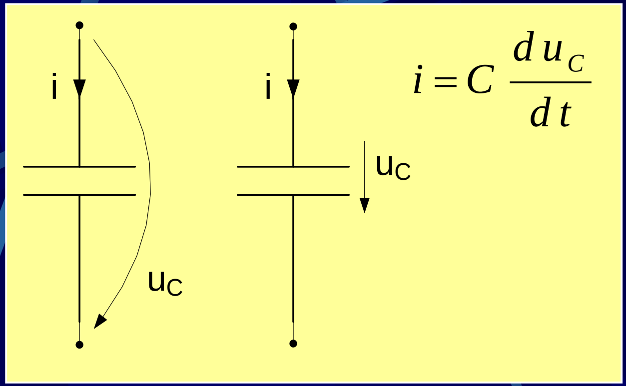
➢A physical device whose principal electrical characteristic is resistance is called a *resistor*.

➢The power dissipated by the resistance is:

$$p = u_R\, i = (Ri)\,i = i^2 R = u_R \frac{u_R}{R} = \frac{u_R^2}{R} \quad [W]$$

Capacitance

- Condenser (Capacitor) is the electric element used to represent the charge storage and, consequently, energy stored in the electric field.



The capacitive effect may be thought of as opposing a change in current.

- As expressed quantitatively, the current through the element is proportional to the derivate of voltage across it:

$$i = C\frac{du_C}{dt}$$

- Solving for the voltage, yields: $$u_C = \frac{1}{C}\int i\,dt = \frac{Q}{C}$$ and: $$C = \frac{Q}{u_C}$$

- The proportionality constant *C* express the charge-storing property of the element and is called the *capacitance* of the element. With *Q* in coulombs and *u* in volts, the capacitance is in farads, *F*. Because a farad is physically a large unit, capacitance is frequently expressed in *mF*, *µF*, *pF*.
- A condenser (capacitor) is a physical element which exhibits the property of capacitance.

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Michael Faraday (1791–1867), an English chemist and physicist, was probably the greatest experimentalist who ever lived.

Born near London, Faraday realized his boyhood dream by working with the great chemist Sir Humphry Davy at the Royal Institution, where he worked for 54 years. He made several contributions in all areas of physical science and coined such words as electrolysis, anode, and cathode. His discovery of electromagnetic induction in 1831 was a major breakthrough in engineering because it provided a way of generating electricity. The electric motor and generator operate on this principle. The unit of capacitance, the farad, was named in his honor.

- The power associated with a capacitance is:

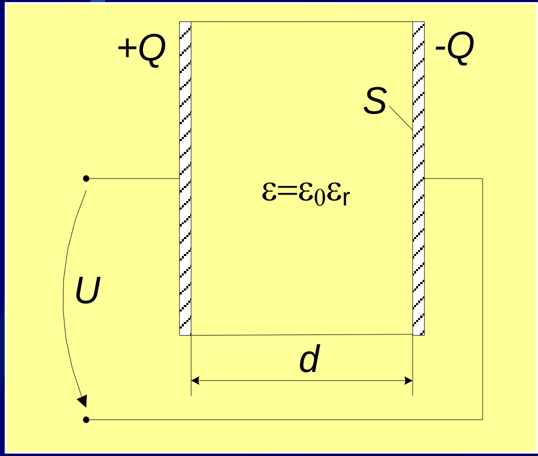
$$p = u_C i = C u_C \frac{d u_C}{d t} \; [W]$$

- The energy stored in the electric field is:

$$W_C = \int p\, dt = \int C u_C \frac{d u_C}{d t} dt = \int C u_C \, du_C = \frac{1}{2} C u_C^2 \; [J]$$

- The value of the energy stored in the capacitance is dependent only on the voltage magnitude and not on the moment of reaching that magnitude.
- The energy stored in the electric field can be also written in the form:

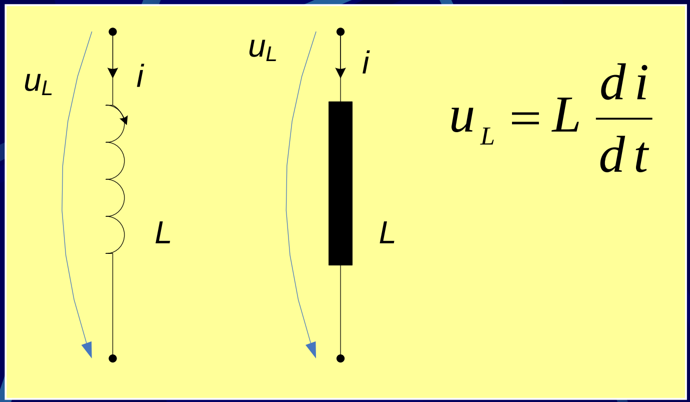
$$W_C = \frac{1}{2} C u_C^2 = \frac{1}{2} Q u_C = \frac{1}{2} \frac{Q^2}{C} \; [J]$$



- In the simplest form a capacitor is constructed by forming a pair of metal plates separated by an insulator material (dielectric). Practical capacitors employ variety of geometries and dielectrics to provide a wide range of capacitance values, usually from a few pico farads to one farad. However, as a given capacitor cannot store an arbitrary amount of energy, the maximum voltage which may exist across the capacitor terminals is limited. Exceeding the maximum voltage rating causes permanent damage to the capacitor as a result of dielectric breakdown.

Inductance

- Inductor (coil) is the electric element used to represent the energy stored in the magnetic field.



The inductive effect may be thought of as opposing changes in the velocity of flow of charge.
Inductance prevents the current from changing instantly.

- As expressed quantitatively, the voltage across the element is proportional to the time rate of change of current through it:

$$\boxed{u_L = L\frac{di}{dt}}$$

- The constant of proportionality *L* is the *self-inductance*, or simply the *inductance* of the element, and is measured in *henrys, H*.
- The voltage u_L is a voltage drop in the direction of the current and can be considered to oppose an increase in current.
- A coil (inductor) is a physical element which exhibits the property of inductance.

Joseph Henry (December 17, 1797 – May 13, 1878) was an American scientist who served as the first Secretary of the Smithsonian Institution, as well as a founding member of the National Institute for the Promotion of Science, a precursor of the Smithsonian Institution. He was highly regarded during his lifetime. While building electromagnets, Henry discovered the electromagnetic phenomenon of self-inductance. He also discovered mutual inductance independently of Michael Faraday, though Faraday was the first to publish his results. Henry developed the electromagnet into a practical device. He invented a precursor to the electric doorbell (specifically a bell that could be rung at a distance via an electric wire, 1831) and electric relay (1835). The SI unit of inductance, the henry, is named in his honor. Henry's work on the electromagnetic relay was the basis of the practical electrical telegraph, invented by Samuel Morse and Charles Wheatstone separately.

- Solving for the current, yields: $$i = \frac{1}{L}\int u_L \, dt$$
- The equation shows that inductance current depends not on the instantaneous value of the voltage but on the its past history, that is, on the integral or sum of the volt-second products for all time prior to the time of interest. For many application, where knowledge of an inductance current following a switching process (usually occurring at an arbitrary time called t=0) is desired, the previous equation may be written in the form:

$$i = \frac{1}{L}\int_0^t u_L \, dt + i(0)$$

where i(0) is the current existing at the time of switching and is a measure of the past history of the inductance prior to the switching process.

- The power associated with the inductive effect in a circuit is:

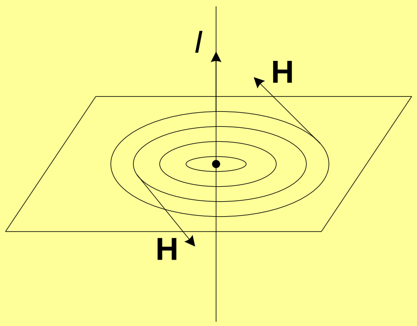
$$p = u_L \, i = L\, i \frac{d\,i}{d\,t} \; [W]$$

- The energy stored in the electric field is:

$$W_C = \int p \, dt = \int L\, i \frac{d\,i}{d\,t} dt = \int L\, i \, di = \frac{1}{2} L\, i^2 \quad [\,J\,]$$

- The value of the energy stored in the inductance is dependent only on current and not on the manner of reaching that magnitude.

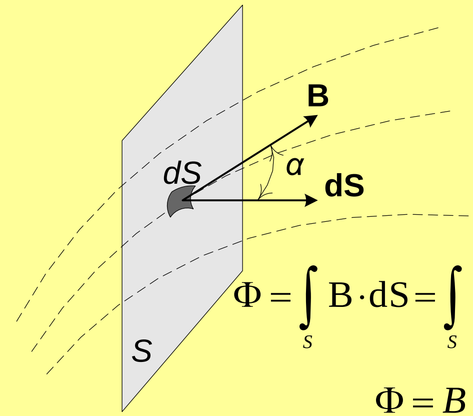
The magnetic field



$$H = \frac{I}{2\pi r}$$

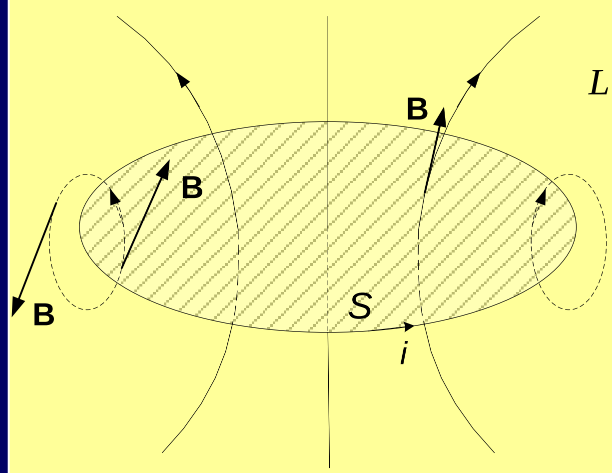
$$\mathbf{B} = \mu_0 \mathbf{H}$$

$$\mu_0 = 4\pi \cdot 10^{-7}\ H/m$$

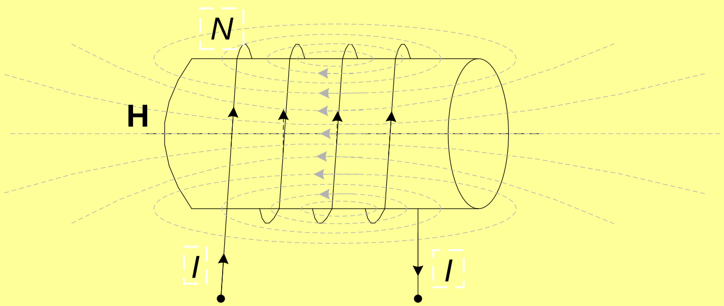


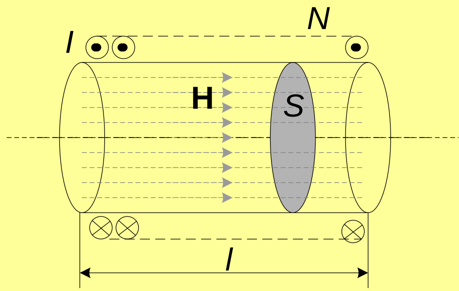
$$\Phi = \int_S \mathrm{B} \cdot \mathrm{dS} = \int_S B \cdot dS \cdot \cos\alpha\ [Wb]$$

$$\Phi = B \cdot S$$

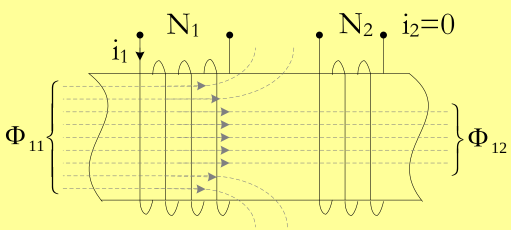


$$L = \frac{\Phi}{i}\ [H]$$

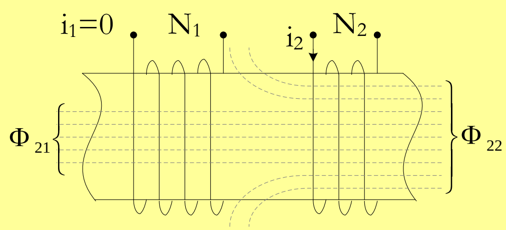




$$L = \frac{\Psi}{i} \qquad L = N\frac{\Phi}{i} \qquad L = \mu_0 \mu_r \frac{N^2 S}{l} = \mu \frac{N^2 S}{l}$$

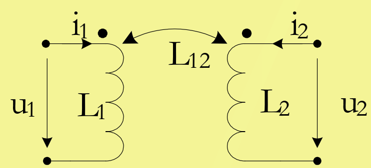


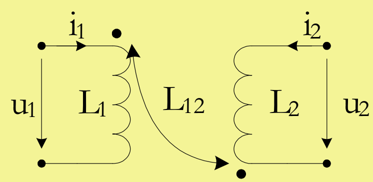
a)



b)

$$\Psi_1 = N_1\left(\Phi_{11} + \Phi_{21}\right) = L_1 i_1 \pm L_{21} i_2 \qquad \Psi_2 = N_2\left(\Phi_{22} + \Phi_{12}\right) = L_2 i_2 \pm L_{12} i_1$$





$$u_{L1} = \frac{d\Psi_1}{dt} = L_1\frac{di_1}{dt} + L_{21}\frac{di_2}{dt}$$

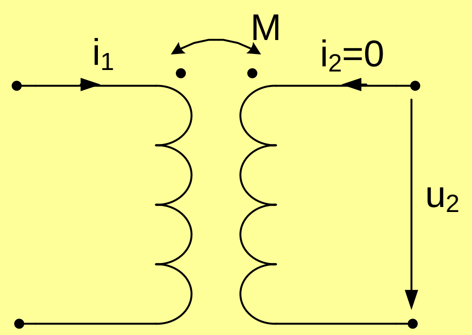
$$u_{L2} = \frac{d\Psi_2}{dt} = L_2\frac{di_2}{dt} + L_{12}\frac{di_1}{dt}$$

$$u_{L1} = \frac{d\Psi_1}{dt} = L_1\frac{di_1}{dt} - L_{21}\frac{di_2}{dt}$$

$$u_{L2} = \frac{d\Psi_2}{dt} = L_2\frac{di_2}{dt} - L_{12}\frac{di_1}{dt}$$

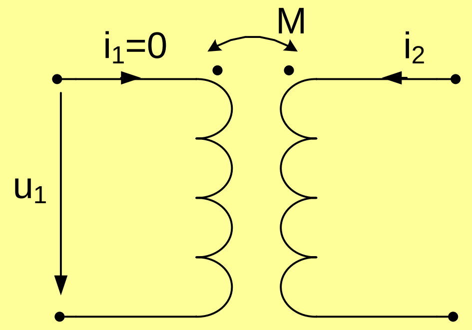
Mutual inductance

- The self-inductance of the circuit is associated with the magnetic field linking the circuit. The self-inductance voltage may be thought of as the voltage induced in the circuit (in the coil) by a magnetic field produced by the circuit current.
- Since a magnetic field exists in the region around the current which produced it, there is also a possibility that a voltage may be introduced in other circuits linked by the field.
- Two circuits linked by the some magnetic field are said *to be coupled* to each other.
- The circuit element used to represent magnetic coupling is called *mutual inductance, M*. Like self-inductance, is measured in *henrys*, *H*.
- The volt-ampere relationship is one which gives the voltage induced in one circuit by a current in another. For the circuit below we have:



$$u_2 = M\frac{di_1}{dt}$$

- A similar equation can, of course, be written giving a voltage u_1 induced by a current i_2.

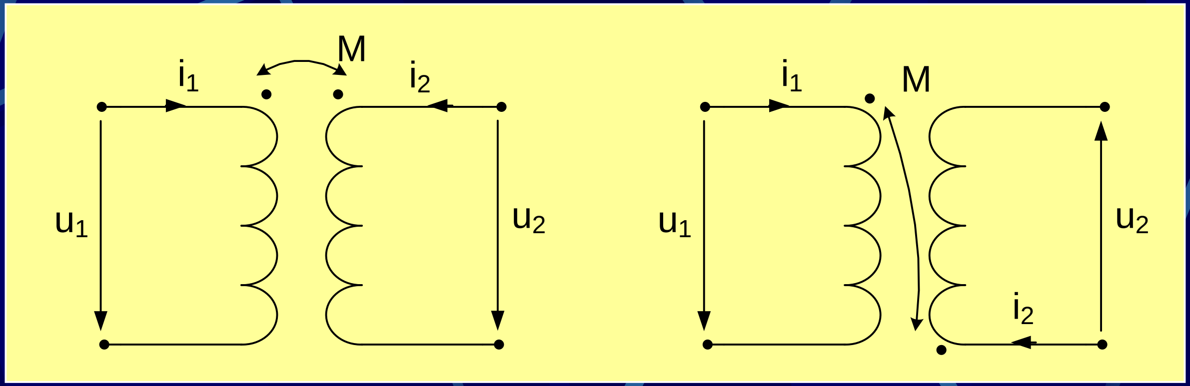


$$u_1 = M\frac{di_2}{dt}$$

- The two dots, called *polarity markings*, are used to indicate the direction of the magnetic coupling between the two coils.
- If currents are present in both coupled circuits, voltage of self-inductance and mutual inductance are induced in each circuit (in each coil). We nave yhe next convention:
  - if the currents direction through the polarity markings is the same, the coupling is considered positive;
  - If the currents have opposite direction through the polarity markings, the coupling is considered negative.
- Coupling between two closed circuits (coils) permits the transfer of energy between the circuits through the medium of the mutual magnetic field. This phenomenon is the basis on which all transformers operate.

- For a positive coupling, we have:

$$u_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$$
$$u_{L2} = L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$



- For a negative coupling, we have:

$$u_1 = L_1 \frac{di_1}{dt} - M \frac{di_2}{dt}$$
$$u_{L2} = L_2 \frac{di_2}{dt} - M \frac{di_1}{dt}$$