Electronics :- Basic Blocks.

Switch. Amplifier

Signals :- ~~So~~ Electrical pulse that contains information.

Signal (generalized) :- Some indication.

Sending end and receiving end.

~~Can be~~ ~~de~~ Situation encoded from the sending end. to something. That something is called the signal and can be decoded at the receiving end.

The receiving end knows the mapping of the signal to the realistic situation or information.

For example.

green → okay.
orange → enemy approaching.
red → war has started.

Sending end.

receiving end. (He sees the colour of the smoke and sends help accordingly).

Here the signal is the colour of the smoke.

The receiving end knows how to decode the colour of the smoke. That is, he knows that red is war, etc. So, the sending end must have the knowledge how to encode an information or situation and the receiving end must know how to decode the information.

In electronics, the information is encoded in the form of electrical pulses or waves. ~~and the~~ Eg: ① When we click with a camera, the photo is ~~stored in the form of a~~ first transformed into an electrical quantity and then stored in a chip. When we open it in a computer, the computer knows how to read ~~the~~ or decode the information and visualize the photo in front of the viewer. Similar is the case for a audio system.

Noise: Wherever there is ~~signals~~ electrical signal, there is also provision to damage the signal via external ~~interf~~ electro-magnetic interference. This electrical or

electromagnetic interference is called noise.
For example: Lightening or thunderstrom destroys the clarity of radio voice. ~~Thunderstrom or light~~ or in older days they used to destroy the clarity of TV signals (when set-top box was not there), lightning creates noise in the analog TV signals and harms the clarity. These TV signals are also electrical waves or pulses.

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

$$I = A\cos\omega t$$

$$v = AR\cos\omega t - AL\omega\sin\omega t$$

$$= X\cos(\omega t + \theta).$$

$$X\cos\theta = AR \qquad X\sin\theta = AL\omega$$

$$X = \sqrt{A^2R^2 + A^2L^2\omega^2} = A\sqrt{R^2+\omega^2L^2}$$

$$\tan\theta = \frac{L\omega}{R}$$

sinusoidal steady state analysis

$$L \to j\omega L$$

$$R \to R$$

$$v = IR + j\omega L I = I(R + j\omega L)$$

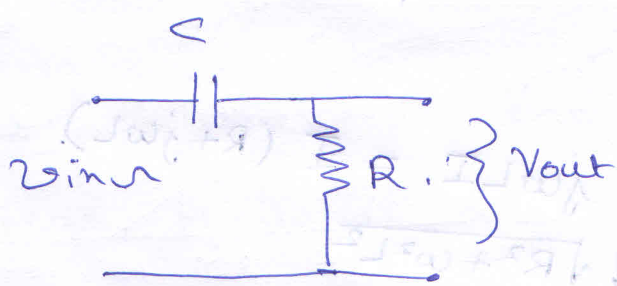
$$|v| = |I|\sqrt{R^2+\omega^2L^2}$$

$$\angle v = \angle I + \tan^{-1}\frac{\omega L}{R}.$$

<u>Filters</u>: What is a filter? It is something that ~~ka~~ takes out unwanted quantities from a desirable quantity. For example a water filter.

When we are transmitting signals it is common to use a range of frequencies while transmitting. For example, the different FM channels transmit over different frequency ranges. That is why these terms are popular like 101.7 Mhz. FM channel. In such cases at the receiving end, we must have something that can filter out the frequency around 101.7 Mhz and reject the rest. That is when we need filters to filter out the unwanted frequency ranges.

<u>Simplest filters</u>: RC and RL filters.



$\cancel{V_{out} = V_{in}}$

$$I = \frac{V_{in}}{R + \frac{1}{j\omega C}}$$

$$V_{out} = I \times R$$

$$= V_{in} \frac{R}{R + \frac{1}{j\omega C}}$$

$$= V_{in} \frac{jR\omega C}{jR\omega C + 1}$$

$$|V_{out}| = |V_{in}| \frac{R\omega C}{\sqrt{(R\omega C)^2 + 1}}$$

So, this acts as a high pass filter.

At $\omega \to 0$, $|V_{out}| \simeq 0$.

At $\omega \to \infty$, $|V_{out}| \simeq |V_{in}|$

This can be shown from there

$\angle V_{out} \to \frac{\pi}{2}$ at $\omega \to 0$.

$\angle V_{out} \to 0$ at $\omega \to \infty$.

You know that in a RL/RC circuit there is a phase lead or lag.

Intuitive reason: The capacitor acts as an open circuit at $\omega = 0$. So, ~~no~~. no voltage drops across the resistor. The capacitor acts as a short circuit at $\omega = \infty$. So, all the voltage drops across the resistor. This is called a first order filter.

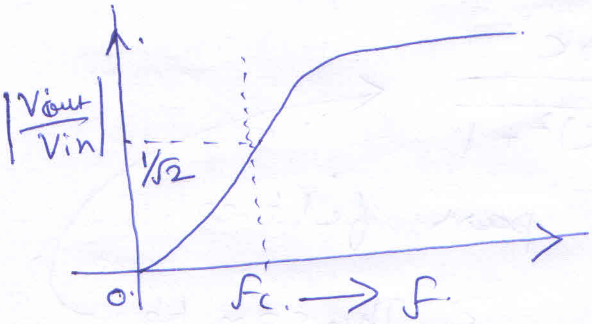
Cut-off Freq: The freq at which $\left|\frac{V_{in}}{V_{out}}\right|$ becomes $\frac{1}{\sqrt{2}}$ of its maximum value, which is 1.

$$\frac{R\omega C}{\sqrt{(R\omega C)^2 + 1}} = \frac{1}{\sqrt{2}}$$

$$\Rightarrow R\omega_c C = 1.$$

$$\Rightarrow \omega_c = \frac{1}{RC} \text{ is the cutoff freq.}$$

$$f_c = \frac{1}{2\pi RC}.$$



$$\angle A = \angle \frac{jR\omega C}{jR\omega C + 1}$$

$$= \angle jR\omega C - \angle jR\omega C + 1$$

$$= \frac{\pi}{2} - \tan^{-1} R\omega C$$

$$= \frac{\pi}{2} - \tan^{-1} \frac{\omega}{\omega_c}$$

$$= \frac{\pi}{2} \text{ at } \omega \to 0 \text{ and } 0 \text{ at } \omega \to \infty$$

<u>Bode plots:</u> $A = \frac{V_{out}}{V_{in}}$.

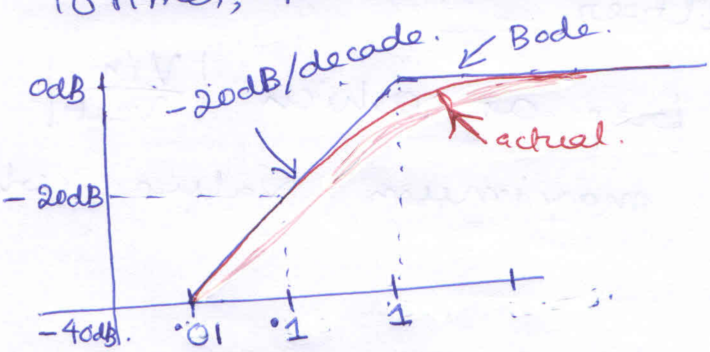
$$20\log_{10}|A| = 20\log_{10}\left|\frac{V_{out}}{V_{in}}\right| = 20\log_{10}\left|\frac{R\omega C}{\sqrt{(R\omega C)^2+1}}\right|$$

$$= 20\log_{10}\left|\frac{1}{\sqrt{1+\frac{1}{(R\omega C)^2}}}\right| = 20\log\frac{1}{\sqrt{1+\left(\frac{\omega_c}{\omega}\right)^2}}$$

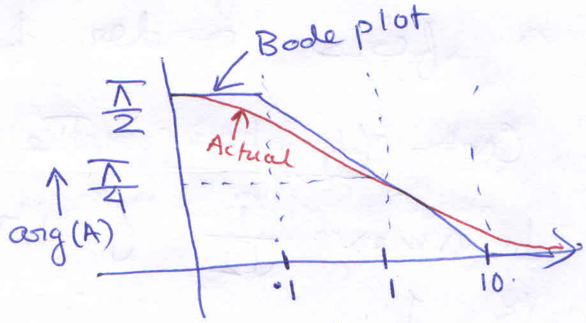
$$= -20\log_{10}\sqrt{1+\left(\frac{\omega_c}{\omega}\right)^2} \cong 0 \quad \text{when } \omega \to 0.$$

$$\cong 20\log\left(\frac{\omega}{\omega_c}\right) \quad \text{when } \omega \to \infty$$

When we draw the plot, we take ω_c as the transition point. The slope is 20dB/decade or 6dB/octave which means that as ω increases 10 times, A increases by 20.



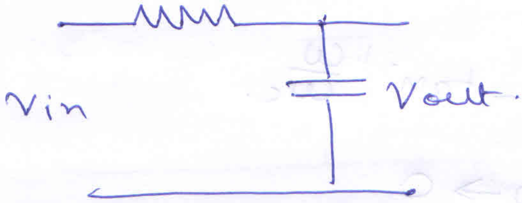
$\rightarrow \log\left(\frac{\omega}{\omega_c}\right)$.



$\rightarrow \log\left(\frac{\omega}{\omega_c}\right)$

Phase $= +\frac{\pi}{4}$ when $\omega = \omega_c$.

Low pass filter:-



$$\frac{V_{out}}{V_{in}} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}}$$

$$= \frac{1}{jR\omega C + 1}$$

$$|V_{out}| = \frac{1}{\sqrt{(R\omega C)^2 + 1}} |V_{in}|$$

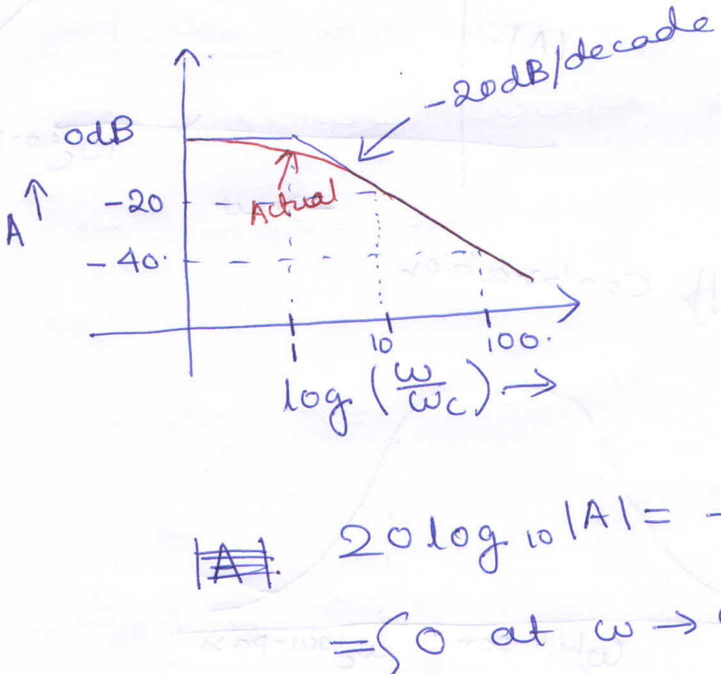
This acts as a low pass filter.

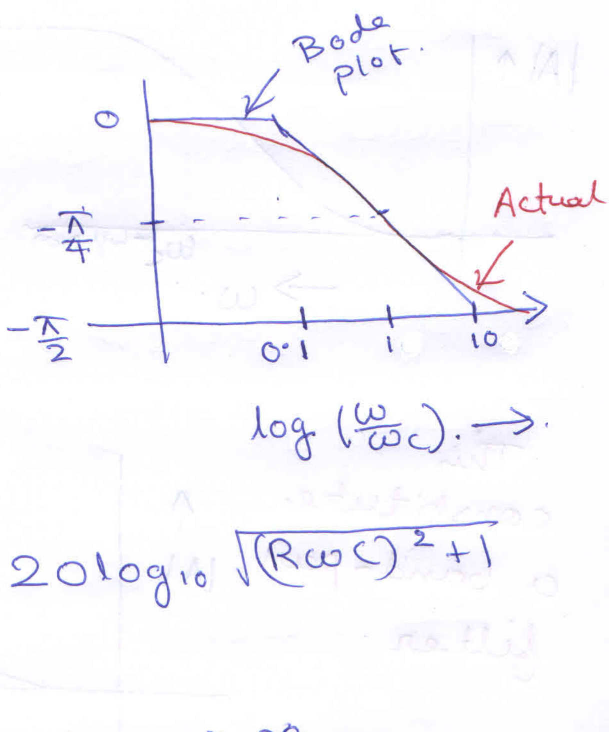
$\angle V_{out} \to 0$ at $\omega \to 0$.

$\angle V_{out} \to -\frac{\pi}{2}$ at $\omega \to \infty$.

Intuitive reasons are ~~at~~ obvious.

Bode plots:





$$\cancel{|A|} \quad 20\log_{10}|A| = -20\log_{10}\sqrt{(R\omega C)^2+1}$$

$$= \begin{cases} 0 & \text{at } \omega \to 0 \\ -20\log\frac{\omega}{\omega_c} & \text{at } \omega \to \infty \end{cases}$$

$$\angle A = \angle \frac{1}{jR\omega C+1}$$

$$= -\angle jR\omega C+1$$

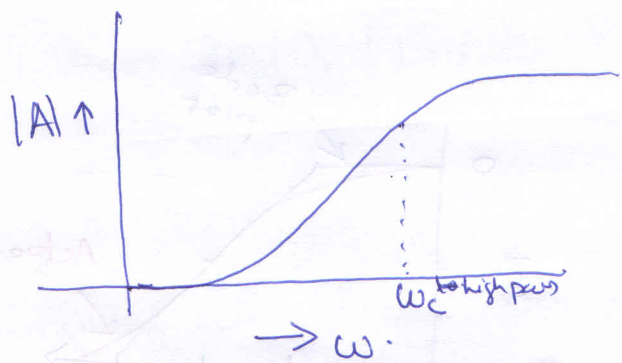
$$= -\tan^{-1} R\omega C = -\tan^{-1}\frac{\omega}{\omega_c}.$$

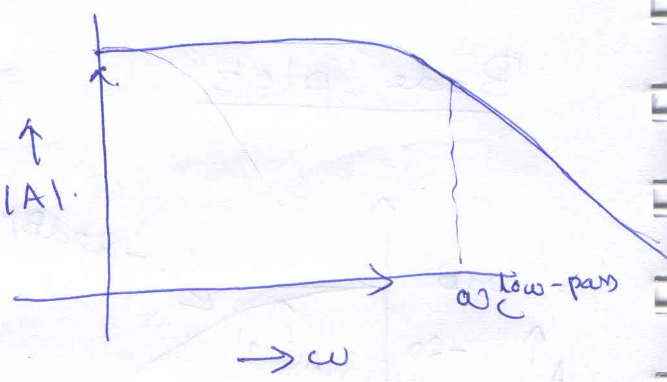
$$= \begin{cases} 0 & \text{when } \omega \to 0 \\ -\frac{\pi}{2} & \text{when } \omega \to \infty \end{cases}$$

RL filters: Use TA for this.

Band Pass Filters: What happens when a low pass filter and a high pass filter are combined ~~ato~~ and the condition

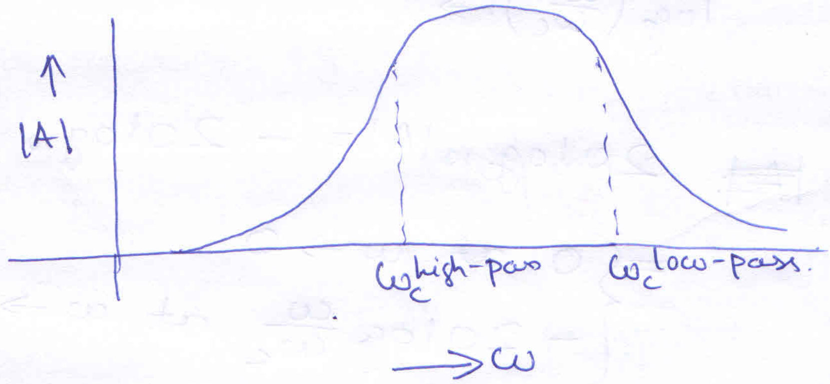
$f_c^{\text{low-pass}} > f_c^{\text{highpass}}$ is satisfied?



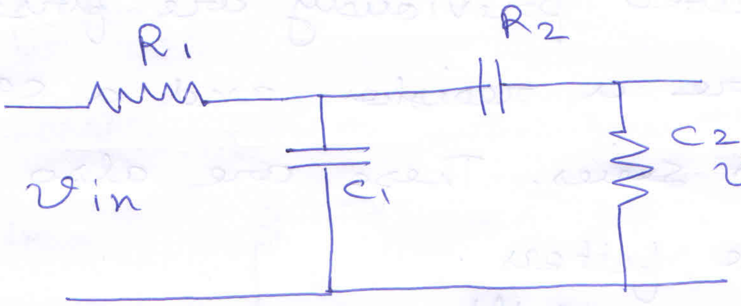


⇓ Combination

This constitutes a band-pass filter.



If $\omega_c^{\text{lowpass}} < \omega_c^{\text{highpass}}$, we donot get a band-pass filter.

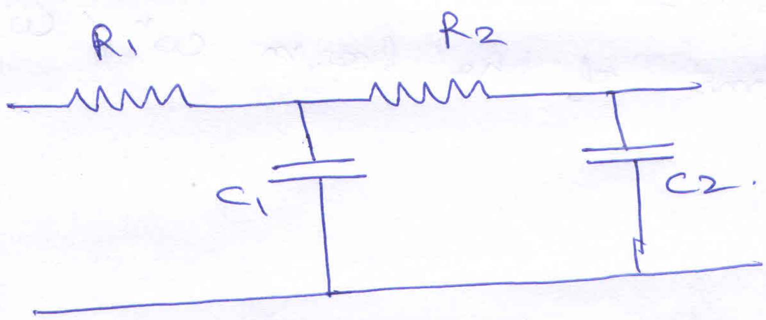


Band-pass filter.

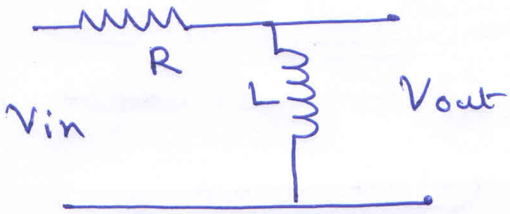
The high pass and low pass filters we ~~Studi~~ just studied are single pole or first order filter which means that the transfer function ~~it does not have a term ω^n for $n > 1$~~ has terms ω^n for $n \leq 1$. The band-pass filter on the other hand is 2nd order, which means there are terms of the form ω^n, $\omega \leq 2$.

All the filters described previously are first order filters where a resistor and a capacitor are connected in series. These are also called single pole filters.

Some times the slope of |A| around the cutoff frequency might not be enough for certain applications. We might need a sharper cut-off ~~freq~~ slope for better ~~unw~~ frequency rejection. That is when we use a second order high-pass or low pass filter.



RL filters:-



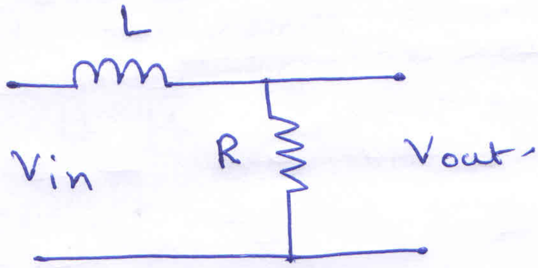
$$V_{out} = \frac{j\omega L}{R + j\omega L} V_{in}.$$

$$|V_{out}| = \frac{\omega L}{\sqrt{R^2 + \omega^2 L^2}}$$

At $\omega \to 0$, $V_{out} = 0.$, $\angle V_{out} = \angle V_{in} \cancel{+} + \frac{\pi}{2}$

At $\omega \to \infty$, $V_{out} = V_{in}.$ $\angle V_{out} = \angle V_{in}.$

So, this is a high pass filter.



$$V_{out} = \frac{R}{R + j\omega L} V_{in}.$$

At $\omega \to 0$, $V_{out} = V_{in}$, $\angle V_{out} = \cancel{0} \angle V_{in}.$

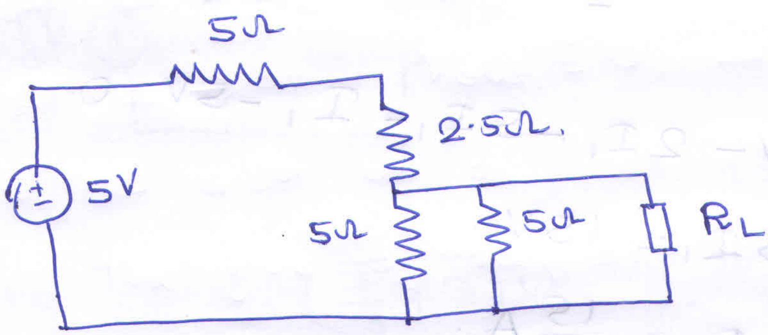
At $\omega \to \infty$, $|V_{out}| \simeq 0$, $\angle V_{out} = \angle V_{in} - \frac{\pi}{2}.$

So, this acts as a low pass filter.

It is the job of the students to do the Bode plots.

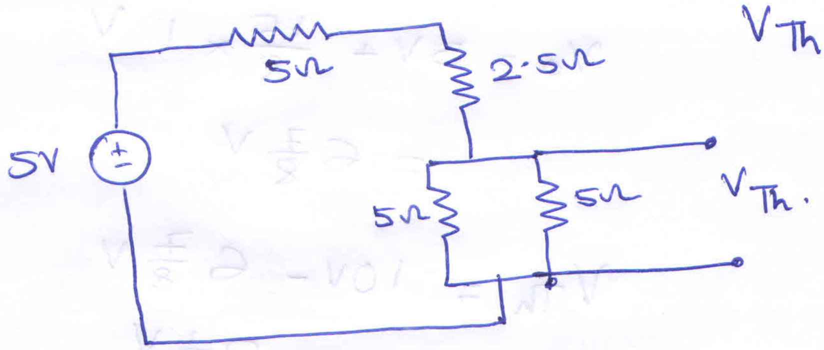
Thevenin's Voltage and Resistance

Thevenin's Theorem: Any combination of ~~volt~~ independent voltage sources, current sources, and resistances (two terminals) can be replaced by a single voltage source ~~and a~~ (V_{Th}) and a series resistor R_{Th}. The value of V_{Th} is the open circuit voltage between the two terminals and the value of R_{Th} is ~~V_{Th}~~ the resistance seen between the two terminals ~~divided by the current when the two terminal are short circuited~~ with the voltage sources replaced by short circuit and the current sources replaced by open ckt. R_{Th} can also be found by other methods.



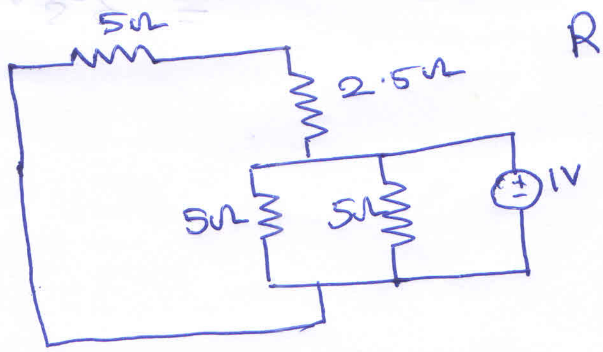
For thevenin's theorem to be valid the network must not have any dependent sources.

V_{Th}:-



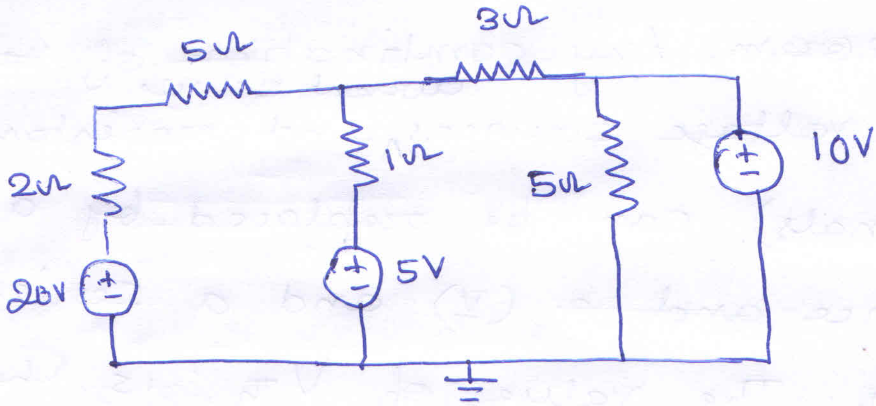
$$V_{Th} = \frac{5V}{10Ω} \times 2·5Ω$$
$$= 1·25V.$$

R_{Th}:-



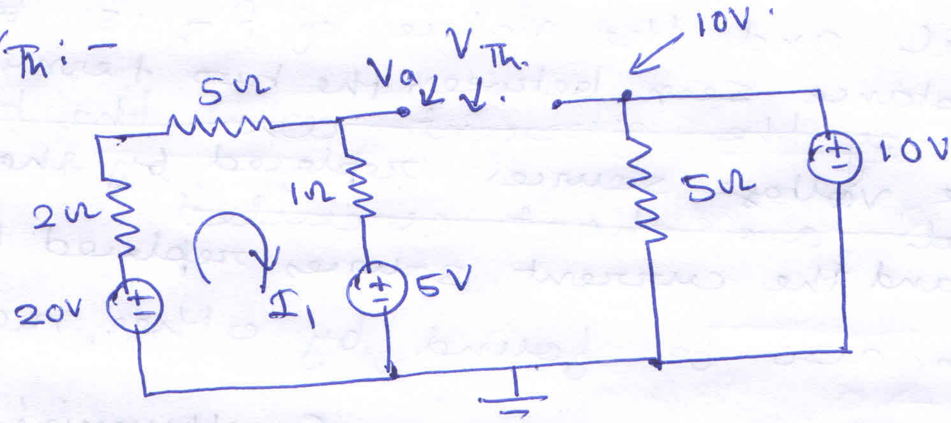
$$R_{Th} = 5Ω \| 5Ω \| 7·5Ω$$
$$= \frac{15}{8} Ω.$$

Task:-



Find the current in the 3Ω resistor.

V_{Th}:-



~~V_a =~~

$$20V - 2I_1 - 5I_1 - I_1 - 5V = 0$$

$$\Rightarrow 8I_1 = 15V$$

$$\Rightarrow I_1 = \frac{15}{8} A$$

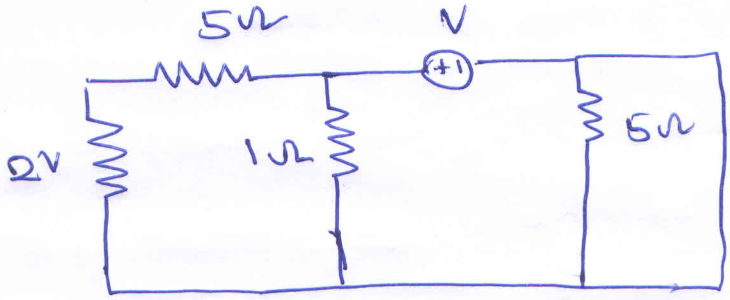
$$V_a = 5V + \frac{15}{8} \times 1 \; V$$

$$= 6\tfrac{7}{8} V$$

$$V_{Th} = 10V - 6\tfrac{7}{8} V$$

$$= 3\tfrac{1}{8} V$$

R_{Th} :-

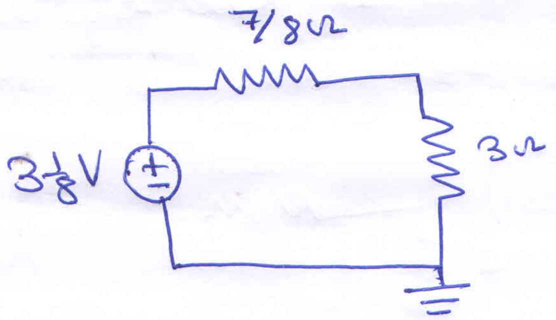


$$R_{Th} = (5\Omega + 2\Omega) \parallel 1\Omega$$

$$= 7\Omega \parallel 1\Omega$$

$$= \frac{7}{8}\Omega$$

Equivalent circuit :-



$$I_{3\Omega} = \frac{3\frac{1}{8}V}{\left(\frac{7}{8}+3\right)\Omega} = \frac{\frac{25}{8}}{\frac{31}{8}} A = \frac{25}{31} A$$

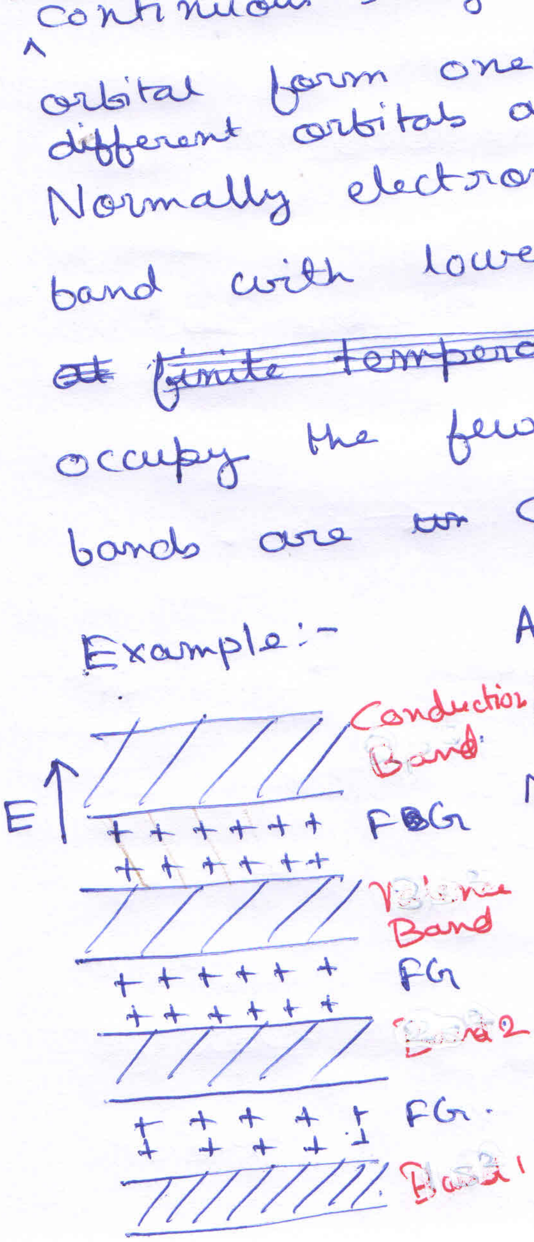
Semiconductor Materials and Diodes..

<u>Orbitals:</u> Shells occupied by electrons.

Silicon: $1s^2\,2s^2\,2p^6\,3s^2\,3p^2$

Discrete atoms have orbitals. Whenever atoms are brought close to each other, they form bands. The difference is that atomic orbitals are discrete while energy band is a quasi-continuous range of energy. Generally each orbital form one band. Energy bands of two different orbitals are separated by bandgap. Normally electrons tend to reside in the band with lower energy. ~~How However~~, ~~at finite temperature~~. At 0K, all the electrons occupy the few lowest bands. The upper bands are ~~un~~ completely empty.

Example:-



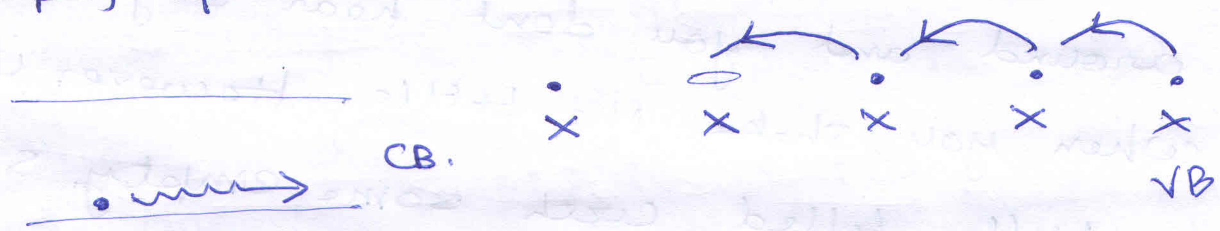
At 0K, ~~2p6 orbi~~ the topmost filled band is known as the valence band. ~~formed by 2p6 orbital is~~ The lowest completely empty ~~while that~~ band is known as the ~~orbital is formed by 3s2~~ conduction band ~~completely filled~~. The two bands are separated by the forbidden gap (FG) and no electrons can reside in the gap.

Now, a completely filled band cannot conduct electricity. Also a completely empty band can't conduct. The situation of a completely empty band is somewhat trivial. No electron, so, no current flow. A completely filled band, on the other hand, is slightly non trivial. For the moment, just know that for electrons to move there needs to be empty space (devoid of electron) in a band. So, the band needs to be partially filled or partially empty for electrons to conduct current. ~~The~~ Treat the situation on a similar footing; suppose you have capsules in a small bottle. If the bottle is completely packed the capsules donot move around and you dont hear any sound when you shake the bottle. However if it is partially filled with some empty space then the capsules can move around while shaking and when the capsules move around they can flow. you hear some noise. There is again no sound when the bottle is completely empty.

From the analogy, we can understand that Si behaves as an insulator at room temp since the $3s^2$ band is completely filled. This is known as the valence band.

The $2p^6$ band, known as the conduction band is empty. ~~filled~~. However this is at 0K only. At finite temperature, on the other hand, some electrons from the valence band can absorb heat energy and jump to the conduction band. So, in one hand, you create a vacant space in the valence band. On the other hand you create an electron in the conduction band.

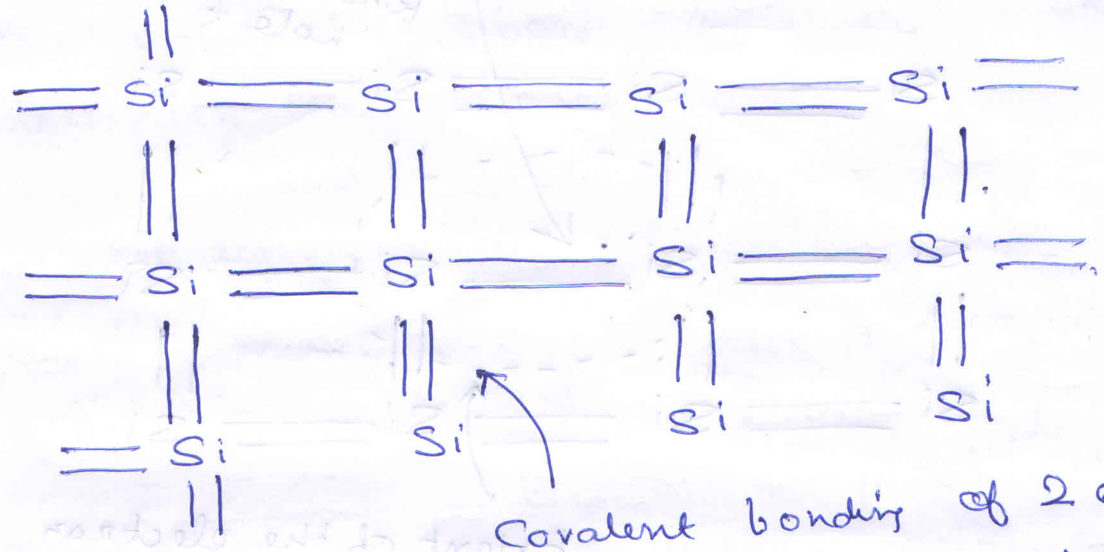
The electron in the conduction band can now move under an electric field and cause a current flow. On the other hand, an electron from adjacent location in the valence band can move to the empty space and cause a flow of current.



This empty space is known as a hole.

The number of electrons in the valence band that can move around at a particular time is proportional to the number of holes and hence the current flow through the valence band is proportional to the number of holes.

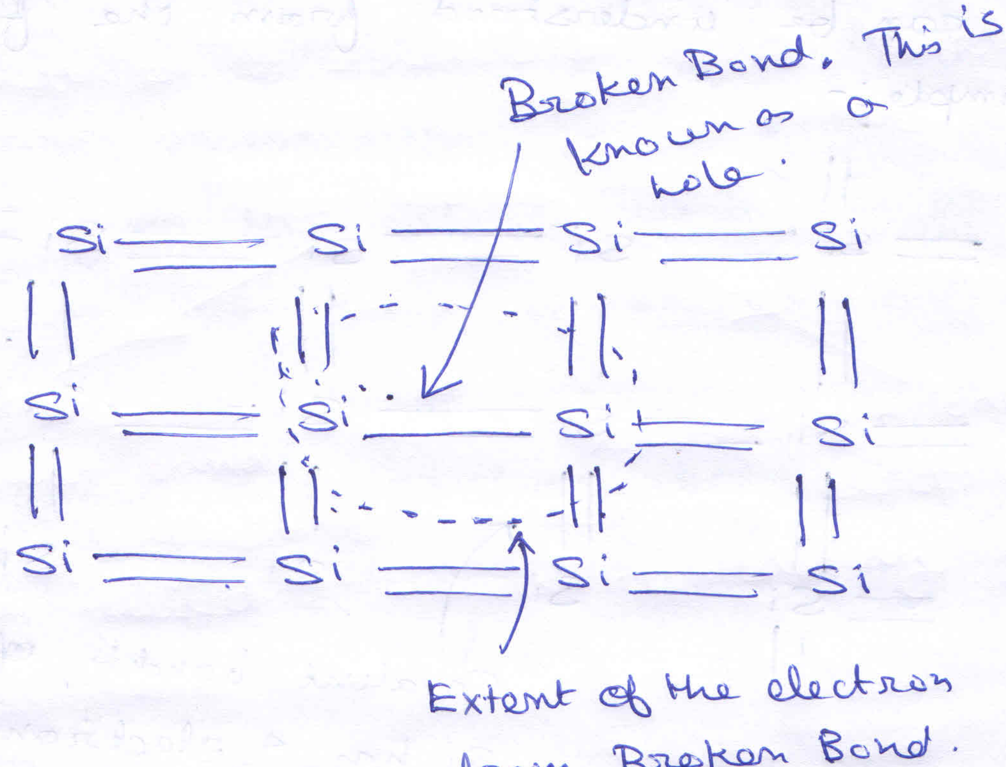
Thi can be understood from the following example:-



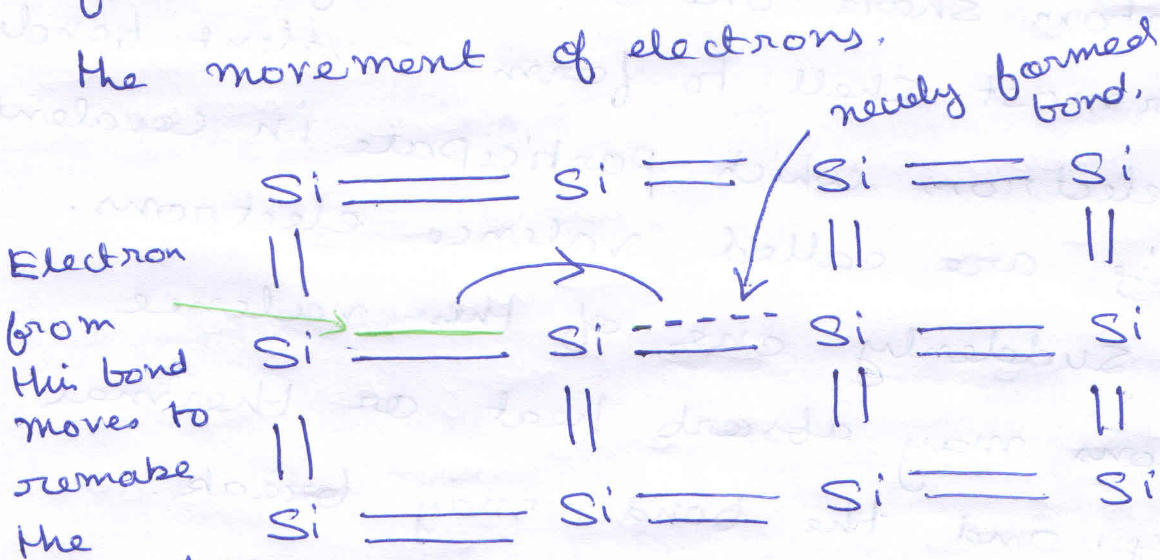
Covalent bonding of 2 electrons.

Si has 4 electrons in the outermost shell.

Each Si atom is surrounded by 4 neighbouring Si atom. Each of Two adjacent Si atom share one electron from the outermost shell to form covalent bonding. The electrons which participate in covalent bonding are called valence electrons. Now, suddenly one of these valence electrons may absorb heat or thermal energy. and the bond may break. Whenever the bond breaks, the electron with higher energy doesnt belong to a particular atom. They are more spread. ~~They are~~ Their nature is more close to free electron. These electrons, after the bond is broken, reside in the conduction band.



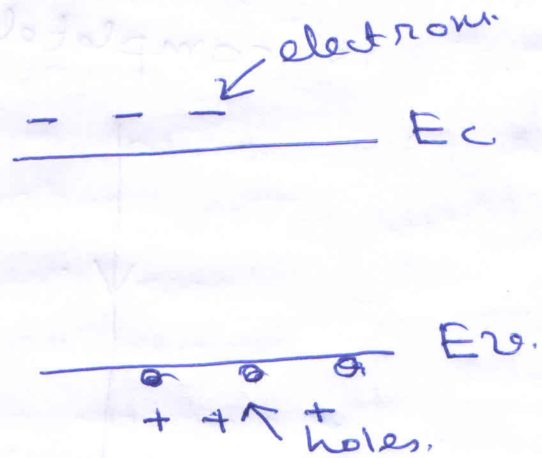
The free electron in the conduction band can now move under the influence of electric field. The broken bond can also aid in the movement of electrons.



So, now the electron from the adjacent bond moves. This is how electrons in the valence band or the valence electrons move. This phenomenon is known as the movement or transport or propagation of hole.

So, current flow in a semiconductor can either be due to movement of electrons in the conduction band, or due to movement of holes in the valence band.

Now, let us see the basic bands in energy space.



It is generally assumed for simplicity that holes have a +ve charge. The intuitive reason is clear. A Si atom with the positively charged nucleus and negatively charged electron is neutral. If we break a bond and take out one electron, what is left behind is a +ve charge. So, it is assumed that the hole has a +ve charge. Also the movement of holes is opposite to the movement of electrons. This can be well understood from the last picture in the previous page.

So, an electron resides in the conduction band. A hole on the other hand resides in a valence band.

Semiconductor, Insulator and Metals :-

Two cases at 0K

The top most band containg electrons is partially filled

Metals.

The top most band containg electrons is completely filled

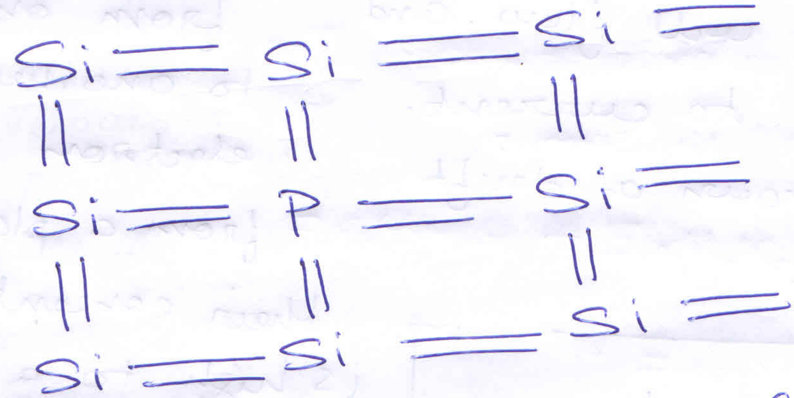
Insulators

Bandgap is such that electrons can't be excited from valence to the conduction band at room temp. Bandgap is larger (> 3 or 4eV) Almost zero conductivity at room temp.

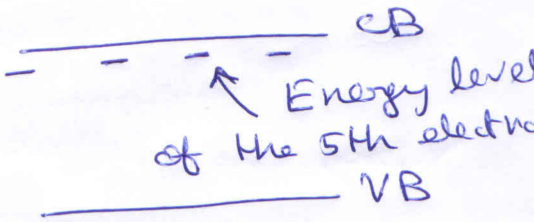
Semi-conductors

Bandgap is such that a few electrons can be excited from valence to conduction band at room temp. Bandgap is close to 1eV or so. They have some conductivity at room temp but the conductivity is much less than metals.

Doping:- The conductivity of semiconductors is so low that it is not useful for device applications. However, they offer the unique ability to enhance the conductivity ~~via~~ via incorporating some impurities. Let us say we add some phosphorous atoms to Si. If the conc. of P is much less than the conc. of Si atoms, then the P atoms are forced to adjust within the Si crystal structure. Here a P atom



donates 4 electrons to form covalent bond with 4 ~~Si~~ adjacent Si atoms. However P is a group V element. It has 5 ~~th~~ valence electrons. The 5th electron doesnt form a bond and hence has a higher energy than the other 4 electrons. With a very small excitation this electron can actually move to the conduction band. ~~By~~



~~adding~~ Thus by adding P atoms to Si, we can

***

actually enhance the conductivity of Si.
Not only that, we can actually manipulate the conductivity of Si to a desirable value by manipulation the conc of P atoms that are introduced within Si.
Normally if N_D ~~number~~ is the concentration of P atoms incorporated within Si, then,

$$n \cong N_D \text{ at room temp.}$$

Similarly when group III elements are incorporated in Si, say Boron, then 3 valence electrons in Boron form bonds with 3 adjacent Si atoms. The bond with the 4th Si atom remains unsatisfied and we have a hole at that unsatisfied bond. In such a case, $p \cong N_A$, where N_A is the concentration of Boron atoms in Si and p is the conc. of holes in the valence band. Note that we can only conclude $n \cong N_D$ and $p \cong N_A$ at finite temp only. This is of course an approximation. But at and above room temperature this approximation gives pretty accurate results.

~~At~~ Generally ~~at~~, ~~when either n-type or p-type dopants are present, then, the~~

~~Semiconductors which are not doped with~~

The process of enhancing the conductivity of semiconductors by introducing other impurities (such as P or B) in them is known as doping. The impurities incorporated in semiconductors are known as dopants. The impurities that introduce a free electron in the semiconductor conduction band are known as n-type dopants while those that introduce a hole in the valence band are known as p-type dopant. P and B are n-type and p-type dopant respectively.

Semiconductors in which no impurities are present ~~is~~ are known as intrinsic semiconductor. In an intrinsic semiconductor $n = p$, i.e, the number of electrons in the CB is equal to the number of holes in the VB. The reason is obvious. ~~The~~

When a semiconductor is incorporated with impurity to enhance its conductivity or other properties, then they are known as extrinsic semiconductor. Here $n \neq p$.

However, in a given doped semiconductor, i.e, say doped Si, the number of electrons are holes are related to the intrinsic electron and hole concentration, by the relation

$$np = n_i p_i = n_i^2 = p_i^2$$

n_i, p_i = ~~no.~~ conc of electron and holes in intrinsic semiconductor.

Follow example 1.2 from the book.

Drift and Diffusion currents:-

Two mechanisms of current flow

An electric field can exert a force on e^-. since electrons are charged particles. So, the electrons will flow. and give rise to current. This is known as drift current.

Electrons are not point particles or classical object. They randomly flow from one place to another. So, electrons will flow from a place where their concentration is high to a place where their concentration is low. Such flow gives rise to a current known as diffusion current. The process is similar to the situation when one end of the room is sprayed with perfume and the entire room smells good after some time.

Total current = drift current + diffusion current

Drift current:-

We define a quantity known as the mobility (μ) which is the average velocity gained per unit electric field. The concept of average velocity come from the fact that electrons in a medium donot continuously accelerate when an electric field is applied. The electrons accelerate for sometime and then scatter from various sources, which kills the gained velocity or momentum. Thus the electron travells with some average velocity. This ~~is kn~~ average velocity is known as the drift velocity.

$$v_d = -\mu_n E.$$

-ve sign due to the fact that electrons flow opposite to the field.

The total drift current density is

$$J_n = -e n v_{dn} = e n \mu_n E.$$

n = average number of electrons per unit volume. This average number of electrons is the average number of mobile electrons that can flow and ~~not the~~ doesnt include the electrons that are tightly bound to the atoms. In other words n is the average number of electrons per unit volume in the conduction band.

Similarly, we can define the hole mobility μ_p and the drift current density due to holes can be written as:-

$$J_p = e p v_{dp} = e p \mu_p E$$

p = hole concentration per unit volume in the valence band. The total drift current is thus:-

$$J = e n \mu_n E + e p \mu_p E$$

$$= \sigma E.$$

$$\sigma = e(n\mu_n + p\mu_p) = \text{conductivity.}$$

<u>Diffusion current</u>:

The diffusion current density due to electrons can be written as:-

$$J_n = e D_n \frac{dn}{dx}$$

Diffusion coefficient for electrons.

So, the diffusion current is proportional to the concentration gradient of electrons $\left(\frac{dn}{dx}\right)$

Similarly for holes:-

$$J_p = -e D_p \frac{dp}{dx}$$

Diffusion coefficient for holes.

Equilibrium vs. Steady-State:-

Equilibrium is the condition when ~~no~~ ~~voltage or~~ the material doesn't have any source of excitation that is applied externally. This is also known as thermal equilibrium.

On the other hand when there is a source of excitation and after the application of the excitation you have waited long enough so, that every thing, for eg n and p. within the material, has reached a constant distribution, then the state of the material is known as steady state.

~~Read Sec 1.1.4~~