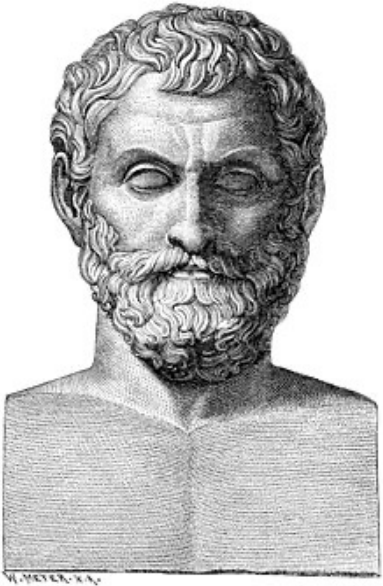


Historical Development of Interest In Electric(tronic)s

And the role played by understanding different materials

What is electric charge ?

Charge (q): It is an indivisible physical property which bears a force upon interaction with an electromagnetic field. Electrons are taken to be negatively charged and protons positively charged (convention).



Thales Miletus 400 – 600 BC

Amber and Fur are inanimate objects having soul



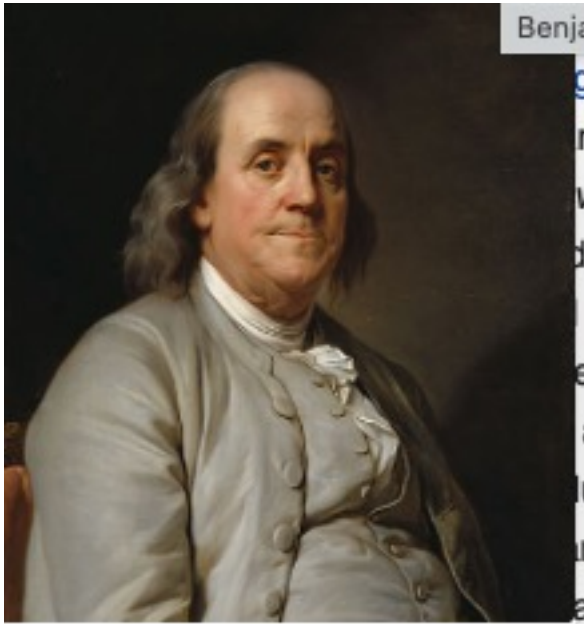
In 1600 **William Gilbert** coins the term *electrica* from Greek word *electron* for Amber



1729 The 'electron' in the Amber-fur flown across distances [Stephen Gray]

1733 Almost all materials can collect electrons by rubbing, other than metals! – C. Fay

Benjamin Franklin



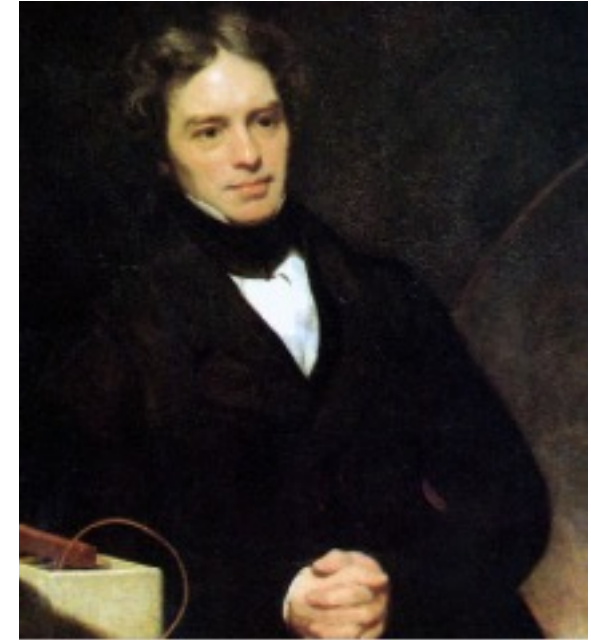
1750 – Rubbing glass with rubber develops equal 'electrons' on both and there exists attractive force. So two kinds of charges – B. Franklin

Alexandra Volta



1800 – Charges can be made to flow in a continuous loop. Alexander Volta

Michael Faraday

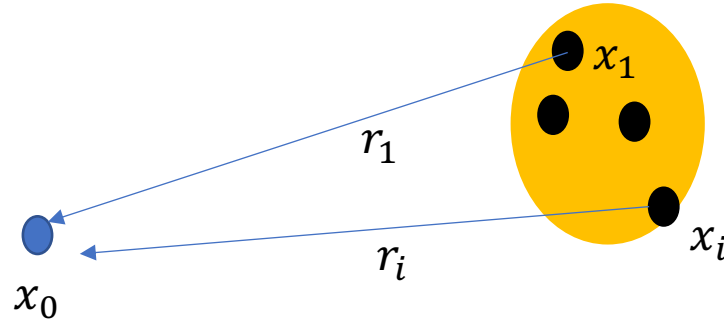


1833- 1838 There are only two kinds of charges. They are independent on its prepared. There is a force of attraction between the two kinds and they want to intermix in normal materials. When you rub one against other, the two types separate to different surfaces - M. Faraday

Charles Augustine Di Coulomb

In 1784:

- There exists a force between two charges
- The force was found to act on the line joining the charges, only either towards/away
 - Thereby giving only two kinds of charges
- The force is proportional to the number of charges
- The force is inversely proportional to the square of the distance between the two



Electric Field E : Force experienced by a unit positive charge

$$E = \frac{F}{q_0} = \frac{1}{4\pi\epsilon_0} \sum_i \frac{q_i}{(x_i - x_0)^2} \hat{r}_i$$



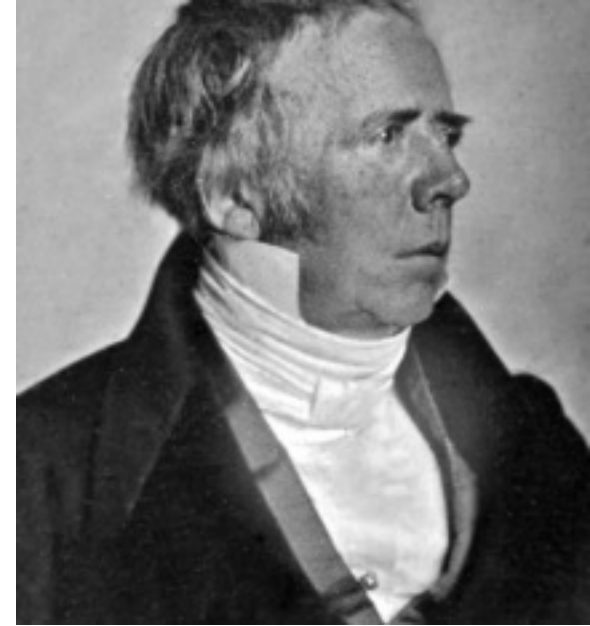
Charge Dynamics

- Force on a charge $F = qE$
- Forces causes charges to move,
- moving charges are called current from hydrodynamics.
- One defines current density $J = \frac{d\rho}{dt}$

1820 – Orsted - flowing charge affects compass. There is an induced magnetic field.

- Magnetic field lines encircle the wire carrying current
- lie perpendicular to the plane of the wire.

Ampere also introduced the equations for the magnetic field and current density called as the circuital law:



Forms of the original circuital law written in SI units

	Integral form	Differential form
Using B -field and total current	$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 \iint_S \mathbf{J} \cdot d\mathbf{S} = \mu_0 I_{\text{enc}}$	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$
Using H -field and free current	$\oint_C \mathbf{H} \cdot d\mathbf{l} = \iint_S \mathbf{J}_f \cdot d\mathbf{S} = I_{f,\text{enc}}$	$\nabla \times \mathbf{H} = \mathbf{J}_f$

James Clarke Maxwell



In dynamical theory of electromagnetic fields (1865)

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho \, dV$	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \left(\iint_{\Sigma} \mathbf{J} \cdot d\mathbf{S} + \varepsilon_0 \frac{d}{dt} \iint_{\Sigma} \mathbf{E} \cdot d\mathbf{S} \right)$	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$

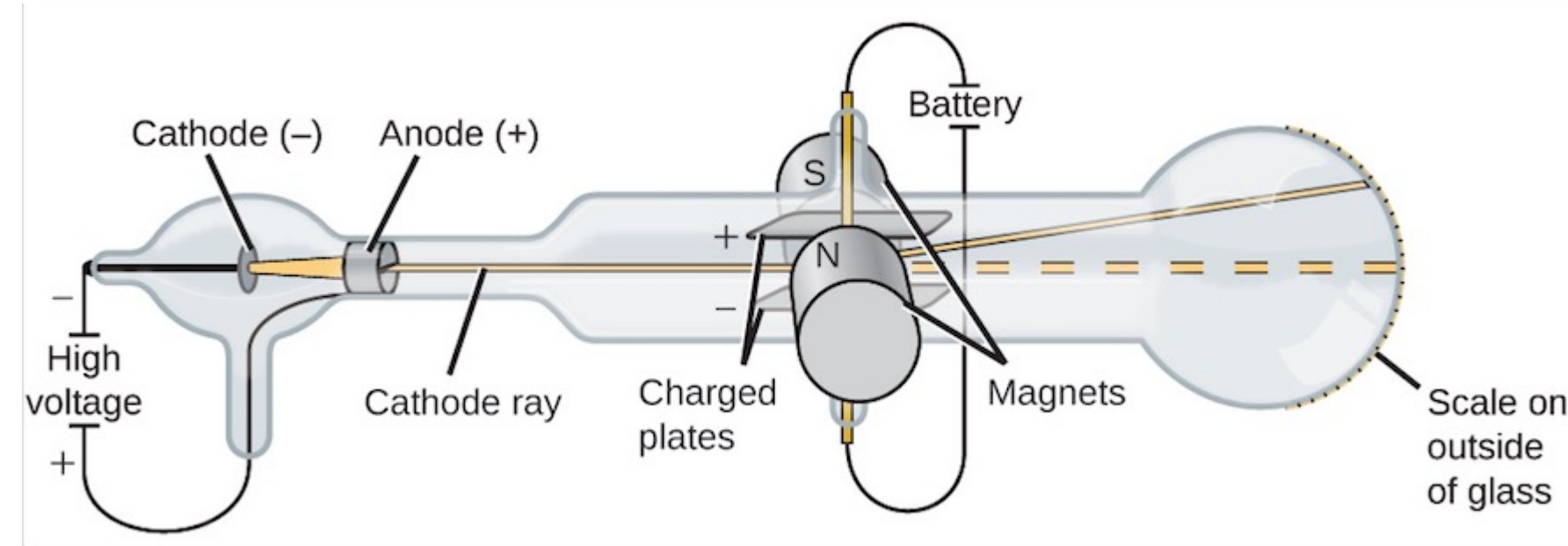
1. In any closed surface, the electric summation of the electric field lines is proportional to the charge density enclosed.
2. In any closed surface, the magnetic field summation should be zero. Or the net magnetic density should be zero. Or there cannot be a magnetic monopole
3. Say, I have a loop, enclosing a surface. If the magnetic field passing the surface changes, then a non-zero emf is induced in the loop.
4. If you have a non-zero field on a loop, you either have a current or a changing electric field line density in the surface enclosed.

Landmark experiments in Solid State Devices

- Thomson's Charge over mass: 1897



J J Thomson

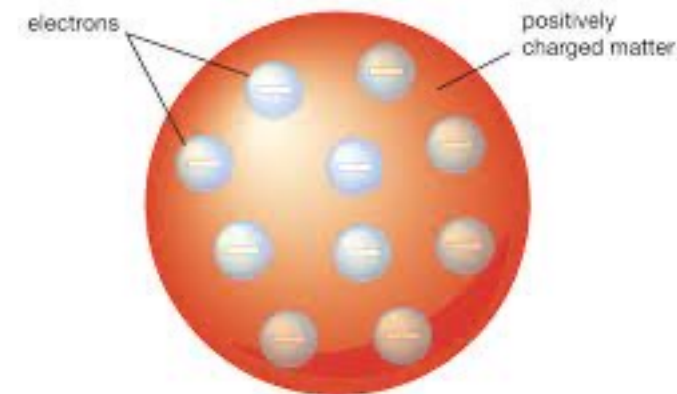


$$F = eE + ev \times B$$

$$y(t) = \frac{1}{2}at^2$$

$$a = \frac{eE}{m}$$

$$y(t) = \frac{1}{2} \frac{e}{m} Et^2$$



A black and white portrait of a middle-aged man with dark, wavy hair, wearing a dark suit, white shirt, and patterned tie. He is looking slightly to the right of the camera with a neutral expression. The background is a plain, light color.



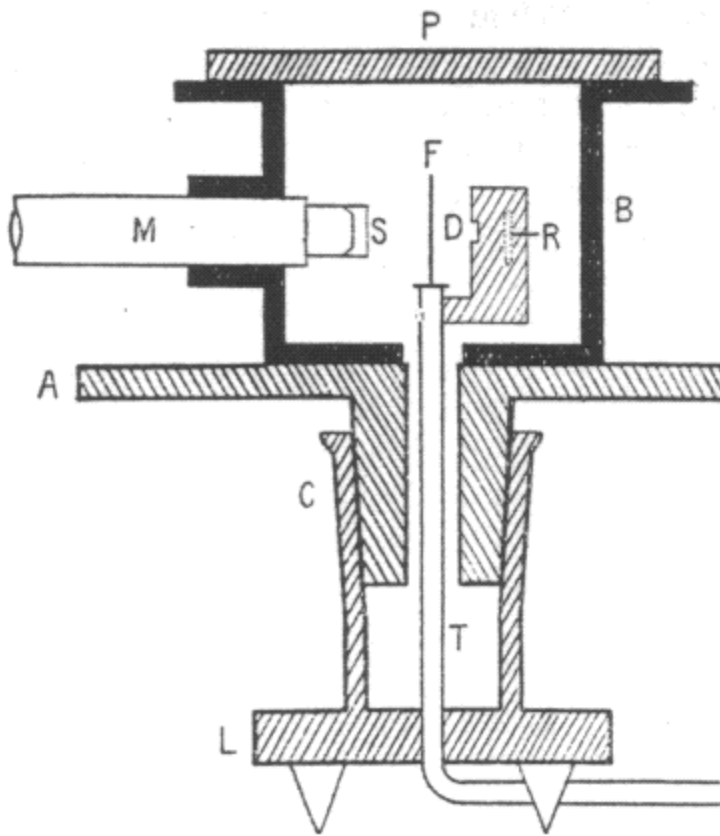
$$F_g = \frac{4}{3}\pi r^3(\rho - \rho_{air})g$$

$$eE = \frac{4}{3}\pi r^3(\rho - \rho_{air})g$$

Remember, No viscous drag for arrested particle!

Electronic charge was measured to an accuracy 1×10^{-24} C to be $1.5924(17) \times 10^{-19}$ C

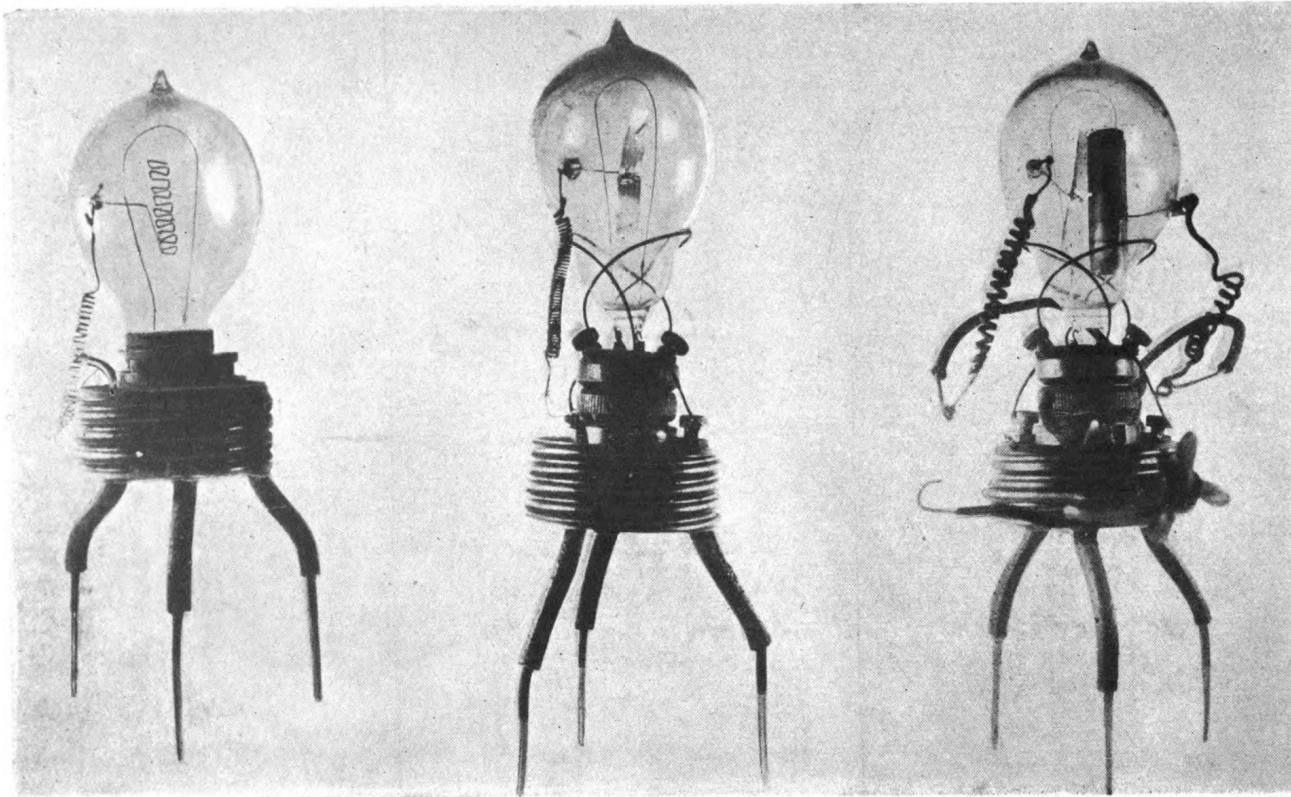
Rutherford, Geiger, Marsden Experiment: 1908



§ 1. It is well known that the α and the β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden** on the scattering of α rays indicate that some of the α particles, about 1 in 20,000 were turned through an average angle of 90 degrees in passing through a layer of gold-foil about 0.00004 cm. thick, which was equivalent in stopping-power of the α particle to 1.6 millimetres of air. Geiger*** showed later that the most probable angle of deflexion for a pencil of α particles being deflected through 90 degrees is vanishingly small. In addition, it will be seen later that the distribution of the α particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexion are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Vacuum Tube Rectifiers (1880 – 19--)

John Ambrose Fleming, Vacuum Tube based Rectifier



Can you think why it rectifies ?

Lenard's Photo electric experiments

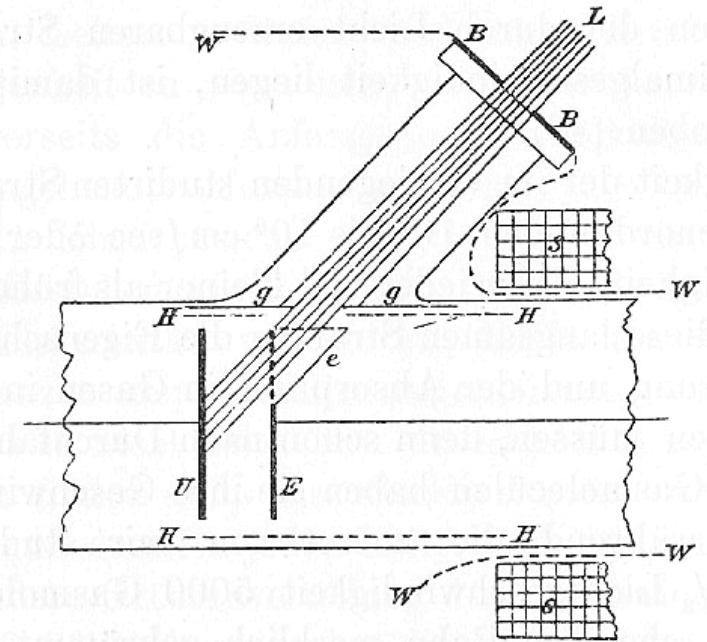


Fig. 1.

Current is proportional to wavelength and not intensity

Lenard's Photo electric experiments, 1899

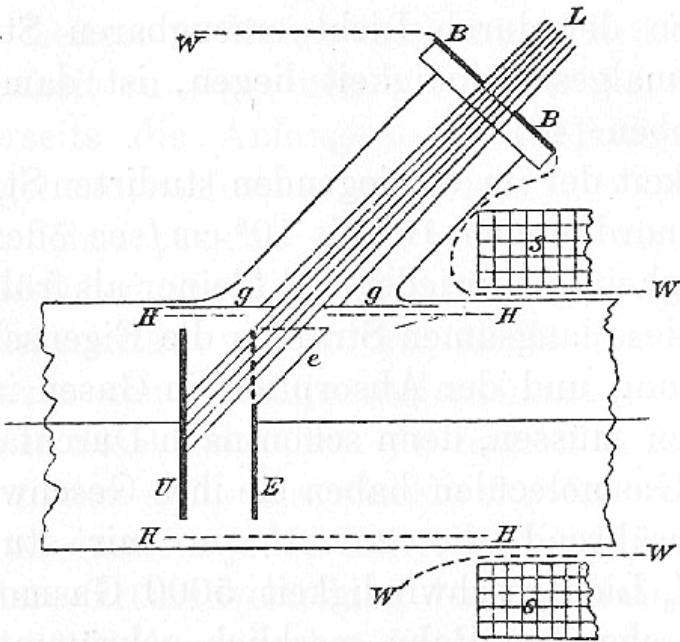
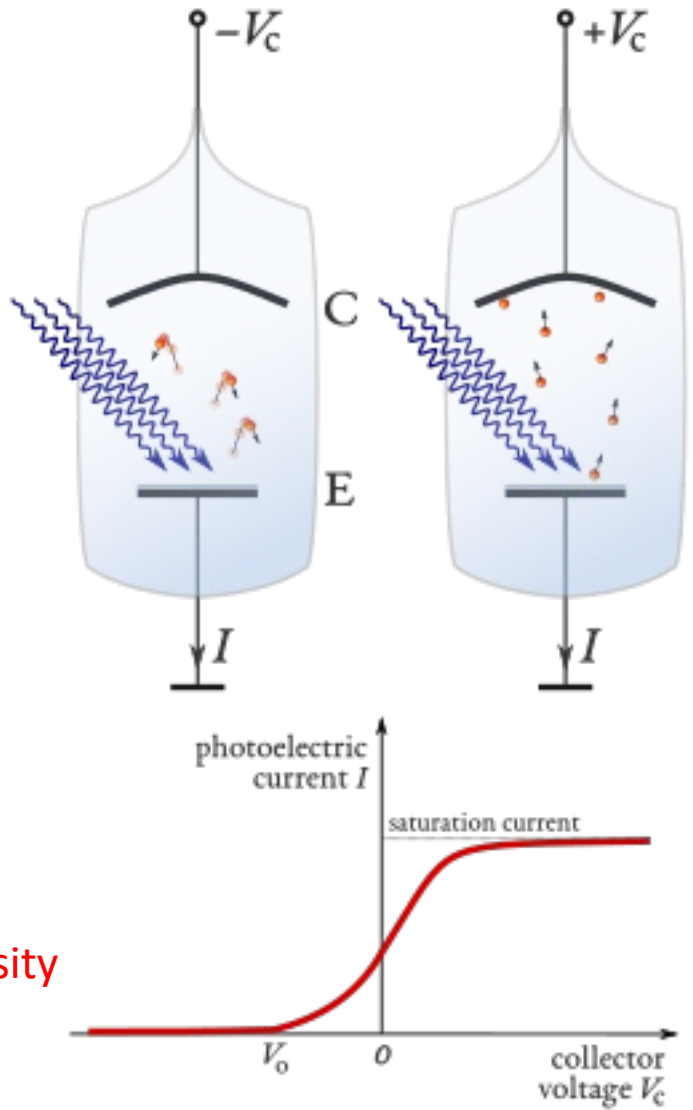


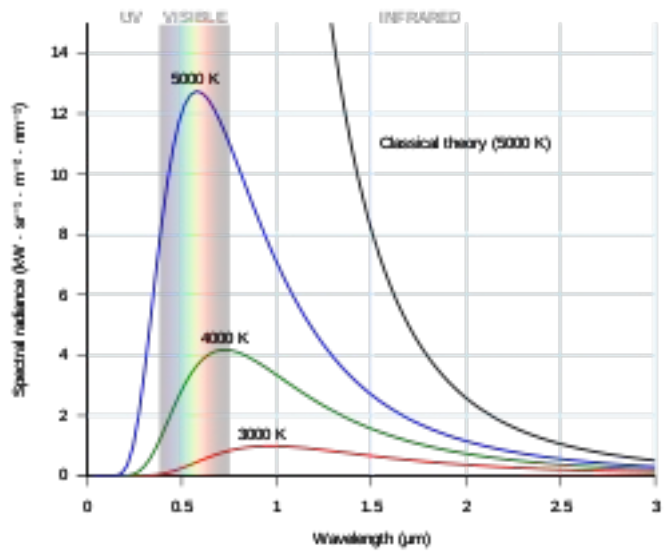
Fig. 1.

Current is proportional to wavelength and not intensity



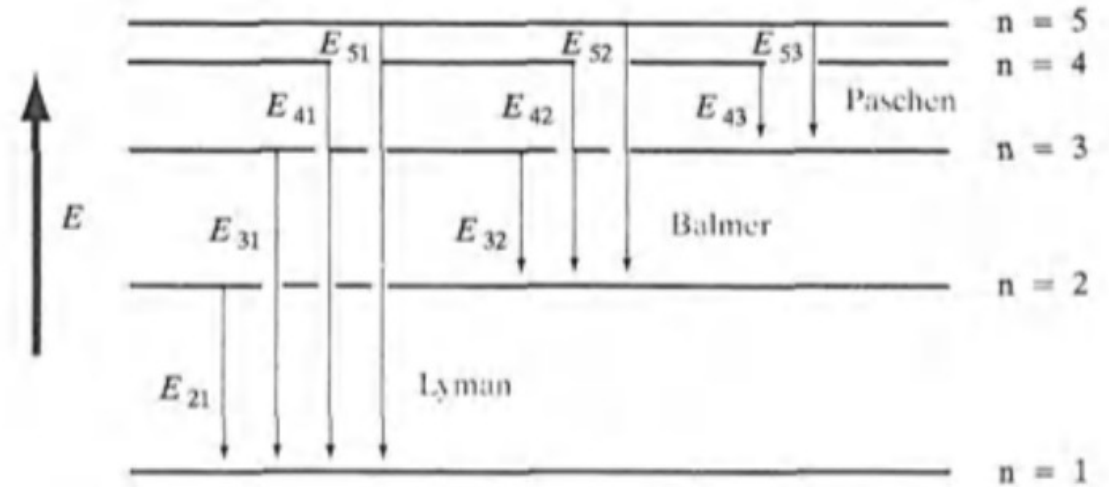
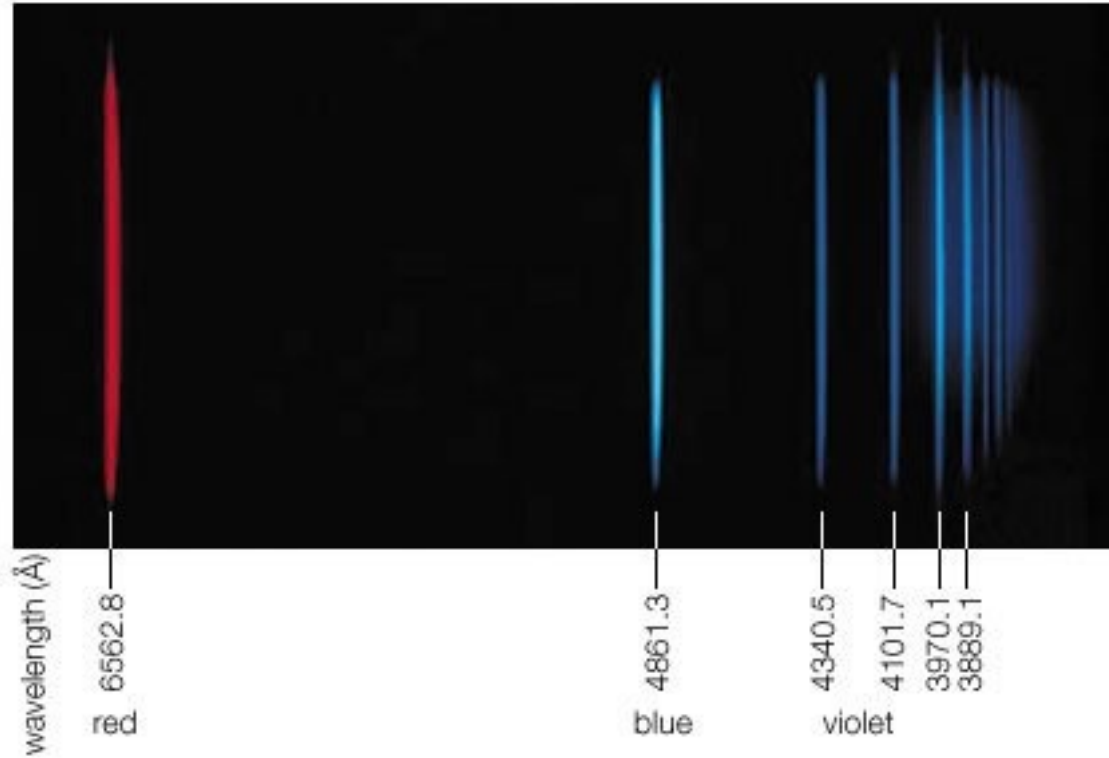
1905 Einstein 's photoelectric effect

Plank's black body radiation



Ultra-violet catastrophe

Atomic Lines of gases (1756 – 1855)

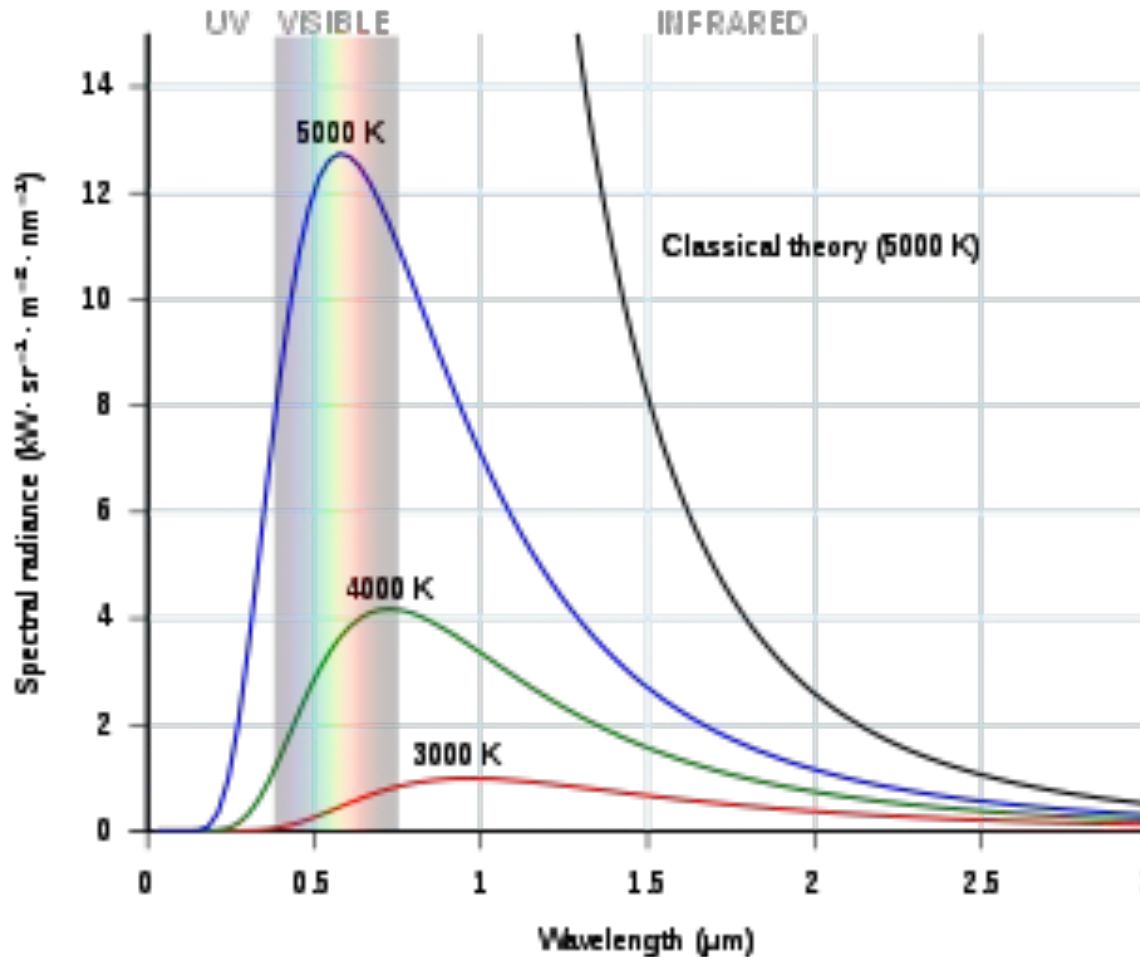


The Balmer series of hydrogen as seen by a low-resolution spectrometer.

Arthur L. Schawlow, Stanford University, and Theodore W. Hansch, Max Planck Institute for Quantum Optics

1900 Max Planck

Ultraviolet Catastrophe



Classical equipartition theorem

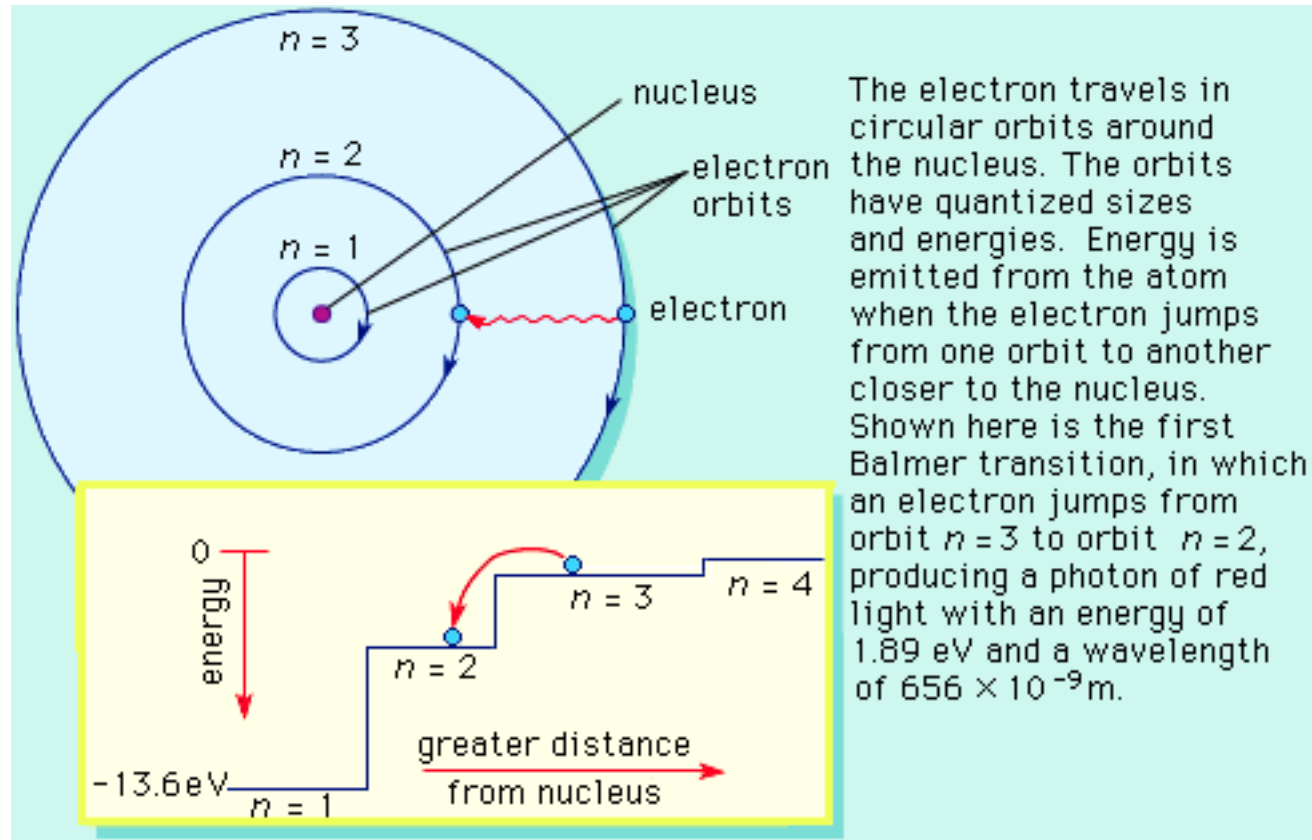
Rayleigh – Jean Law

$$B_{\lambda}(T) = \frac{2cK_B T}{\lambda^4}$$

Planck's weird particle law

$$B_{\lambda}(T) = \frac{2c^2 h}{\lambda^5} \left[\frac{1}{e^{\frac{hc}{\lambda K_B T}} - 1} \right]$$

Understanding the Atom (Neil Bohr 1913)



De Broglie

- Every particle with mass m moving with a velocity v , can be associated with a wave

$$\lambda = \frac{h}{p} = \frac{h}{mv} \sqrt{1 - \frac{v^2}{c^2}}$$

If, according to Bohr, the electrons are on orbits (of radius R), they must be standing waves.

$$n\lambda = 2\pi R$$

If we lose the relativistic correction

$$n\hbar = mvR = L$$

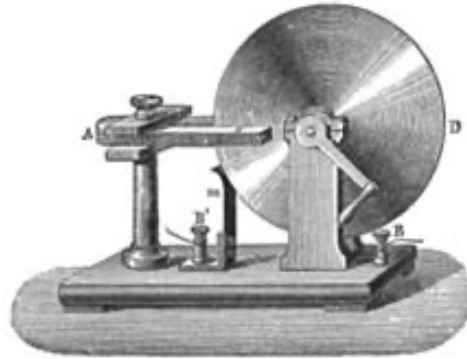
Where L is the angular momentum, and it can be seen that it is quantized!

Electrical Components



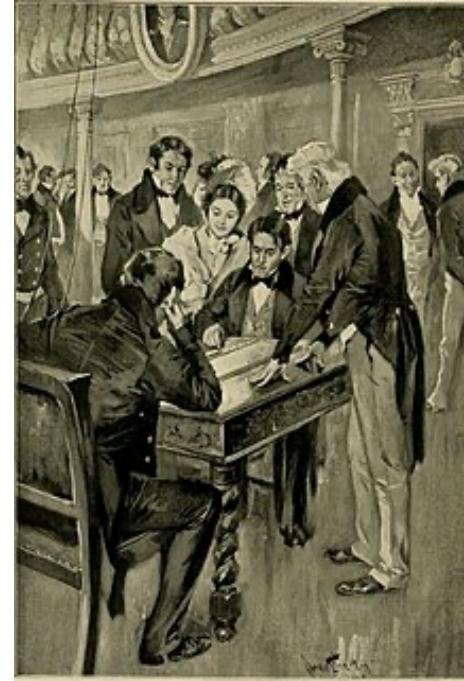
Leiden Jar, 1745

First notion of storage of charges,
First unit of capacitance was Jar.



Faraday's Motor, 1820

Faraday thought a wave will flow between two coils wound on an iron core when one of them is carrying current. He also saw that current can flow in the coil as the magnet/iron rod can be moved fast enough. Hence he name inductance, where the wave is induced.



Morse code, 1844
Transmission of electric signals on long wires to communicate information.



Marconi,
Bose Radio waves
1886-1888



Resistor



If there exists a current density (j) with smoothly varying electric field (E) across a segment,

$$J = \sigma E$$

Where σ is the conductivity [Sm^{-1}]
we define the potential

$$V = -\int E \cdot dl$$

Capacitor



A charge density ρ separated by a distance d [m] develops a potential difference

$$V = \frac{d\rho}{\epsilon}$$

Defining a capacitance density $C = \epsilon/d$ [F/m]

Current through the plates: $i = C \frac{dV}{dt} = C \int \frac{dE}{dt} dl$

Inductor



Correspondence: $I \leftrightarrow V$

$$V = L \frac{di}{dt} [\text{V}]$$

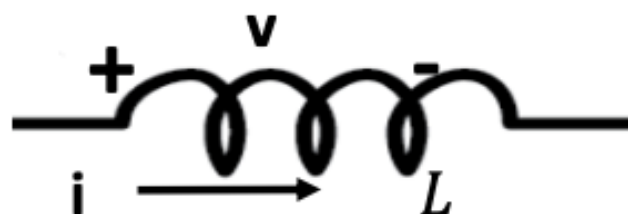
Faradays law : If magnetic flux is ϕ

$$V = -\frac{d\phi}{dt}$$

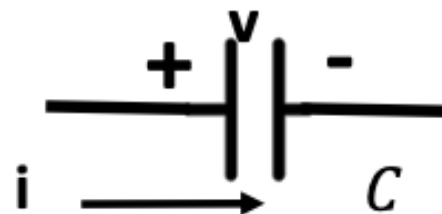
Power sources and elements



Resistor



Inductor



Capacitor

$$v = iR \text{ (Ohm's Law)}$$

$$p = vi = i^2 R = \frac{v^2}{R}$$

$$I(0) = 0 \rightarrow E = \frac{1}{2} LI^2$$

- Instantaneous change in I will lead to infinite power which is not possible
- $i(t)$ will be a continuous function

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

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

$$P(t) = L \cdot i(t) \frac{di(t)}{dt}$$

$$\begin{aligned} \int_0^t p(t) dt &= \int Li(t) di(t) = \frac{Li^2}{2} \Big|_{I(0)}^I \\ &= \frac{Li^2}{2} - \frac{Li(0)^2}{2} \end{aligned}$$

$$i(t) = C \frac{dv(t)}{dt}$$

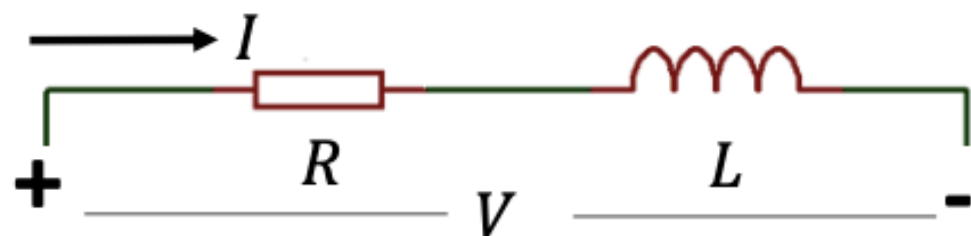
$$v(t) = \frac{1}{C} \int_0^t i(t) dt + v(0)$$

$$p(t) = Cv(t) \frac{dv(t)}{dt}$$

$$\begin{aligned} \int_0^t p(t) dt &= \int Cv(t) dv(t) = \frac{Cv^2(t)}{2} \Big|_{v(0)}^v \\ &= \frac{Cv^2}{2} - \frac{Cv(0)^2}{2} \end{aligned}$$

R,L vs R,C circuits

RL series circuit



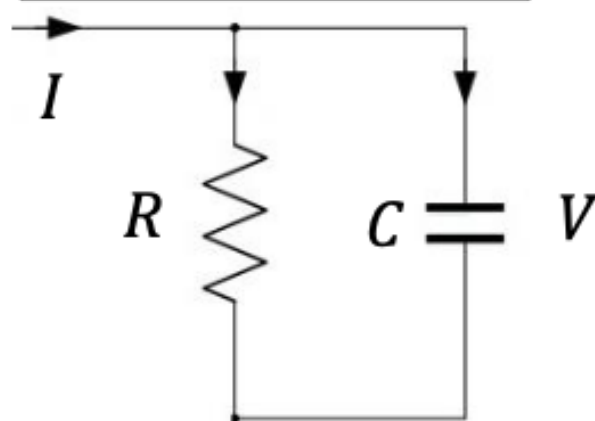
$$V = IR + L \frac{dI}{dt}$$

$$\frac{V}{L} = \frac{I}{L/R} + \frac{dI}{dt}$$

First order differential equations in I and V respectively

$$\tau = \frac{L}{R} \text{ or } RC$$

RC parallel circuit

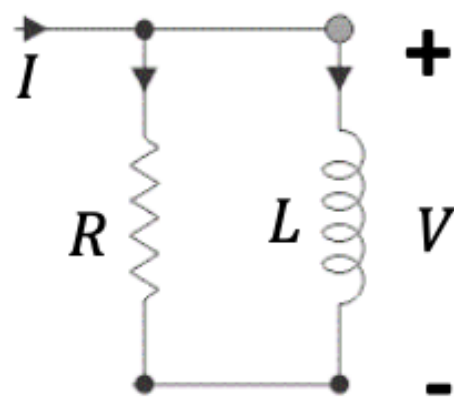


$$I = \frac{V}{R} + C \frac{dV}{dt}$$

$$\frac{I}{C} = \frac{V}{RC} + \frac{dV}{dt}$$

R,L vs R,C circuits

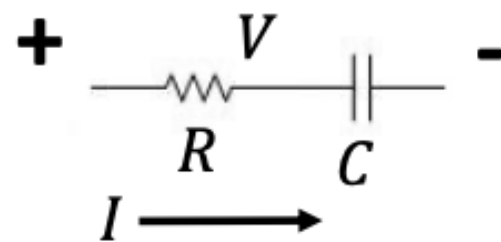
RL parallel circuit



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

$$V = L \frac{dI}{dt}$$
$$I(t) = \frac{V}{R} + \frac{1}{L} \int V dt$$
$$R \frac{dI}{dt} = \frac{dV}{dt} + \frac{V}{L/R}$$

RC series circuit



$$\tau = RC$$

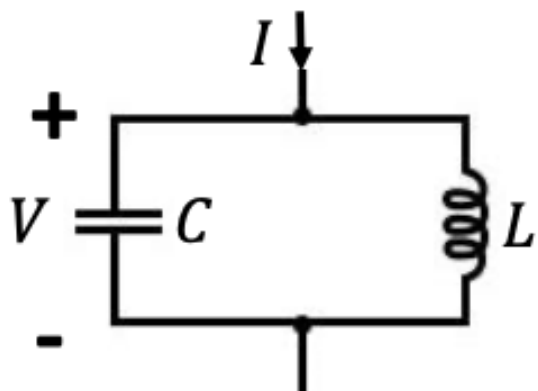
$$V(t) = IR + \frac{1}{C} \int I dt$$

$$\frac{dV}{dt} = R \frac{dI}{dt} + \frac{I}{C}$$

$$\frac{1}{R} \frac{dV}{dt} = \frac{dI}{dt} + \frac{1}{RC} I$$

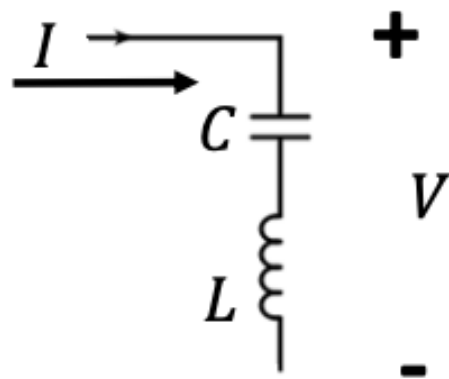
L ,C circuits

LC parallel circuit



$$V_L = L \frac{dI}{dt}$$
$$I(t) = \frac{1}{L} \int V dt + C \frac{dV}{dt}$$
$$\frac{1}{C} \frac{dI}{dt} = \frac{V}{LC} + \frac{d^2 V}{dt^2}$$

LC series circuit

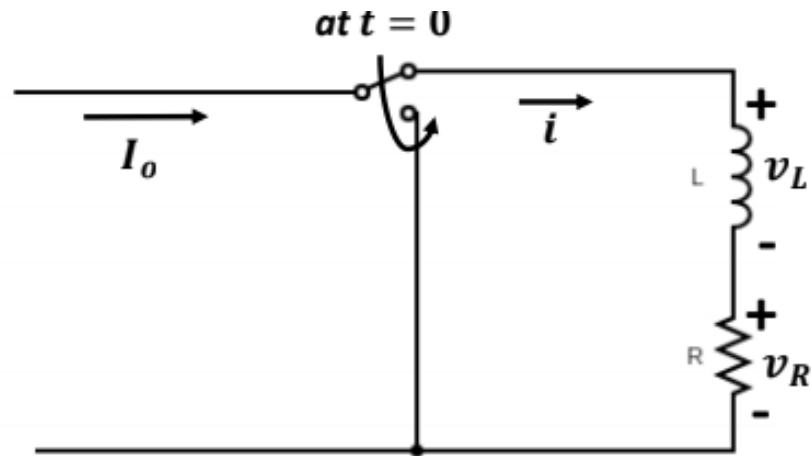


$$V(t) = L \frac{dI}{dt} + \frac{1}{C} \int I dt$$

$$\frac{dV}{dt} = L \frac{d^2 I}{dt^2} + \frac{I}{C}$$

$$\frac{d^2 I}{dt^2} + \frac{I}{LC} = \frac{1}{L} \frac{dV}{dt}$$

Circuits with passive components:

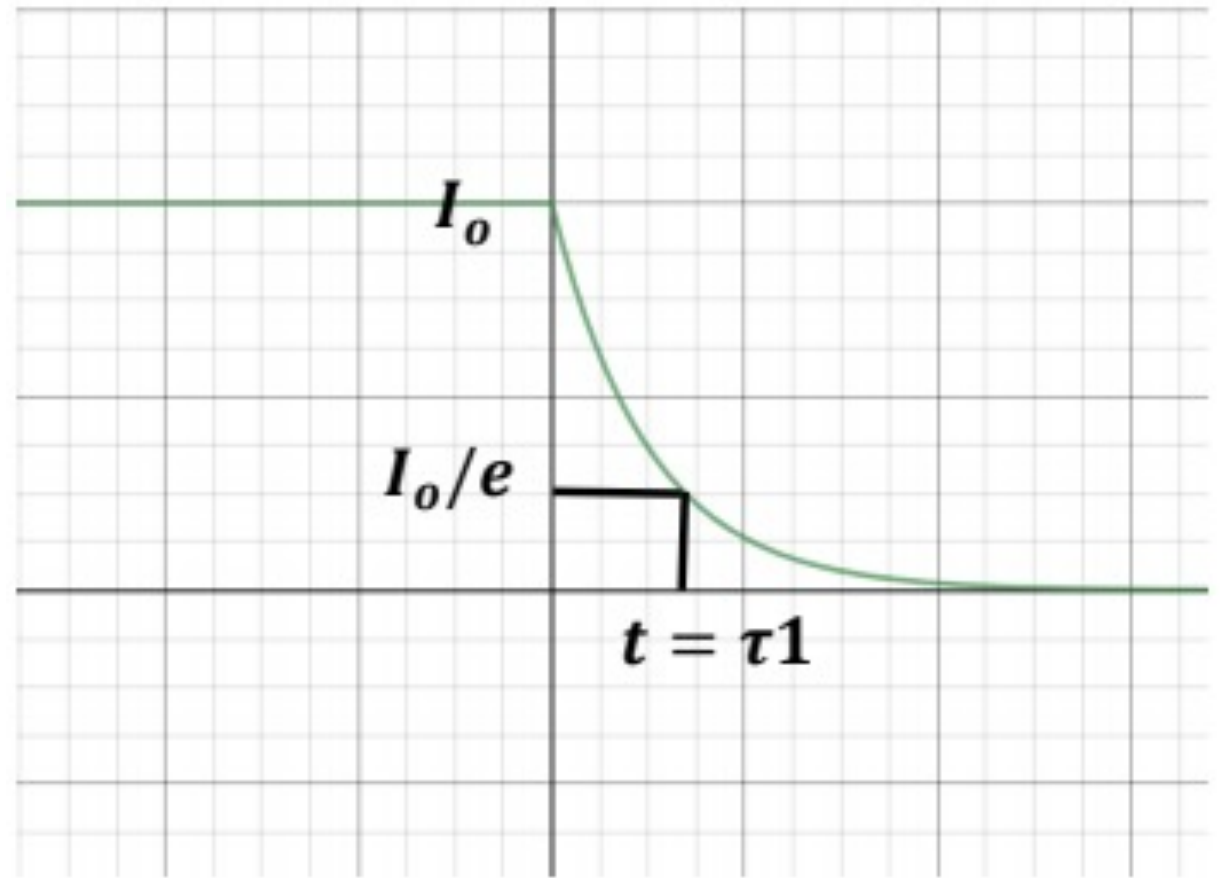


L carrying an initial current I_o .

Switch is closed at $t = 0$ and the energy dissipates through R .

By KVL,

$$v_L + v_R = 0$$
$$L \frac{di}{dt} + iR = 0$$
$$\frac{di}{dt} + \frac{i}{L/R} = 0$$



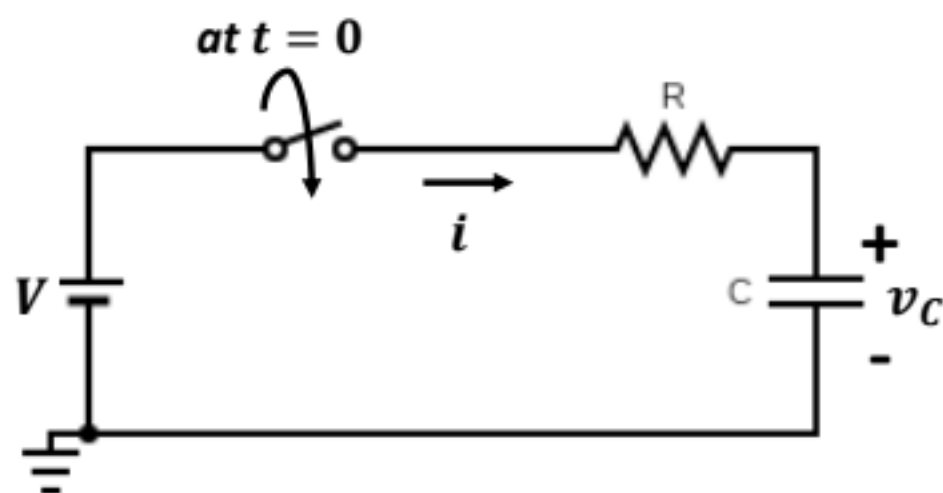
RC Circuit Step Response

Initial Condition: $v_C(0) = V_o$

$$V = iR + v_C ; i = C \frac{dv_C}{dt}$$

$$\Rightarrow V = RC \frac{dv_C}{dt} + v_C \quad \text{--- (1)}$$

$$\text{or } \frac{V}{RC} = \frac{dv_C}{dt} + \frac{v_C}{RC}$$



Let $\tau = RC$

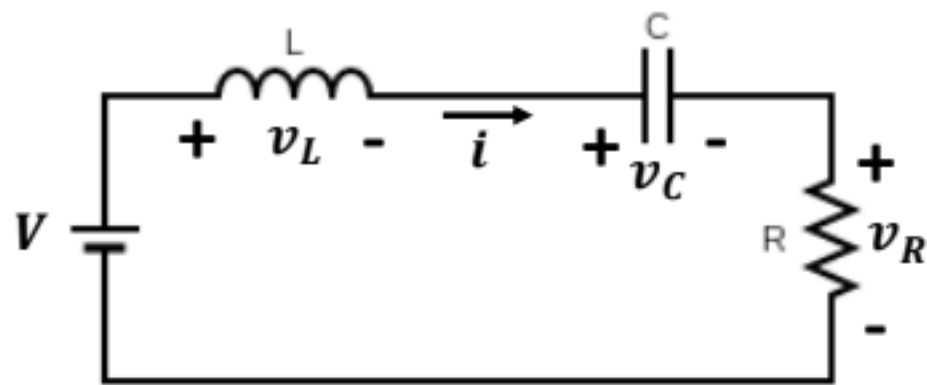
Series R,L,C Circuit

If $V = 0$, then:

$$L \frac{di}{dt} + v_C + iR = 0$$

$$\text{or } L \frac{d^2 i}{dt^2} + \frac{dv_C}{dt} + R \frac{di}{dt} = 0$$

$$\text{or } \frac{d^2 i}{dt^2} + \frac{R}{L} \frac{di}{dt} + \frac{i}{LC} = 0$$



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

Diodes – Nonlinearity of IV

- What are the fundamental properties of a diode?

- Two terminal device
- Non-linear
- Conducts in one direction.

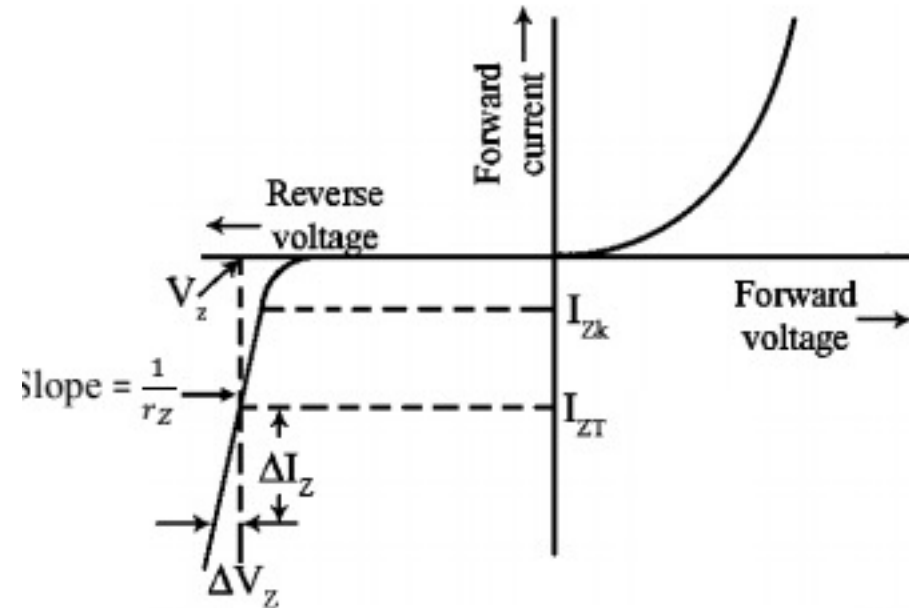
- $I = I_S \left[e^{\frac{V_D}{\eta V_T}} - 1 \right]$

- I_S depends on material, temperature

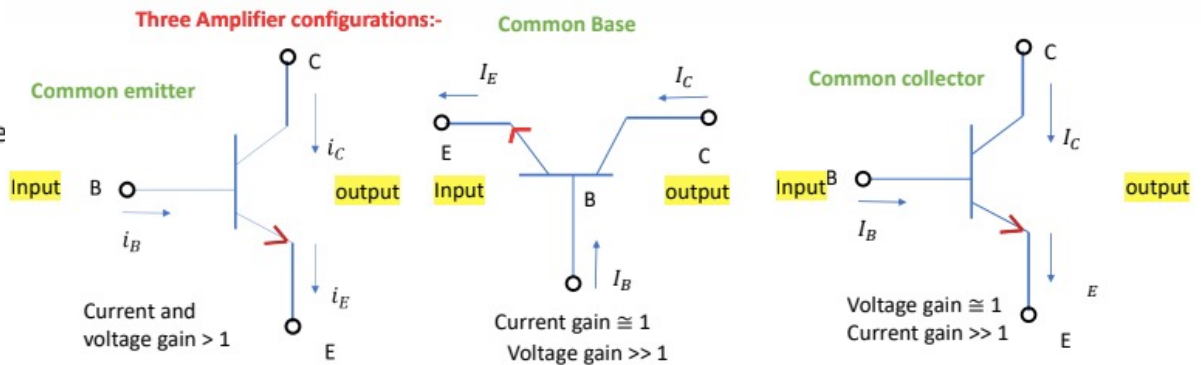
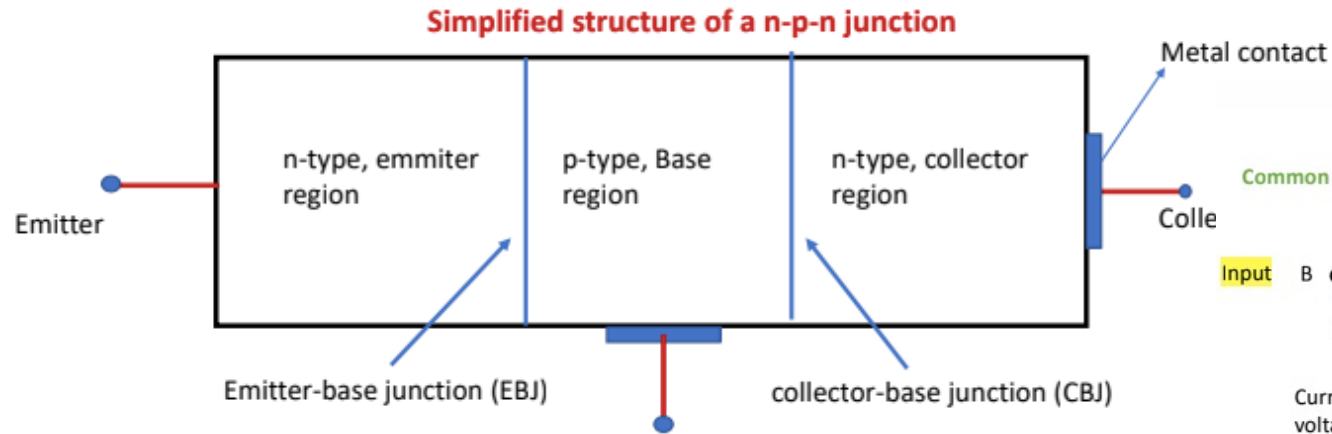
- In the on-state $r_D = \frac{\eta V_T}{I_D}$

- In the reverse bias,

$$\Delta V_Z = \Delta I_Z * r_Z$$



Bi-Polar transistors



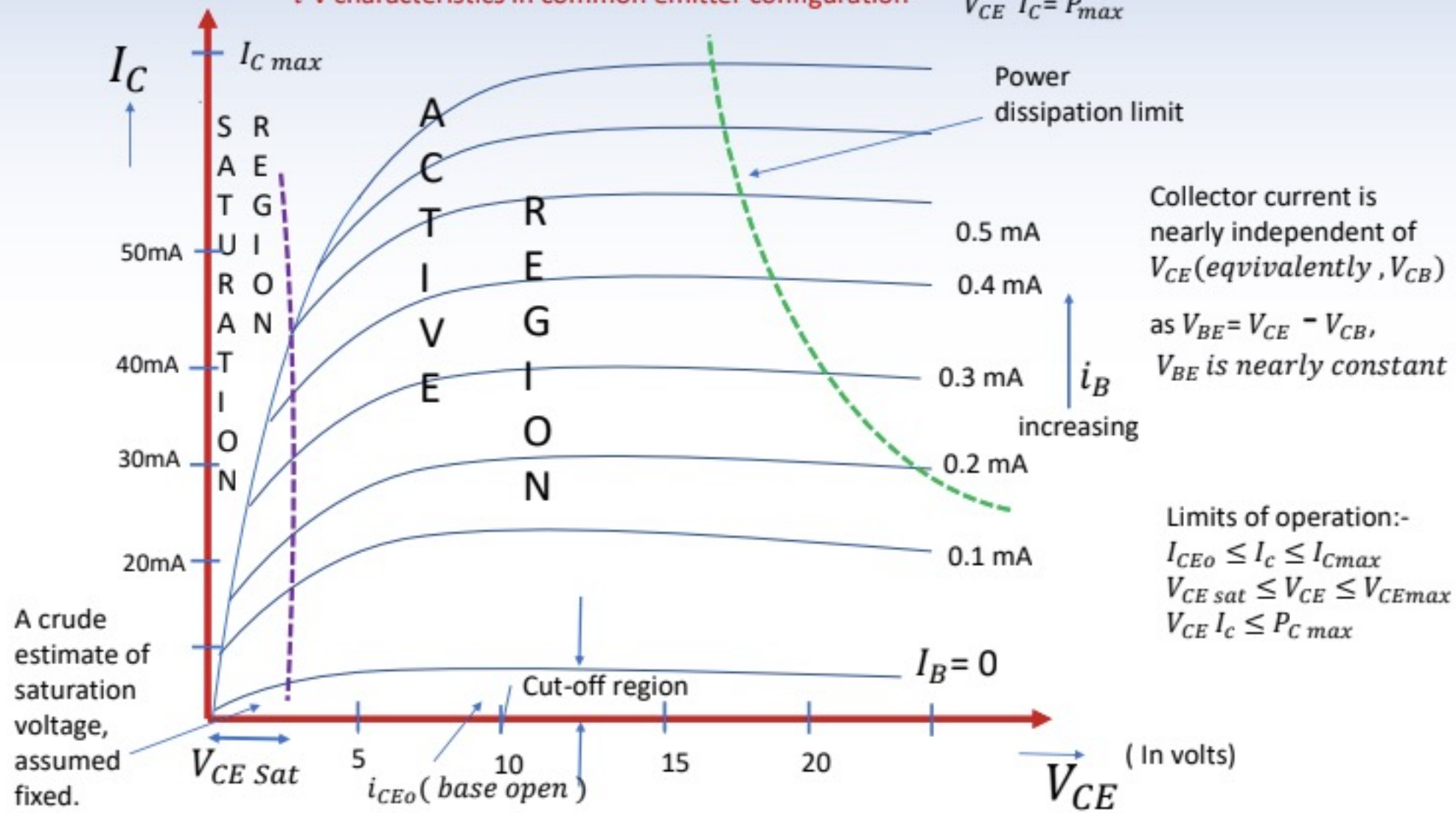
Mode	EBJ	CBJ	Application
Cut-off	Reverse	Reverse	Used as a switch
Saturation	forward	forward	Used as a switch
Active	forward	Reverse	Used as an amplifier
Reverse active	Reverse	Forward	Rarely used

$$\begin{aligned}
 I_E &= I_C + I_B \\
 I_C &= \beta I_B \\
 I_E &= (\beta + 1)I_B = \frac{I_C}{\alpha} \\
 \alpha &= \frac{\beta}{\beta + 1}
 \end{aligned}$$

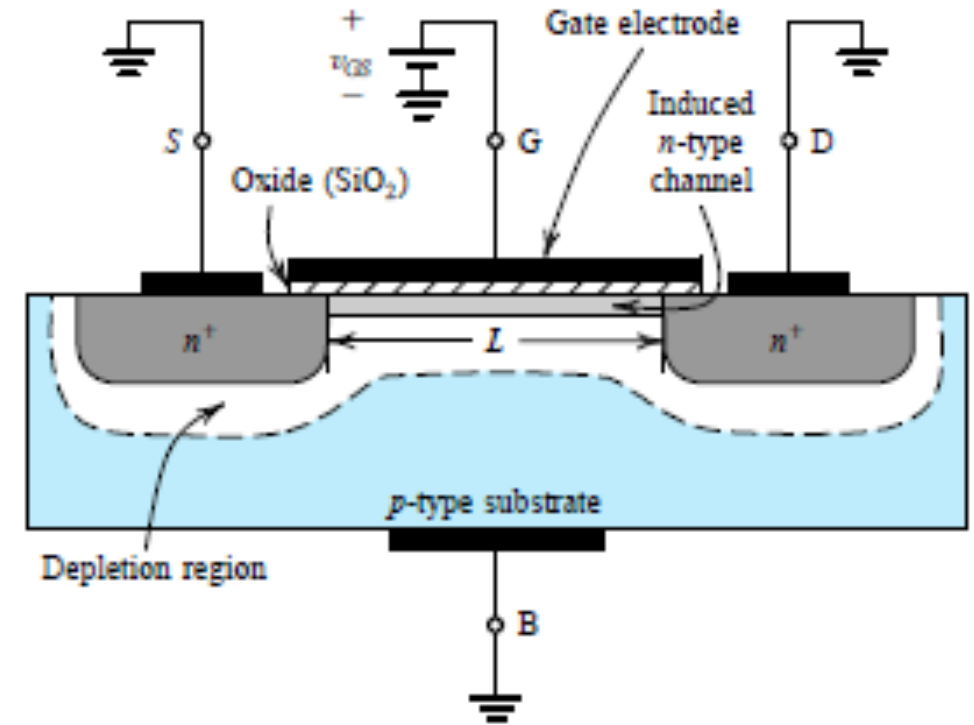
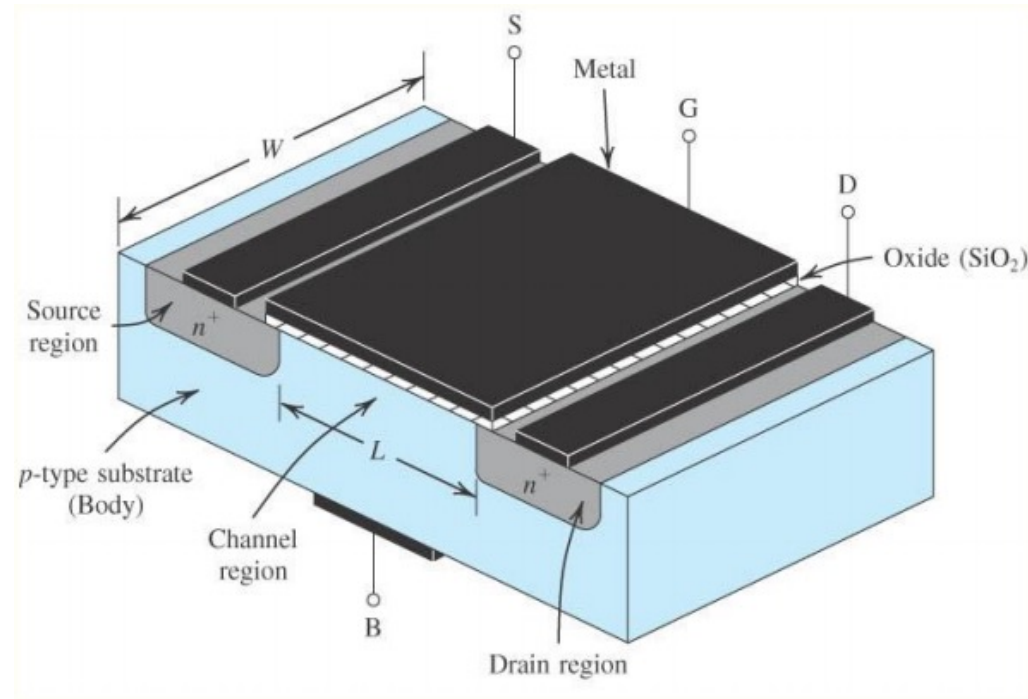
Power consumed is then
 $V_{CE}I_C + V_{BE}I_B$

i-v characteristics in common emitter configuration

$$V_{CE} I_C = P_{max}$$

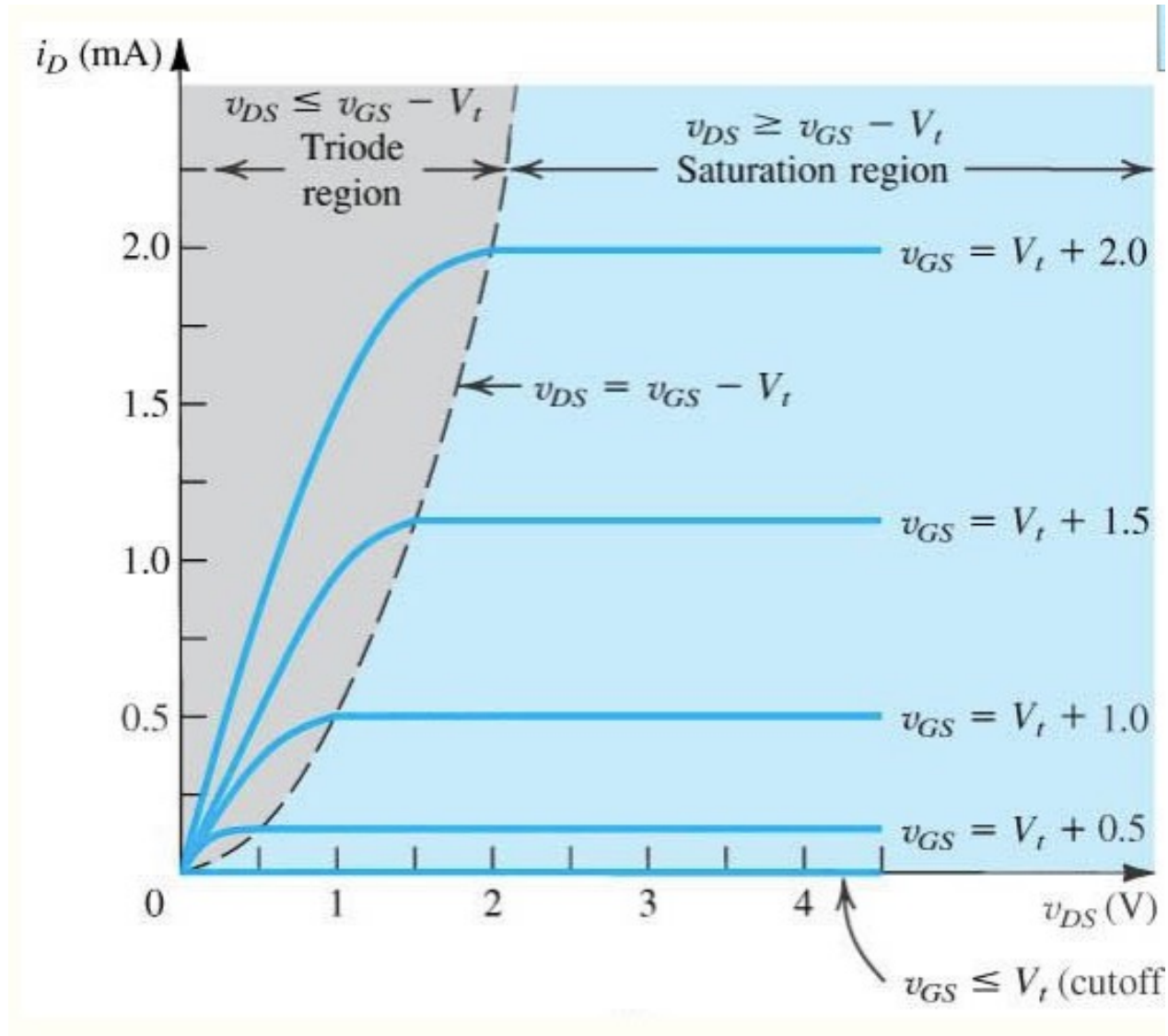


Metal-Oxide Semiconductor



5.2 The enhancement-type NMOS transistor with a positive voltage applied to the gate

MOSFET as a Switch



In the triode region

$$I_D = \frac{\mu C_{ox} W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

In saturation

$$I_D = \frac{\mu C_{ox} W}{L} (V_{GS} - V_T)^2$$

So what's so important about a switch ?

- Right, now we have a fancy switch. So, what ?
- One can do Logical operations with switches
- One can do arithmetic with logical operations
- With these two, one can watch Netflix!