# Fundamentals of Electric Theory and Circuits

**by**

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# Additional Practice Questions for all chapters

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# Chapter 1

**Q.1.1*** A dipole is located at the origin, and is composed of charged particles with charge +*e* and –*e*, separated by a distance $2\times10^{-10}$ m along the *x*-axis.
a) Calculate the magnitude of the electric field due to this dipole at location $\langle 0, 2\times10^{-8}, 0\rangle$ m.
b) Calculate the magnitude of the electric field due to this dipole at location $\langle 2\times10^{-8}, 0, 0\rangle$ m.
c) Calculate the magnitude of the force on a proton placed at the location where you calculated the electric field in part (a).
Hint: Use the formulas derived in "Electric field due to a Dipole" in Appendix A.

**Q.1.2*** A dipole consisting of point charges +4 nC and −4 nC separated by a distance of 2 mm is centered at location $\langle 0.03, 0.15, 0\rangle$ m (the size of the dipole is exaggerated in the diagram). A hollow plastic ball with radius 3 cm and charge −0.2 nC distributed uniformly over its surface is centered at location $\langle 0.11, 0.15, 0\rangle$ m, as shown in the Fig. Q.1.2. What is the net electric field at location C, $\langle 0.03, 0.04, 0\rangle$ m ? (1 nC = 1 nanocoulomb = $1\times10^{-9}$C.)

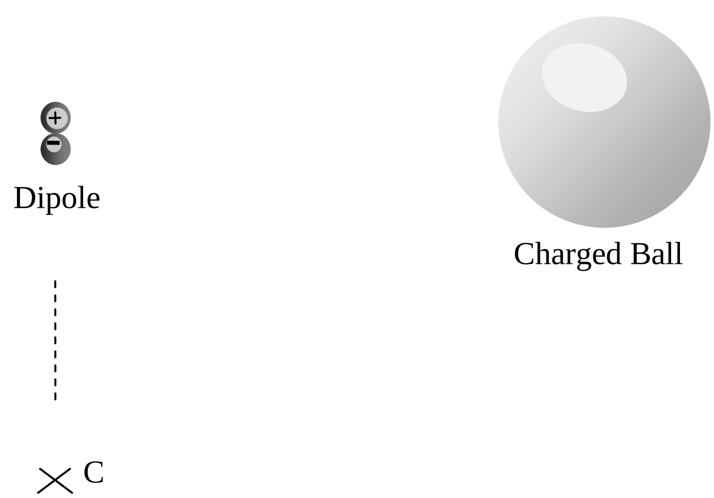



**Fig. Q.1.2** A dipole and a charged ball. Dipole size is exaggerated (not to scale).

**Hint**
Step 1: Write the net electric field by applying the superposition principle.
Step 2: Calculate the distance between the dipole and the location C. Calculate the electric field due to the dipole at C using the approximate expression used when the distance between the dipole and location C is large. Express the electric field in vector notation.
Step 3: Calculate the distance between the ball and the location C. (Use vector notations and then obtain the magnitude of the distance from the distance vector).
Step 4: Calculate the electric field due to the charged ball at the location C in vector notation.
Step 5: Now using the expression you wrote for the electric field (net) in Step 1, calculate the electric field expressing it in vector notation.

**Q.1.3*** A Nichrome wire 48 cm long and 0.25 mm in diameter is connected to a 1.6 volt flashlight battery. What is the electric field inside the wire ? Next, the wire is replaced by a different Nichrome wire with the same length, but diameter 0.20 mm. Now what is the electric field inside the wire ?

**Q.1.4*** Sketch the surface charges for the circuits shown in Fig. Q.1.4. The surface charge and their gradients you draw should generate the strength of the field indicated by thick and thin arrows in different parts of the circuit.

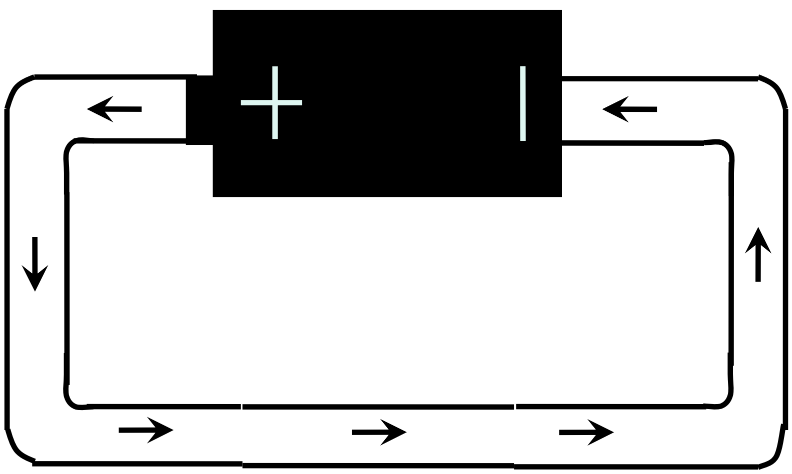


**Fig. Q.1.4 (a)**

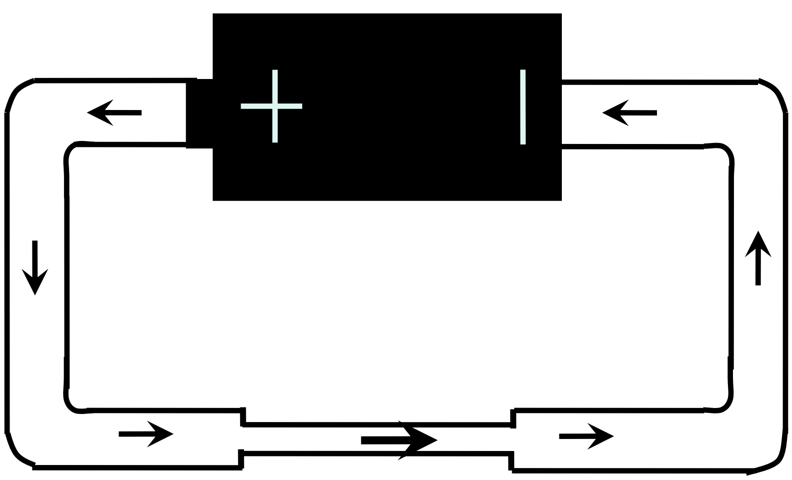


**Fig. Q.1.4(b)**

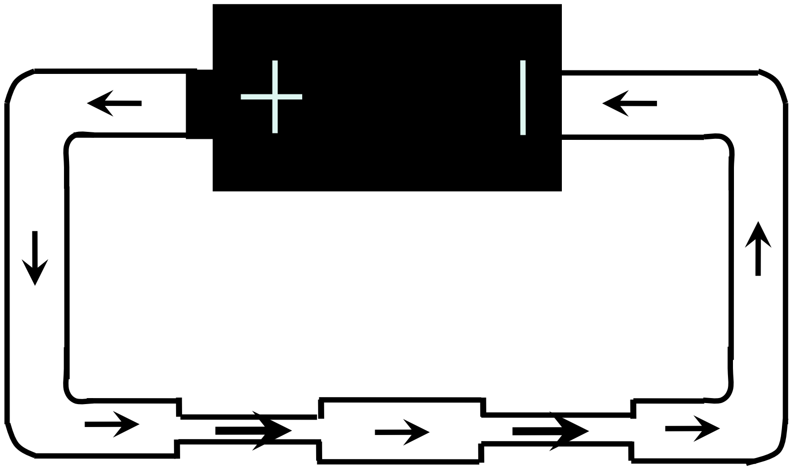



**Fig. Q.1.4(c)**

**Q.1.5*** The circuit shown in Fig. Q.1.5 uses two flashlight batteries and two Nichrome wires of different lengths and different thicknesses.

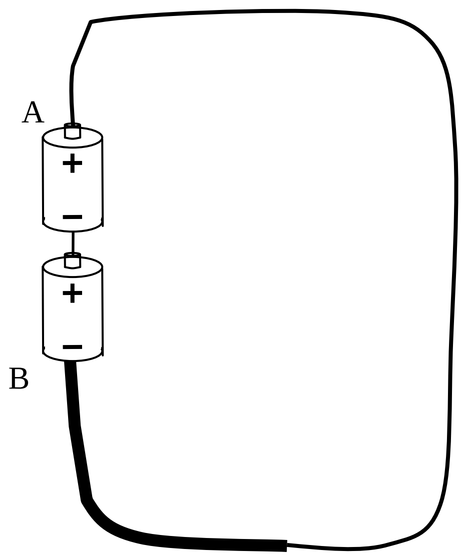



**Fig. Q.1.5** A dc circuit with nichrome wires of different thicknesses.

The thin wire is 50 cm long, and its diameter is 0.25mm. The thick wire is 15 cm long, and its diameter is 0.35mm.

i) The emf of each flashlight battery is 1.5 volts. Determine the steady-state electric field inside each Nichrome wire. Remember that in the steady state you must satisfy both the current node rule and energy conservation. These two principles give you two equations for the two unknown fields.

ii) The electron mobility in room-temperature Nichrome is about $7 \times 10^{-5}$ (m/s)(N/C). Show that it takes an electron (one among the millions and millions inside the wires) 36 minutes to drift through the two Nichrome wires from location B to location A.
iii) On the other hand, about how long did it take to establish the steady-state when the circuit was first assembled ? Give a very approximate numerical answer, not a precise one.
iv) There are about $9\times10^{28}$ mobile electrons per cubic meter in Nichrome. How many electrons cross the junction between the two wires every second ?
v) If you were told that the average walking speed of a human is about 5 km/hr, do the electrons drift faster than this speed in the thin wire in the steady-state ? If not, by what fraction do they drift of the walking speed of a human ? What is the drift speed of the electrons in the thick wire ? Again, express the speed of the electron in the thick wire as a fraction of the walking speed of a human.
vi) Compare the drift speeds of electrons in the thick wire and the thin wire in the steady-state and explain qualitatively why they are different.

**Note:** Could scientists count the number of mobile electrons in a metal or semiconductor ? No ! The number of mobile electrons in different metals can be calculated if one knows the atomic mass, atomic number and Avogadro's constant. A description of how these were determined is available in an article "Determining the Atomic Number and Avogadro's Number" in the folder "Additional Practice Questions for all chapters" in the CD.

**Q.1.6** The expression $I^2R$ represents a power, i.e. the rate at which energy is transferred or dissipated, and not the energy itself. $P = I^2R$ emphasizes the power-dissipation effect of a current which creates heat in a conductor, and is usually called the heating effect of a current and is termed the $I^2R$ loss since the energy transferred in this way is lost to the electrical system.
In the heating rods of an electric radiator or the heating element of a cooker, the $I^2R$ loss is beneficial, but in other cases it may be simply energy lost to the surroundings.

However, the expression "IsquareR loss" is more frequently used to describe power transfer and dissipation, which is why it could be misleading and the power lost describes energy lost !
This is because most electrical engineers are preoccupied with power and is a consequence of current being the rate of flow and not the flow itself. Ref. [15].

A current of 3A flows through a 10 Ω resistor.
Find:
(a) the power developed by the resistor.
(b) the energy dissipated in 5 minutes.

# Chapter 2

**Q.2.1*** What is the net charge of a sodium ion ($Na^+$) ?

**Q.2.2** A charging circuit using a battery, bulb and an uncharged capacitor is made as shown in Fig. Q.2.2. Sketch the evolution of surface charges, charges on the plates and fields in the wires and between the plates (from initial transient to steady-state) as the capacitor charges in 3 or 4 sketches of the circuit. After a long time what will be the polarity of charge on plates A and B ?

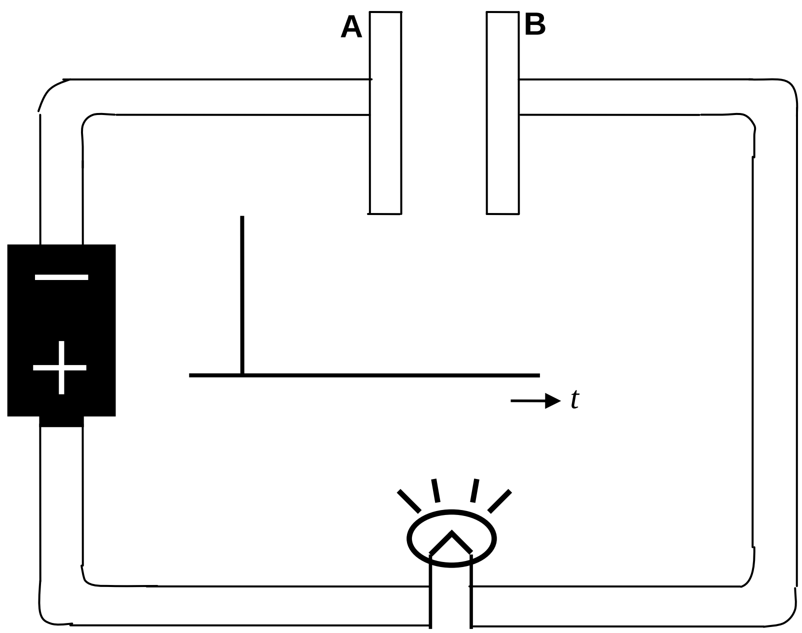



**Fig. Q.2.2** Charging a Capacitor

**Q.2.3** A capacitor has displaced excess charge on its plates. Which one of these technical terms describes correctly the state of the capacitor ? i) The capacitor is neutral ii) The net charge of the capacitor is zero. Hint: Is a fringe field present ? Follow notes at the end of Section 1.8 of the book.

**Q.2.4**

The following two questions are from the article "Macroscopic phenomena and microscopic processes: Student understanding of transients in direct current electric circuits," by Beth Ann Thacker, U. Ganiel, and D. Boys, Am. J. Phys. 67(7), S25–S31 (1999).

A circuit (Fig. Q.2.4) comprises a battery, a switch S, capacitor with plates A and B, a resistor and ammeters 1 and 2. The resistance R is roughly 100 Ω and the capacitance C is about 0.1 F. The exact values are not important. The capacitor is initially uncharged and the switch S is initially open.

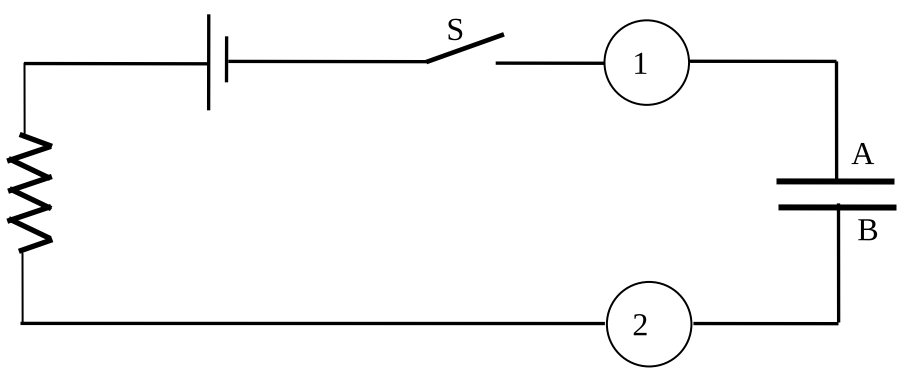



**Fig. Q.2.4**

1. Switch S is closed. Describe qualitatively what ammeter 1 will read as a function of time, starting at the moment the switch S is closed.
2. Describe qualitatively what ammeter 2 will read during the same time interval.
3. If at a certain moment ammeter 1 indicates a current $i_1$, and at the same moment ammeter 2 indicates $i_2$, which of the following is correct ?

i) $i_2 < i_1$

ii) $i_2 = i_1$

iii) $i_2 > i_1$

iv) Cannot determine

4. Initially, when switch S was open, plates A and B were not charged. From the moment S is closed (circle all correct statements)
i) Will charges accumulate on plate A ? If so, which (positive or negative) ?
ii) Will charges accumulate on plate B ? If so, which (positive or negative) ?

5. Following each question now, we suggest a number of possible answers. Choose one answer and explain your choice. In your explanations try to use some of the following terms: charge, current, force, electric field, potential, potential difference, voltage.

a) How does the current in ammeter 1 behave as a function of time from the moment the switch is closed ?

i) The current is zero and stays zero. Why ?
ii) The current is constant, different from zero. Why ?
iii) The current increases to a maximum value and stays constant at that value. Why does it increase initially, and why does it stay constant ?
iv) The current jumps instantaneously to some initial value and then gradually decreases to zero. Why is there an initial current ? Why does the current increase ? Why does it stop ?
v) Any other possibility. Describe and explain.

b) How does the current in ammeter 2 behave as a function of time from the moment the switch is closed ?

i) The current is zero and stays zero. Why ?
ii) The current is constant, different from zero. Why ?
iii) The current increases to a maximum value and stays constant at that value. Why does it increase initially, and why does it stay constant ?
iv) The current jumps instantaneously to some initial value and then gradually decreases to zero. Why is there an initial current ? Why does the current increase ? Why does it stop ?
v) Any other possibility. Describe and explain.

c) Recall that plates A and B are not charged initially, when switch S is open. After switch S is closed

i) No charges accumulate on the capacitor. Why ?

ii) Charges do accumulate on both plates. Why do charges accumulate ? What is the source of these charges (battery only, wires only, both ?). Assume that at a given moment charge Q1 accumulate on plate A and a charge Q2 has accumulated on plate B. How is charge Q1 related to charge Q2 ? Refer to both magnitude and sign.
iii) Any other possibilities. Describe and explain.

**Note to Instructor**

Provided below is one suggested answer to Question 5 a) and all correct answers to this and other questions should contain the formalism and clarity in technical expression.

"*The current jumps instantaneously to some initial value due to the electric fields in the circuit and the path being a closed path. The capacitor plates build up charge and the electric field outside the capacitor increases as charge on the plates increases. Eventually, the electric field is equal in magnitude and opposite in direction of the electric field due to the battery and the surface charges on the wires. As the electric field outside the capacitor plates increases, current decreases. When static equilibrium is reached due to the electric fields inside the circuit,* $E_{net} = 0$ *and the current stops*.

**Q.2.5** The circuit of Fig. Q.2.5 shows a circuit of a battery, a switch S, three ammeters −1, 2, and 3, two capacitors, and 2 resistors. The resistance R is roughly 100 Ω and the capacitance C is about 0.1 F. Initially, when the switch S is open, there is no charge on any of the capacitor plates.

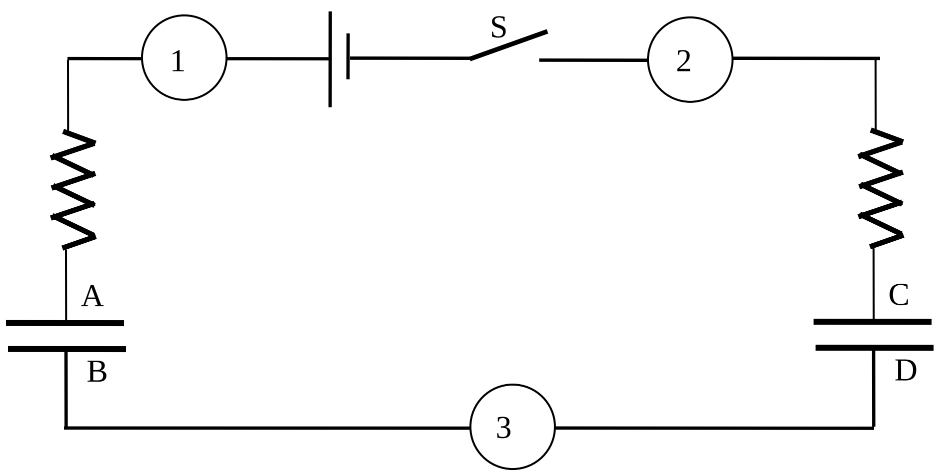



**Fig. Q.2.5**

Switch S is closed. Discuss each of the following questions qualitatively.

a) What will each of the three ammeters show from the moment the switch is closed and thereafter ?

b) Plates A, B, C, and D were initially uncharged. Form the moment switch S is closed, will charge accumulate on the plates ? If so, which (positive or negative) ?

The following questions refer to the part of the circuit composed of plate B, the connecting wire, ammeter 3, and plate D.

After each question, we suggest a number of possible answers. Choose one answer and explain your choice.

d) From the moment the switch is closed, what does ammeter 3 indicate ?

i) The current is zero. Why ?

ii) The current is not zero. Why ? How does the current change with time ?

e) Remember that plates B and D were not charged when switch S was open. After it is closed.

i) No charges will accumulate on plates B and D. Why ?

ii) There will be charges on plates B and D. Why do the charges accumulate ? What is the source of these charges ? Assume charge $Q_B$ is on plate B, and charge $Q_D$ is on plate D. What is the relationship between $Q_B$ and $Q_D$ ? Refer to both magnitude and sign.

**Note:** the next question relates to the process of Grounding

f) Consider what would happen if, after the switch S had been closed for a long time, the **capacitor was removed** from the circuit (carefully without touching the leads nor allowing the leads to touch and create a short-circuit).

i) Would there be charge on either plate of the capacitor ? What would be the net charge on the capacitor ? Explain.

ii) Would there be a potential difference across the capacitor ? Explain.

iii) If one plate of the capacitor were then connected to **ground,** would the charge on either plate change ? Explain your answer.

iv) If one plate of the capacitor were connected to **ground**, would the potential difference change ? Explain your answer.

**Q.2.6** Two experiments are described next and the reader is urged to think through the process and answer the questions.

**Experiment 1**: A positively charged metallic sphere is brought near a thin uncharged metallic rod. Electrons in the bulk of the rod migrate to the surface of the rod near the sphere making the surface acquire a negative charge and the opposite surface of the rod acquires a positive charge shown in Fig. Q.2.6(a).

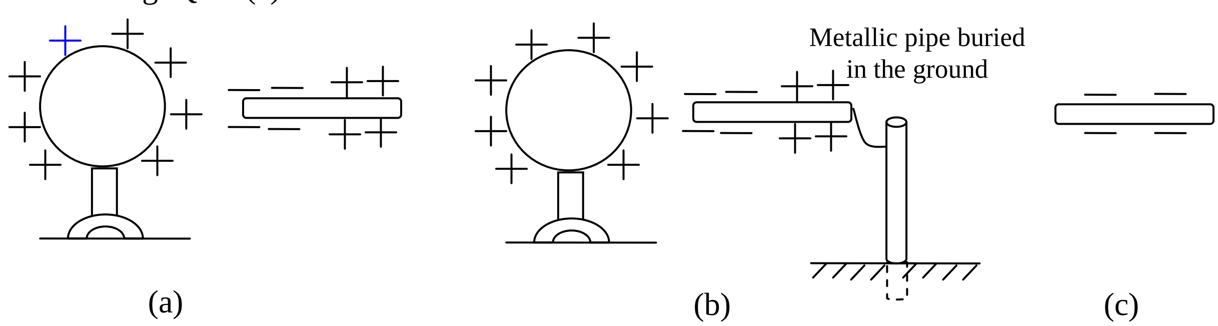



**Fig. Q.2.6** (a) A charged sphere near a thin metallic rod. (b) Excess positive charge on the rod removed by grounding. (c) The excess negative charges redistribute themselves on the rod.

The right side of the metallic rod which has the excess positive charge (with the positive sphere still in position) is grounded by connecting the surface using a thin metallic wire to a metallic pipe buried in the ground as shown in Fig. Q.2.6(b). When the sphere and the ground connection are removed, the negative charge remaining on the thin rod, spreads uniformly on the surface of the rod as shown in Fig. Q.2.6(c).

a) Do all the charges (electrons) in the thin rod move to the left in Fig. Q.2.6a ? Explain.

b) Do the charges remain in the interior of the rod in the left end of the rod (Fig. Q.2.6a) ? Explain the condition multi-atom regions in the bulk of the thin rod.
c) What is the positive charge composed of ?
   i) positrons
   ii) lattice ions (or atomic cores)
   iii) protons
d) Are the positive charges you chose in part (a) mobile ? Explain.

**Experiment 2**: One plate of an isolated charged capacitor is grounded as shown in the Fig. Q.2.6(d).

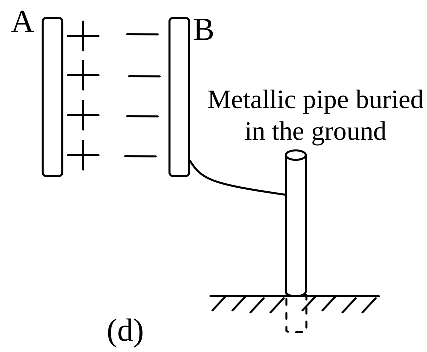



**Fig. Q.2.6** (d) One plate of an isolated charged capacitor is grounded.

Are there negative charges on the left surface of plate A ? Explain. Are there positive charges on the right surface of plate B ? Explain.
What are the differences in effects produced on the sphere and the capacitor by the process of grounding. Would the potential difference of the capacitor change ? Explain detailing the process.

**Q.2.7** For each of the following statements, state whether right or wrong giving reasons.
1) Magnitude can have several different dimensions such as length, length per time and so on.
2) Magnitude is related only to the size of vectors such as velocity and is not associated with scalars such as temperature.
3) Amplitude is a quantity which is associated with sinusoidally varying quantities.
4) Amplitude is the maximum magnitude of varying quantities; periodic and non-periodic.

# Chapter 3

**Q.3.1**
**I** In the design of transistorized amplifier circuits, circuit designers locate a quiescent dc operating point by plotting a dc load line on the transistor characteristics as shown in Fig. 3.29, Chapter 3.
In the following, we will learn more about the currents both dc and pulsating in the circuit and how they combine to produce a harmonious operation of the circuit used to amplify tiny input sinusoidal signal voltages.

Consider the circuit of a simple transistor amplifier with a self-bias arrangement as shown in Fig. Q.3.1(a). Such a biasing arrangement is also called voltage-divider bias. The reader may note that there is no emitter-bypass capacitor in the circuit.

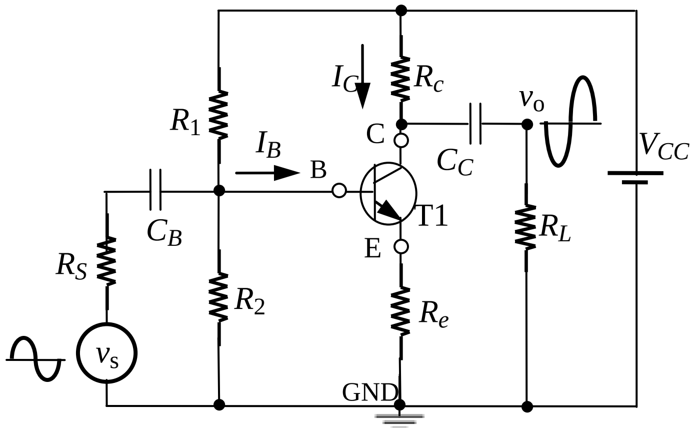



**Fig. Q.3.1(a)** A transistor amplifier with a self-bias arrangement.

A capacitor acts as an open-circuit to extremely slowly-varying signals and dc inputs as we had demonstrated in Section 2.13, Chapter 2. Therefore, in principle when establishing a quiescent operating point for the transistor T1 in the transistor amplifier with a self-bias arrangement, we may assume that no dc current is present in both the branches with the capacitors $C_B$ and $C_C$.

The dictionary meaning of *quiescent* is: being at rest; quiet; still; inactive or motionless. But, electronic engineers know very well that it is merely the operating point that is drawn on the graph of a transistor's output characteristics, which is motionless (!).

When the circuit is made with the input signal source turned ON, but with zero input signal voltage, and the dc voltage source turned ON, there is an initial transient that lasts a few nanoseconds when, electric fields are set up in the wires, resistors and the transistor. The electric field which fills the wires and the bulk crystal and junction regions of the transistor is due to the process by which charges arrange themselves intricately, mostly on the surface leaving aside the few interface charges at the boundary between components and at the junctions of transistors. These charges are sourced from the signal source, the dc voltage source ($V_{CC}$), connecting wires and all other components that make up the circuit. The capacitors $C_B$ and $C_C$ charge up to $V_{BGND}$ and $V_{CGND}$ and prevent dc current in the branches of the circuit with the resistors $R_S$ and $R_L$. GND is the circuit zero and is the negative terminal of the DC supply voltage as shown in Fig. Q.3.1(a). This may take a few milliseconds to a few hundred milliseconds from circuit turn ON given the values of capacitances and resistances usually preferred in such amplifier circuits. The voltage between the base and emitter for a silicon bipolar junction transistor will not be significantly different from 0.7 volts dc.

Currents, steady as they are being conventional dc currents to be more precise, flow into the base and into the collector. The sum of the two, flows through the emitter to the circuit zero and return to the negative terminal of the dc supply voltage.

Physically, the electron currents flow in an opposite sense to the direction of the current indicated by the arrows in the base and collector and are driven by electric fields in the wires and the resistors and the transistor. The currents comprise millions and millions of electrons moving with a start-stop motion with a drift superimposed.

A *static* (dc) load line corresponding to the resistance $R_c$ through the point $i_c = I_C = 0$, $v_{CE} = V_{CC}$, is drawn with slope $1/R_c$ as indicated in Fig. Q.3.1(b). The slope is $1/R_c$, because the *y*-axis represents current and the *x*-axis, voltage. The quiescent operating point Q (with no input signal) is chosen and a biasing network comprising resistances $R_1$, $R_2$, and $R_e$ with a suitable dc voltage source is designed to establish it in the amplifier using Kirchhoff's voltage law and a Thevenin equivalent circuit. The details are beyond the scope of the textbook and a detailed design procedure is available in Ref. [17].

**Note:** We have used the variable notation from the Table "Notation Summarized", Chapter "The Transistor at Low Frequencies", in Integrated Electronics by Millman, Halkias and Parikh,

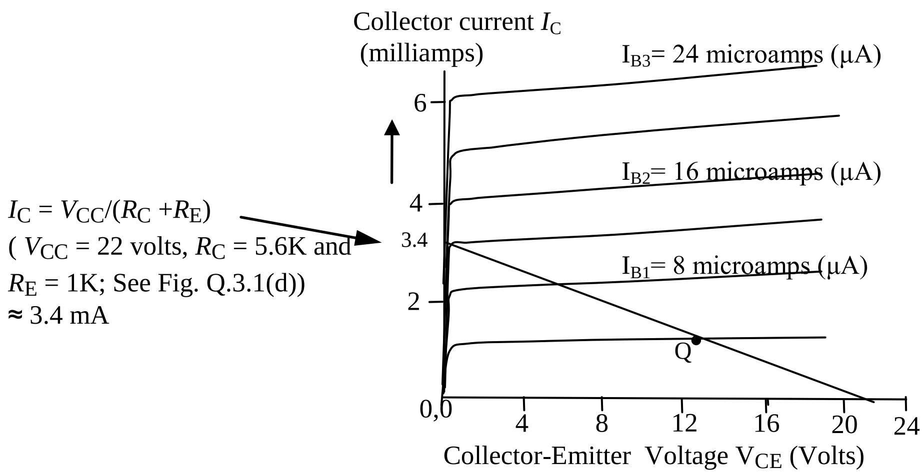



**Fig. Q.3.1(b)** Typical output characteristics of a transistor with a load assuming $V_{CC}$ = 22 volts

The motionless operating point Q, in reality masks a tremendous amount of activity that is going on within the circuit; stillness in motion, in a sense !

The drift velocity of electrons in the resistors is greater than that of the velocity in the wires. This ensures that the number of electrons crossing any cross section of the circuit say, the wire that connects $V_{CC}$ to $R_1$ and in $R_1$, in a given time interval is the same. In short, the current will be uniform in the wire from $V_{CC}$ and in $R_1$, a natural consequence of the law of conservation of charge and of current.

In the transistor however, there is a slightly different process at work. For example, if the base voltage due to the signal were to be increased, a larger number of electrons are injected into the base region from the emitter; this is the heart of amplifier action. While there is no significant change in the drift velocity of electrons at the collector base junction despite it being reverse-biased in the active region of transistor operation, their number would have increased and therefore, the collector current increases, because current is the number of electrons that cross a region in a given time interval ($i = nAv$). The distinction between the two processes; that of current in wires and resistors and in *p-n* junctions is useful to remember.

When a small input sinusoidal signal (ac) is applied, there is a dramatic turn in the activity inside the amplifier circuit. The signal energy transfers through the capacitor $C_B$ to the base of the transistor. This action was studied in quite some detail in Sections 3.1 and 3.2, Chapter 3. An ac signal voltage pulsates at the base terminal and by transistor action (or a diode action if you want to look at it that way) causes an injection of charge carriers from the emitter into the base region.

If a measurement of the dc voltage is made between the base and emitter, it would not be significantly different from about 0.7 volts dc. The signal voltage however superimposes on that and may appear distorted slightly if one were to view the waveform using an oscilloscope.

The reason for the distortion is not because of some gross abnormality in the construction of the *n-p-n* bipolar junction transistor, but because of the essential nature of the behavior of the base-emitter junction which can be approximated as a *p-n* junction.

**II** It would be instructive to visualize the pulsating currents in the circuit due to the input sinusoidal signal voltage.
We begin with the input circuit redrawn partially from Fig. Q.3.1(a) in the Fig. Q.3.1(c).

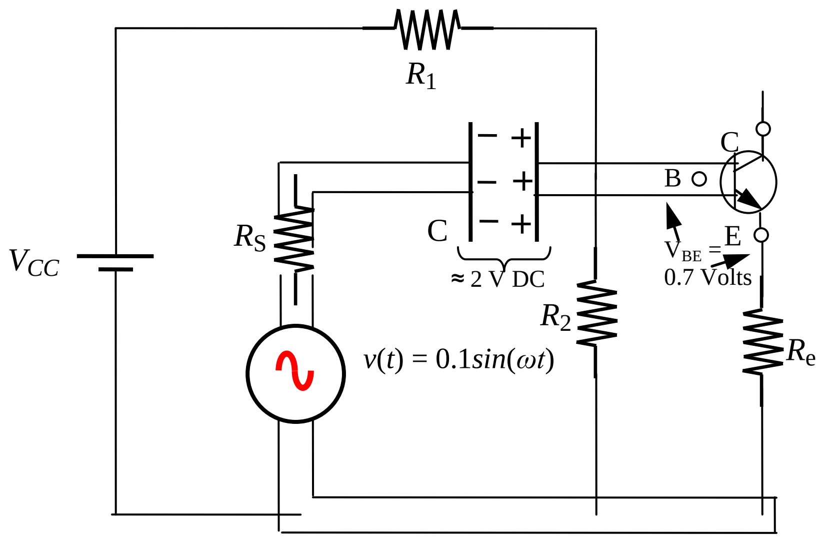



**Fig. Q.3.1(c)** A common-emitter amplifier with self-bias and the input circuit.

When the circuit is switched ON, the capacitor being initially uncharged will charge up to the voltage set by the voltage divider comprising resistors $R_1$ and $R_2$.

Displaced electrons on the right plate of the capacitor move into its lead towards the left plate, while the capacitor charges. Simultaneously, electrons in the lead of the left plate move onto the left plate and the movements register as a negative current on the ammeter AM1 connected with polarity as shown in Fig. Q.3.1(d). I urge the reader to check the direction of the current that will be measured by ammeter AM1.
Because the sinusoidal generator VG1 is ON simultaneously, a pulsating current of a small amplitude superimposes on the charging current of the capacitor; tiny pulsations of current on a growing strength of charging current. There is no reversal in the pulsating current; it ebbs (reduces in strength) and flows (increases in strength) by small amounts on the growing charging current in one direction which is conventionally away from the left plate of the capacitor and into the right plate.
Fig. Q.3.1(d) shows the circuit schematic that was entered into the TINA Schematic Editor.

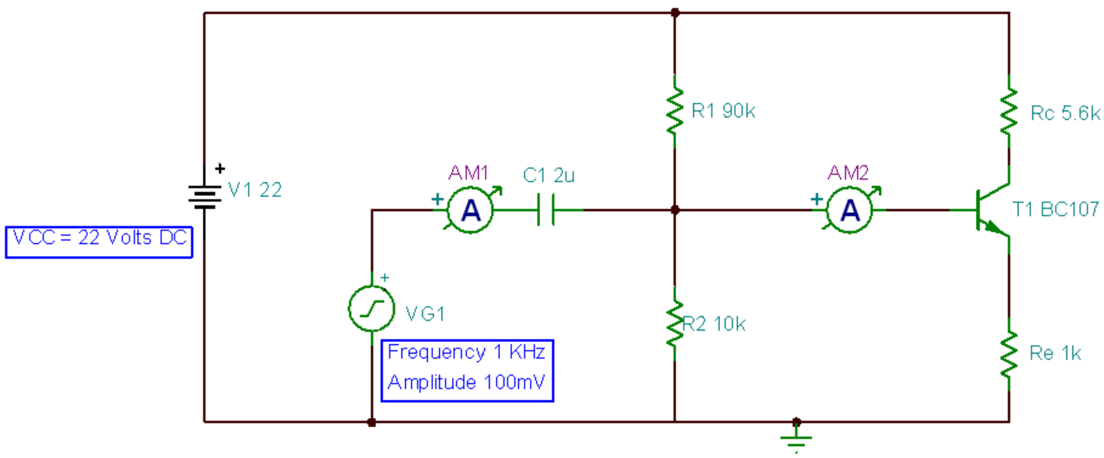



**Fig. Q.3.1(d)** Circuit Schematic in TINA Schematic Editor.

The capacitor $C_B$ (shown as C1 in the TINA schematic) is 2 microfarad (2μF) and the transistor is a type BC 107. The frequency of the input signal was set at 1 KHz with amplitude 100 millivolts.

The voltage at the junction of the two resistors $R_1$ and $R_2$ that comprise the voltage-divider bias circuit is about 2 volts with respect to circuit zero or ground. The capacitor $C_B$ (C1 in TINA) takes approximately 150 milliseconds to charge up to this voltage and this may be seen in the input signal and base current waveforms of a simulation run using TINA, and depicted in the screen shot of Fig. Q.3.1(e) which shows the charging current waveform upto 100 milliseconds.

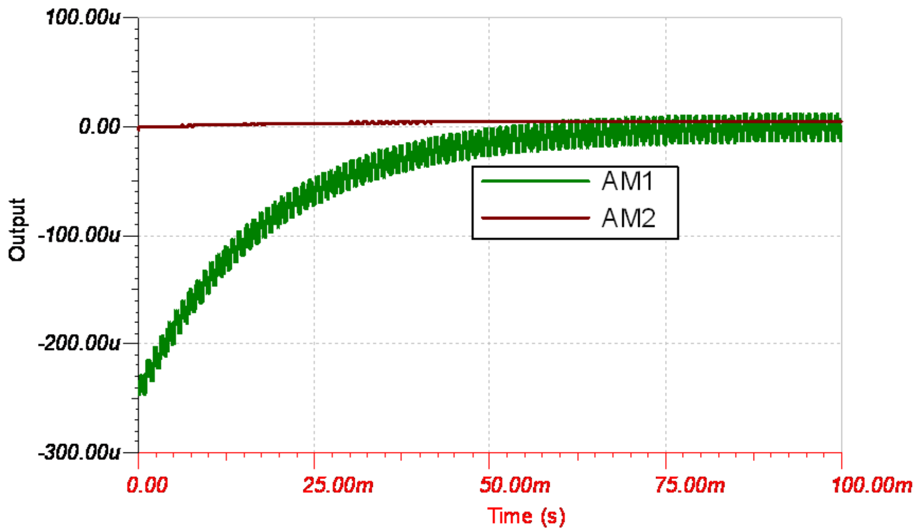



**Fig. Q.3.1(e)** Input (signal and base) current waveforms of simulation of circuit Fig. Q.3.1(d) using TINA.

Note that the current in the capacitor does not reverse and is negative with respect to the polarity of the ammeter AM1 connections. The tiny current pulsations produced by the pulse generator are superimposed on the capacitor charging current waveform recorded by AM1. The pulsations are seen to swing clearly after about 150 milliseconds, above and below zero amps.
This may be observed from the AM1 ammeter waveform in Fig. Q.3.1(f).

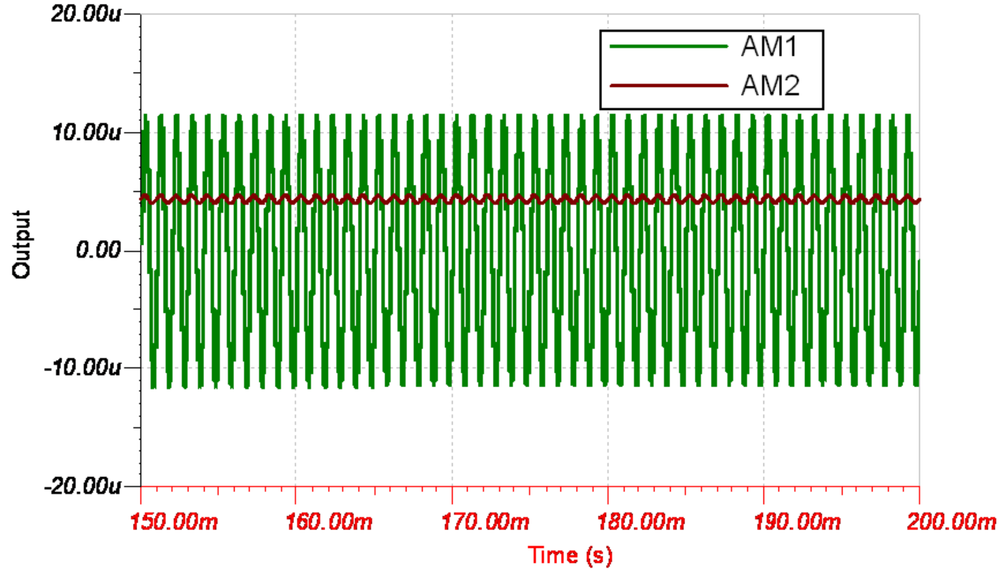



**Fig. Q.3.1(f)** The pulsating current in the capacitor branch measured by AM1.

The reader should note that the current is pulsating in the leads to the capacitor after it is fully charged to around 2 volts, which is the voltage of the junction of the voltage divider resistor network (comprising $R_1$ and $R_2$). The situation is a little similar to what we observed after a charged capacitor was fully discharged in Fig. 3.17, Chapter 3 with the difference that the capacitor is now charged to around 2 volts.

Remember, the signal and fringe fields are both present and pulsating in the capacitor and its leads and in the wires. Any deficit or excess charge will be absorbed by the voltage divider to maintain the junction voltage at around 2 volts.

For the simulation run using TINA, we have not connected the coupling capacitor $C_C$ and the load resistor $R_L$ (circuit schematic of Fig. Q.3.1(d)). Had they been connected, there would be a transient period when the capacitor $C_C$ charges up and the collector current enters the *sinusoidal steady-state*. The inquisitive reader may verify this by properly setting up the TINA software after reading the section "Visualizing the circuit in operation" at the end of this question.

As an aid to visualizing the current reversal when it crosses zero, the attention of the reader is drawn to Slide #48, power point presentation of Chapter 2 "Current Reversal – Visualization".

Ammeter AM2 records the pulsating signal current input into the transistor but is too small in magnitude on the same scale as that used for ammeter AM1, in the waveform screenshot shown in Figs. Q.3.1(e) and Q.3.1(f).

Fortunately, the time and output scales can be magnified in TINA and the resulting waveform more clearly depicts the current in Ammeter AM2 which is the current in the base of the transistor. This is shown in Fig. Q.3.1(g).

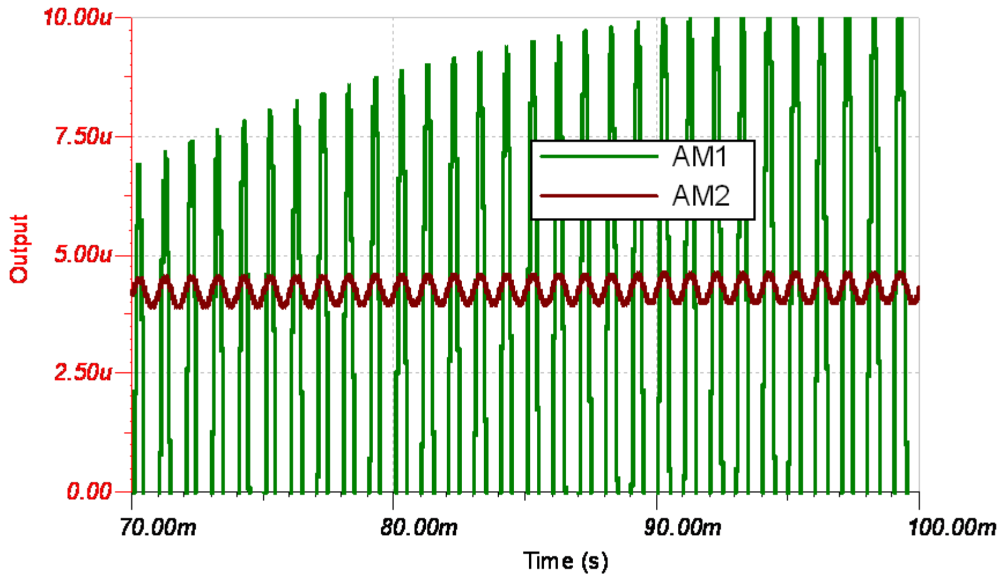



**Fig. Q.3.1(g)** The pulsating current into the base of the transistor measured by AM2.

It is interesting though not surprising to see that the current in the base is pulsating and unidirectional i.e., not symmetrical about the zero of the current axis. In the steady-state, the current grows in strength and weakens and again gains in strength and weakens, alternating in strength and weakening every cycle.

In essence, these tiny alternations superimpose over the steady dc biasing current, which appears to be about 4 microamperes. All the current components, steady and the pulsating, are unidirectional.

I urge the reader to pause and visualize the movement of the charge; the steadily increasing current with a tiny pulsating strength of the current superimposed. The visualization is not easy, but with some persistence it would be beneficial in understanding circuit operations.
Perhaps, visualizing the flow of thick slurry in pipes may help, with the alternating tiny (say about 0.5 microamperes) increase in flow followed by an ebbing (say about 0.5 microamperes), both in the *same direction*, once every cycle superimposed over the steady flow (4 microamperes).

The above was meant to aid in visualizing the rich dynamics of current in an amplifier circuit and develops a deeper understanding of the operation of the amplifier.

**III** We now return to the graphical analysis of amplifier operation and the use of the load line in its analysis. We reproduce the output portion of the circuit of Fig. Q.3.1(a) in Fig. Q.3.1(h).

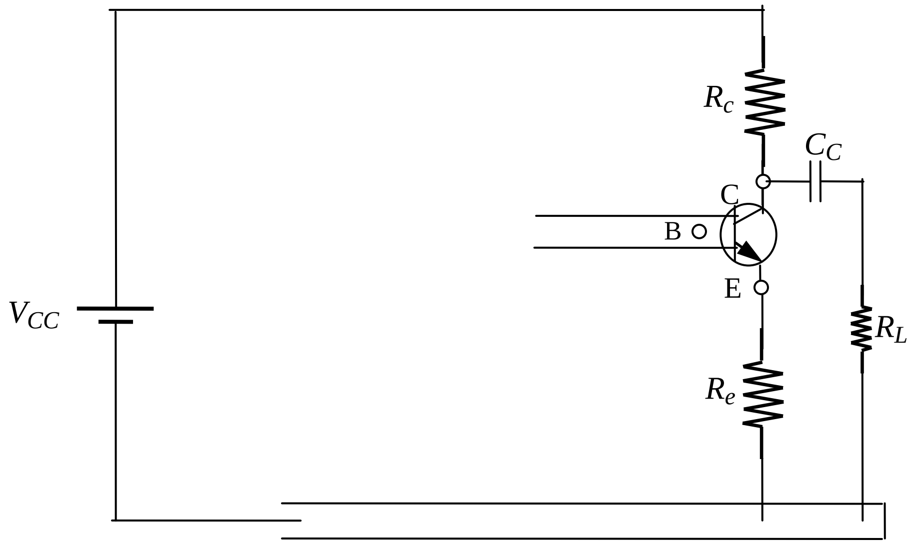



**Fig. Q.3.1(h)** The output circuit of the transistor amplifier with the coupling capacitor $C_C$.

The output circuit builds and couples the amplified output voltage and current to loads and subsequent stages of multistage amplifiers. The coupling is achieved by the capacitor $C_C$ and the load shown in Fig. Q.3.1(h) is a resistor $R_L$. The current in the collector driven by electric fields which fill the connecting wire, lead and the collector, is due to surface charges (not shown) on them. On the collector terminal this charge is the source for the output voltage.

The current pulsates powerfully and rhythmically in the output circuit; in the collector, in the base collector junction, in the base, and in the base emitter junction and in the emitter and the emitter resistor $R_e$.

The capacitor $C_C$ is usually large and is there primarily to block the dc component of the output signal into the load resistor $R_L$ which we set to 1 kilo-ohm. If we assume $C_C$ to be 2 μF, a 1 KHz signal in it will offer a reactance of $\frac{1}{2\pi f C}$ ohms = $\frac{1}{2\pi \times 10^3 \times 2 \times 10^{-6}}$ = 80 ohms approximately. This is quite small in comparison to say, a 1 kilo-ohm load resistor. The output signal voltage may be applied to another amplifier without affecting its bias, because of the blocking capacitor $C_C$.

**The static and dynamic load lines**

Fig. Q.3.1(b) shows a load line with a quiescent operating point set at location Q on the output characteristics of the BC 107 transistor. The load line is a dc or static load line. If $R_L$ is an infinitely large resistance and if the input signal (base current) is large and symmetrical, we must locate the operating point at the center of the load line. In this way, the collector voltage and current may vary approximately symmetrically around the quiescent (motionless) values $V_{CEQ}$ and $I_{CEQ}$, respectively.
It may be seen that the point Q is certainly not at the center of the load line.

If $R_L \neq \infty$ in the circuit of Fig. Q.3.1(a), however, a dynamic (ac) load line must be drawn. Since we have assumed that, at the signal frequency, $C_C$ (chosen to be 2 μF) has a very small reactance in comparison to the load, it may be treated as a short-circuit, and the effective load $R_L'$ at the collector is $R_C$ in parallel with $R_L$.

When an input sinusoidal signal is applied, an alternating current in the transistor is superimposed on the quiescent (dc) current. Waveforms of the base current, base voltage, collector current and collector voltage may be seen in Ref. [17]. The ac (or dynamic) load line must be drawn through the operating point Q and must have a slope corresponding to $R_L' = R_c \| R_L$, (if $R_e$ = 0). DC (or static) load line analysis gives the variation of collector currents and voltage for static situation of zero input signal voltage. An ac load line indicates the maximum possible output voltage swing or the maximum possible peak-to-peak output voltage from a given amplifier.

We do not use rms or average of ac variables. Instead we use maximum values of the ac signals to determine the maximum voltage swing. Circuit designers are interested to determine and set the quiescent operating point such that there is little distortion produced at the output.

**IV** The ac load line may be understood by using the ac equivalent circuit. A simple ac equivalent assumes that at the frequencies the amplifier is expected to amplify input sinusoidal signals in, the coupling capacitors $C_B$ and $C_C$ can be replaced by short circuits. Such an ac equivalent circuit of the output circuit is shown in Fig. Q.3.1(i).

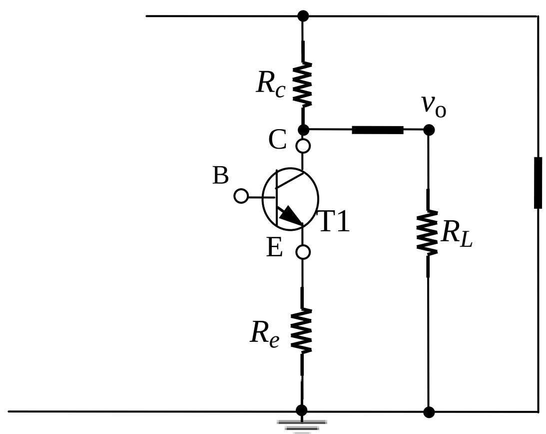



**Fig. Q.3.1(i)** The output circuit of the transistor amplifier with the coupling capacitors $C_B$ and $C_C$ and the dc voltage source replaced by short circuits.

A few hundred milliseconds after turn ON, in the transistor amplifier, ac currents are a superposition of pulsating currents on the quiescent dc currents and the transistor is in the sinusoidal steady-state.

As the input base voltage swings positive, the collector current increases over the quiescent value $I_{CQ}$ (the collector current at the quiescent operating point). And, because the load is now $R_L' = R_c \| R_L$, the current in the ac mode is larger and can exceed 3.4 milliamps which was the maximum in the dc mode.

The procedure for drawing the ac load line is formulated with the following constraints: i) the transistor should not be driven to either regions of operation; cut-off and saturation. ii) Output distortion should be a minimum. iii) dc quiescent power dissipation should be minimum, and iv) operation should lie within the transistor's power dissipation curve. The details of design are beyond the scope of this discussion and an excellent treatment is available in reference is Ref. [17].

From the above we may note that the dc load line is different from the ac load line. The dc load line represents variations in dc collector current given a transistor, a DC voltage source and the network resistances when the base current is varied slowly. We begin by drawing the static or dc load line on the transistor characteristics as shown by the **blue line** in Fig. Q.3.1(j).

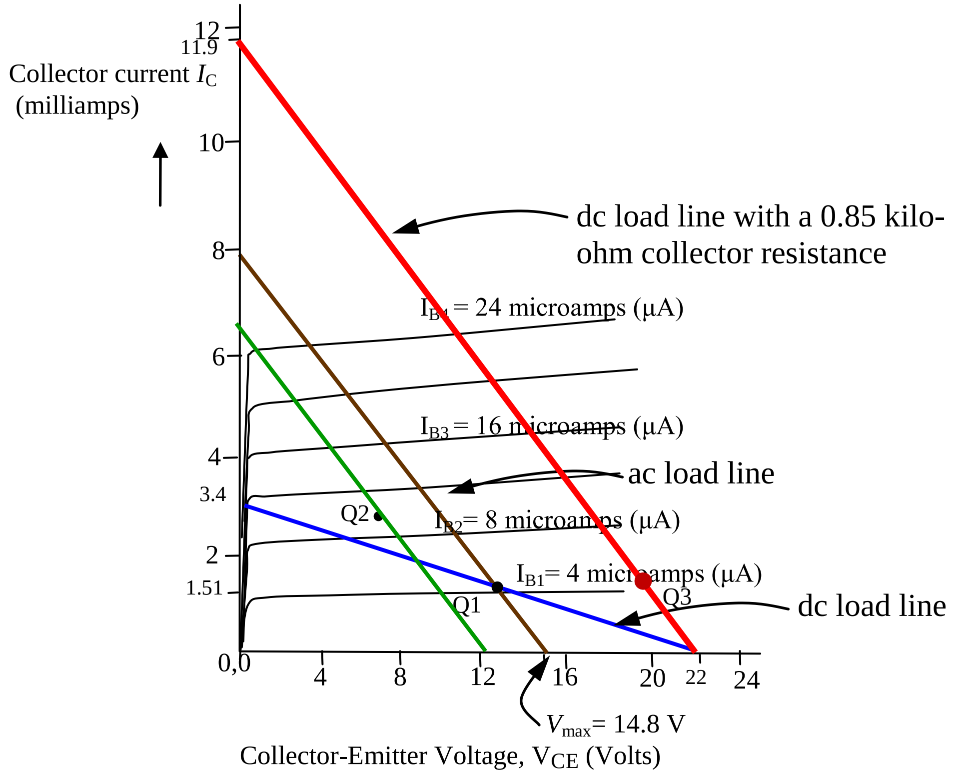



**Fig. Q.3.1(j)** Typical output characteristics of a transistor with a load assuming $V_{CC}$ = 22 volts.

The quiescent operating point established by the biasing network of Fig. Q. 3.1(d) is $V_{CEQ}$ = 12 Volts, $I_{CQ}$ = 1.51 mA and is marked Q1 in the Fig. Q.3.1(j). The dc load line also represents the variations in collector current and voltage to low frequency input signals around the quiescent values $V_{CEQ}$ and $I_{CQ}$, if the load was none other than the collector resistor $R_c$, i.e., if $R_L = \infty$.

An ac load line represents the variation in current to an input signal voltage when $R_L$ is finite (the coupling capacitor $C_C$ acts as a short-circuit), which makes the time-varying collector current *superimpose over* $I_{CQ}$, when the circuit enters the sinusoidal steady-state at the end of a transient period which charges up the coupling capacitors and an emitter-bypass capacitor if included in the circuit. This also means that the transistor will draw only the dc quiescent current when the input ac signal is zero.

As was noted earlier, with an input sinusoidal signal applied to the transistor base, at the output the capacitor $C_C$ couples amplified output signals to a load ($R_L$), the ac load line should rightly be drawn with a slope of $R_L' = R_c \| R_L$ and passing through the dc quiescent operating point. Because the maximum current is the maximum magnitude of the ac voltage divided by the equivalent load resistance ($R_L'$) which superimposes on the quiescent collector current, we can calculate the maximum collector current (ac) using the formula $I_{max} = I_{\mathrm{CQ}} + \frac{V_{CEQ}}{R_L'+R_e}$.

Let us understand each term in the formula. The first term on the right hand is $I_{\mathrm{CQ}}$ and is the current when the signal is zero. The $V_{\mathrm{CEQ}}$ (quiescent collector-emitter voltage) was fixed by the designer and set to 12 volts DC. At the same time, the $I_{\mathrm{CQ}}$ (quiescent collector current) value of 1.51 mA was chosen and fixed by the designer when the biasing network was designed for the chosen quiescent (dc) operating point. This current belongs to *both*, the dc static and ac time-varying signal applied condition and is present because of the self-bias of the circuit.

The second term on the right hand, $\frac{V_{CEQ}}{R_L'+R_e}$ denotes the amount by which the collector current (theoretically) may be increased to until, $V_{\mathrm{CE}}$ becomes zero, at which point the transistor will enter the saturation region and no amplification is possible.

Using $R_{\mathrm{c}}$ = 5.6 KΩ, $R_{\mathrm{L}}$ = 1 KΩ, we get $R_L' = \frac{5.6\mathrm{K}}{6.6\mathrm{K}} = 0.85\mathrm{K}$. With $R_e$ = 1 KΩ, we get $I_{max}(\mathrm{mA}) = 1.51 + \frac{12V}{1.85K\Omega} \approx 8$ mA.

The ac load line is drawn as a **brown line** in Fig. Q.3.1(j) and is a straight line between the dc quiescent operating point Q1 and the point 8 mA on the collector current $I_{\mathrm{C}}$ axis.

The $V_{\mathrm{max}}$ point is located on the $V_{\mathrm{CE}}$ axis by the load line. It may also be calculated using the formula $V_{\mathrm{max}} = V_{CEQ} + I_{CQ}(R_L' + R_e)$.

Let us examine the formula for $V_{\mathrm{max}}$. It contains two terms; the first $V_{CEQ}$ and represents the collector-emitter voltage when the signal is zero and is there because of the biasing circuit. The second term $I_{CQ}(R_L' + R_e)$ is interesting because it tells us when the transistor cuts off or, the amount of collector voltage swing available (for signal reproduction without distortion) below the quiescent point given the network with the equivalent ac load $R_L'$ with the $R_e$ which is always present.

To determine where it intersects the collector-emitter voltage axis, we use the formula and after substituting values, we have $V_{\mathrm{max}} = 12V + 1.5 \times 1.85K\Omega$ = 12V + 2.775 ≈ 14.8 volts, from which we note that the available swing for the collector-emitter voltage from $V_{\mathrm{CEQ}}$ = 2.8 volts.

It is quite obvious from the location of the quiescent point Q1 that the input signal may swing a maximum of approximately 4 μA and no larger around Q1 because, if the base current decreases by more than 4 μA, the transistor is driven off. Therefore, the designer should consider shifting the operating point to location Q2 as shown in Fig. Q.3.1(j). Note that the slope of the ac load line is not changed when the operating point Q1 is shifted to Q2 which may be made by adjusting the values of $R_1$ and $R_2$ of the biasing network.

*Why can we not use a formula $I_{max} = \frac{V_{CC}}{R_L'+R_e}$ to get the maximum current for the ac load line ?*

The formula if used, gives us an $I_{max} = \frac{V_{CC}}{R_L'+R_e} = \frac{22V}{1.85K} =$ 11.9 mA approximately, but the application of the formula is wrong. It assumes that the collector resistor is 0.85 K ohm. In reality, the collector resistor is 5.6 K ohm.

For illustration, we have drawn a static load line (**red line**) assuming the collector resistor to be 0.85 Kohm in the Fig. Q.3.1(j). We find that the load line does not pass through the quiescent operating point which was established by the biasing network. What has gone wrong ? Our

assumption of a 0.85 kilo-ohm collector resistor is wrong. With this assumption we have conjured an entirely different configuration of the transistor amplifier; a third system.
What the original circuit design (represents is of two systems; i) the static case dc load line (**blue line**) which is applicable to the amplifier with its signal zero, and ii) the dynamic case ac load line (**brown line**) which is applicable when the signal input is given. The operating point on the load line switches between the two systems; it stays for an instant on the dc load line when the signal is zero and traverses the ac load line when the signal is other than zero.
What was wrong with the third system is it did not account in a sense, for the switch from dc to ac modes when the signal is swinging through zero which the coupling capacitor $C_C$ enables.
When the transistor operates as an amplifier and an input signal is applied, there is a quiescent dc collector operating current and a pulsating ac collector current. The system would have changed from *one* (without an ac signal or rather the ac signal set to zero volts) in which one resistor the load $R_L$ is effectively disconnected from the transistor by the coupling capacitor $C_C$, to another *system* in which the ac collector current signal is superimposed on the quiescent current and the load resistor $R_L$ is connected because the capacitor $C_C$ acts as a short-circuit. Obviously, there is no real *switching* between load lines of systems; i) only $R_c$ and ii) load with $R_c$, $C_C$ and $R_L$. The circuit of Fig. Q.3.1(a) is on the ac load line all the time and the collector current and collector emitter voltage are $I_{CEQ}$ and $V_{CEQ}$ respectively (where the dc and ac load lines meet) on the dc load line when the VG1 signal is reversing.

*Why does the cut-off of the transistor occur at 14.8 volts and not 22 volts ?*

If we did not have a separate load resistor and no coupling capacitor $C_C$ and had simply a 0.85 kΩ load resistor and a 1KΩ emitter resistor, we would draw the static load line **(red line)** as shown in Fig. Q.3.1(j). This intersects the collector-emitter voltage axis on 22 Volts, the value of the DC supply voltage. The maximum collector current would be 11.9 mA. The quiescent operating point is now 19.2V, 1.51mA with the same biasing network and is indicated by the **red dot Q3** (the graph of Fig. Q.3.1(j) is not drawn accurately to scale).
This is not the quiescent operating point of the original circuit with the output stage as shown in Fig. Q.3.1(i). The original circuit is constrained to be at the quiescent operating point ($V_{CEQ}$ = 12 Volts, $I_{CQ}$ = 1.51 mA) by the biasing network and therefore, the static load line **(red line)** of the third inaccurate system should in reality be shifted to the left. And, when we do that we will find that the line coincides with the ac load line (**brown line**) of the original system with the coupling capacitor $C_C$ and load resistor $R_L$ at the output. On this load line (the **brown** colored ac load line) the transistor cuts-off when $V_{CE}$ is 14.8 volts.

*With the transistor in cut-off in the operational circuit* (Fig. Q.3.1(a)) *when $V_{CE}$ reaches 14.8 volts, where does the voltage amount* (22 – 14.8) = 7.2 volts *drop ?*

It drops across the resistor $R_c$. This may be difficult to view using TINA software. In reality, the voltages and current undergo rapid transformations when the transistor enters the cut-off region. This is one among several other reasons that circuit designers will prefer to operate the transistor with the quiescent operating point marked Q2 in the Fig. Q.3.1(j). It affords a larger input signal swing and a corresponding large output collector current swing as well. The ac load line through the new operating point Q2 is shown in **green colour**.
The biasing network of Fig. Q.3.1(d) will need to be changed to set this operating point.

I urge the reader to check the onset of distortion at the output using different combinations of resistor $R_1$ and by varying the amplitude of the input signal using TINA software. To view the distortion (near transistor cut off), may require the input signal amplitude to be set to nearly 2 volts or more. In the TINA editor, a table of ac results can be displayed by clicking in the menu, Analysis →AC Analysis to view the currents in ammeters AM1, AM2 and $R_c$.
There is a virtual oscilloscope feature in the TINA software also that may be used to view the signal waveforms. A circuit set up, such as the one in the Fig. Q.3.1(k) for viewing the output waveform with SPDT and SPST switches will be useful. (Note Labels: $C_C$ is C2 and $R_L$ is R3)

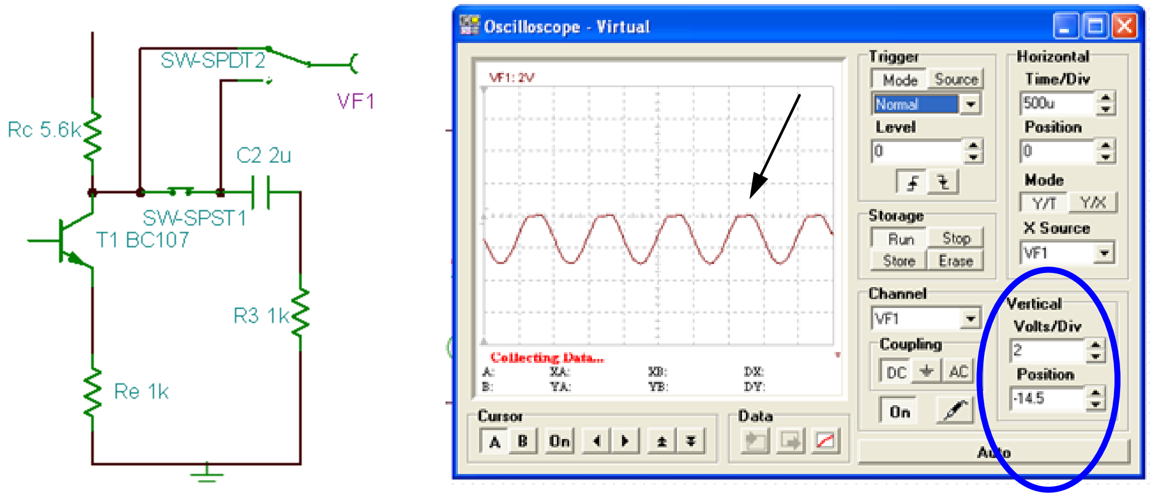



**Fig. Q.3.1(k)** A connection to view the onset of cut-off on the TINA (Virtual) oscilloscope

The onset of distortion when the transistor enters cut-off is visible (shown by the arrow) with the settings of Position, Volts/Div and Time/Div in the screen shot. The input signal voltage amplitude when distortion due to the transistor entering the cut-off region is about 2 volts.

**Visualizing the circuit in operation**

I will urge the reader to pause for a moment to visualize the harmonious rhythmic pulsations to the beat (frequency) of currents and fields, their strengthening and weakening in all the components, the lead wires and at the junctions in a well designed circuit in response to properly sized input signal amplitudes. When visualizing, do not bother about the circuit entering the cutoff region or saturation region of the transistor. Instead, assume all is well and the output is without distortion, and visualize the entire circuit with the pulsating currents and fields (filling the wires, and the components).

**Q.3.2** Design a biasing network for the amplifier circuit of Fig. Q.3.1(a) with the operating point at location Q2 in the Fig. Q.3.1(j) such that $I_{CQ}$ = 2.5 mA and $V_{CEQ}$ = 6.1 volts DC. Given: $R_c$ = 5.6 KΩ, $R_e$ = $R_L$ =1 KΩ and $C_B$ = $C_C$ = 2μF, $R_2$ = 10 KΩ. a) Draw the dc and ac load lines for the amplifier. b) What is the input and output signal amplitude when the transistor enters the cut off region and signal distortion occurs ? c) Does the output voltage across $R_L$ swing around a dc voltage or around zero volts ? Explain.
**Note:** The output characteristics of the BC 107 are not accurate as shown in Figs. Q.3.1(j) and may look different from those that are found on the Internet.

## Chapter 4

**Q.4.1*** In the vicinity of the earth's orbit around the sun, the energy intensity of sunlight is about 1400 $W/m^2$. What is the approximate magnitude of the electric field in sunlight ? (What you calculate is actually the "root-mean-square" or "rms" magnitude of the electric field, because in sunlight the magnitude of the electric field at a fixed location varies sinusoidally, and the intensity is proportional to $E^2$.)

**Q.4.2*** A small laser used as a pointer produces a beam of red light 5mm in diameter and has a power output of 5 milliwatts. What is the magnitude of the electric field in the laser beam ? (Remember the Poynting vector S is the rate of energy flux in watts per square meter).

## Chapter 5

**Q.5.1*** What is the direction of the magnetic field at the indicated locations inside the current-carrying rectangular coil of wire in Fig. Q.5.1 ? Explain briefly. (The direction of conventional current is shown.)

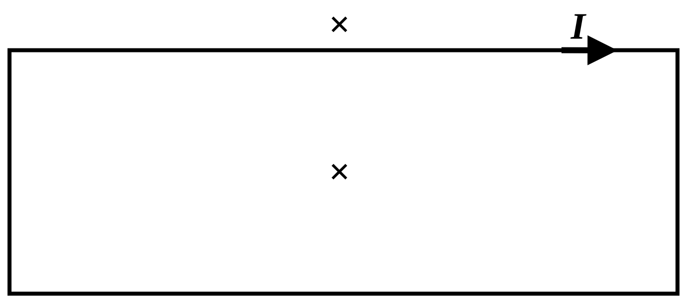



**Fig. Q.5.1**

**Q.5.2*** To get an idea of the size of the magnetic fields at the atomic level, consider the magnitude of the magnetic field due to the electron in the simple Bohr model of the hydrogen atom. In the ground state the Bohr model predicts that the electron speed would be $2.2 \times 10^6$ m/s, and the distance from the proton would be $0.5 \times 10^{-10}$ m. What is $B$ at the location of the proton.

**Q.5.3*** In a circuit consisting of a long bulb and two flashlight batteries in series the conventional current is about 0.1 ampere.
What is the magnetic field 5 mm from the wire ? (This is about how far away the compass needle is when you place the wire on top of the compass.) Is this a big or a small field ?

**Q.5.4*** A loop of wire carries a conventional current of 0.8 amperes. The radius of the loop is 0.09 m.

i) Calculate the magnitude of the magnetic field at a distance of 0.32 m from the center of the loop, along the axis of the loop.

ii) What would the magnitude of the magnetic field be at the same location if there were 100 loops of wire in a coil instead of one loop ?

**Q.5.5*** i) Calculate the maximum magnitude of the alternating magnetic field, 50 cm away from the center of long straight cord that carries a current of 15 amperes to power a home appliance as shown in the Fig. Q.5.5a. Both wires are at the same height as the observation location.

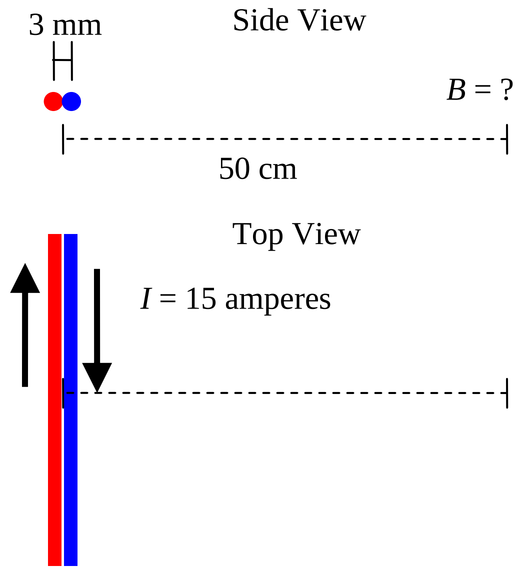



**Fig. Q.5.5a**

ii) Explain briefly why twisting the pair of wires into a braid as shown in Fig. Q.5.5b would minimize the magnetic field at the location discussed in (i).

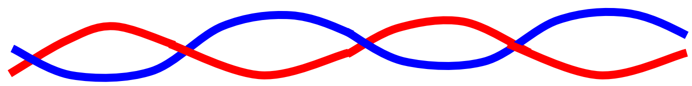


**Fig. Q.5.5b**

**Q.5.6*** In Fig. Q.5.6 the magnetic field in the solenoid (of radius $r_1$) increases from 0.1 tesla to 0.7 tesla in 0.2 seconds, and the area of the solenoid is 3 $cm^2$.

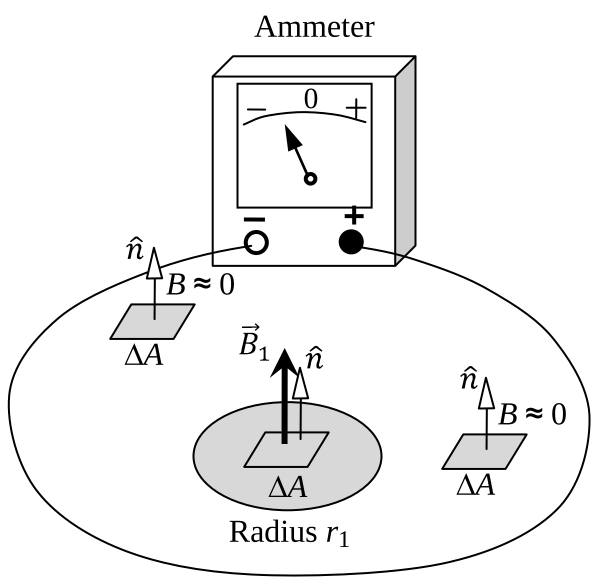



**Fig. Q.5.6**

a) Calculate the magnetic flux $\phi_{mag}$on the area enclosed by the solenoid, the flux on the other portions of the area encircled by the circuit, and the total flux on the area encircled by the circuit.

b) What is the emf around the circuit ?

c) If the resistance of the wire plus ammeter is 0.5 ohms, what current will the ammeter display.
Hints: Consider the magnetic field on every small area outside the solenoid is zero.

**Q.5.7** According to the Emission Theory of Leigh Page, an accelerating charge sends out circular waves. i) Using this principle and Huygens' principle, show how the waves propagate in a transmission line. ii) Describe briefly how there is an opposite wave (reflected wave) propagates from a discontinuity.
Hint: See **Section 3.8** in "Prof. Härtel A qualitative approach to electricity A Guide to visualization of electrodynamics" in the Teacher's Guide in the CD.

**Q.5.8** Traditionally it is shown that when charging a capacitor, charges accumulate on the plates of the capacitor and the electric field lines on the two plates meet in the gap between the plates. This explanation does not conform to the definition of electric field lines which should be continuous with no discontinuity.

With the help of neat sketches, describe the process based on Transmission line theory.

Hint: See **Section 3.9.4** in "Prof. Härtel A qualitative approach to electricity A Guide to visualization of electrodynamics" in the Teacher's Guide in the CD.

**Q.5.9** A TEM wave is guided between two perfectly conducting parallel planes as shown in Fig. Q.5.8. (Ref. [16].)

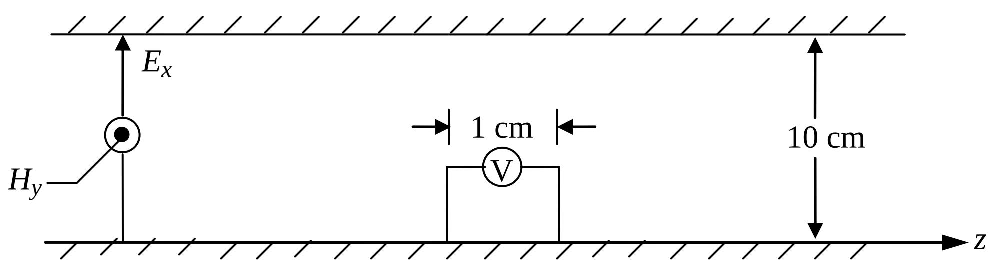



**Fig. Q.5.8** A transverse electromagnetic (TEM) wave between parallel planes

The frequency is 300 MHz. Determine the voltage reading of the (infinite impedance) voltmeter
(a) by using Maxwell's electromotive force law (Faraday's Law);

(b) in terms of voltages induced in conductors which are parallel to the electric field.

# Chapter 6

**Q.6.1*** The Fig.Q.6.1 shows sketches of an electron in space where there is an electric and a magnetic field in four different scenarios.

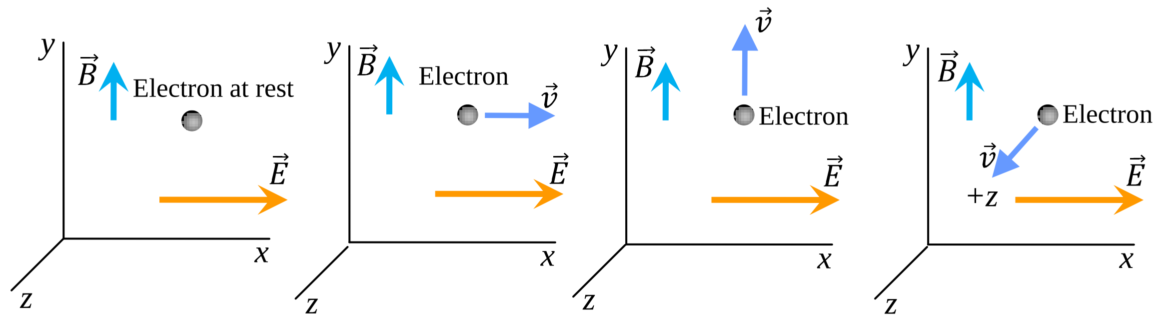



**Fig. Q.6.1**

In each example in Fig.Q.6.1, what is the direction of the net electric and magnetic force on an electron at this instant.

**Q.6.2*** Consider a bar of iron of length 5 cm, height 2 cm, and depth of 0.5 mm, carrying a conventional current of 15 A to the right in the presence of a perpendicular magnetic field of magnitude 2 T, as shown in Fig. Q.6.2. There are about $8.4 \times 10^{28}$ electrons per cubic meter in iron.

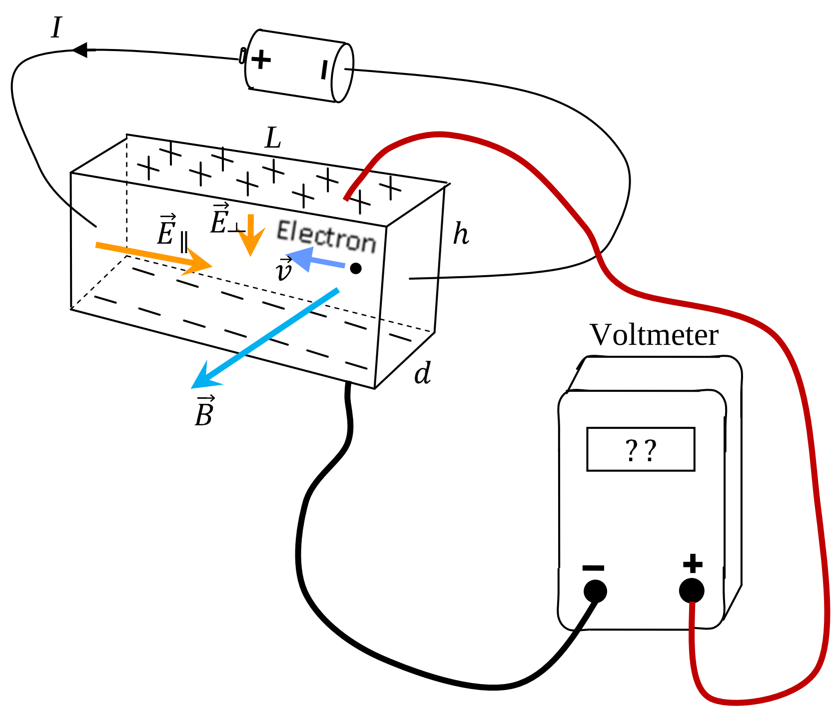



**Fig. Q.6.2**

a) Determine the transverse potential difference also called the Hall effect voltage across the bar.

Step – 1 First determine the average drift speed of the moving electrons using the formula for current.

Step – 2 Then, because in the steady state, the vertical force (force perpendicular to current flow) on a moving charge is zero, obtain a formula for the perpendicular component of the electric field.

Step – 3 The electric field multiplied by the distance it acts gives the Hall voltage.

b) Comment on the tininess of the magnitude of the voltage.

c) Calculate the density of mobile charges in the metal and comment on how many electrons an individual atom could have given up into the free-electron sea.

## Chapter 7

**Q.7.1*** The Fig. Q.7.1 shows a neutral metal rod of length 0.45 m sliding horizontally to the left at a constant speed of 7 m/s on frictionless *insulating* rails through a region of uniform magnetic field of magnitude 0.4 tesla, directed out of the page.

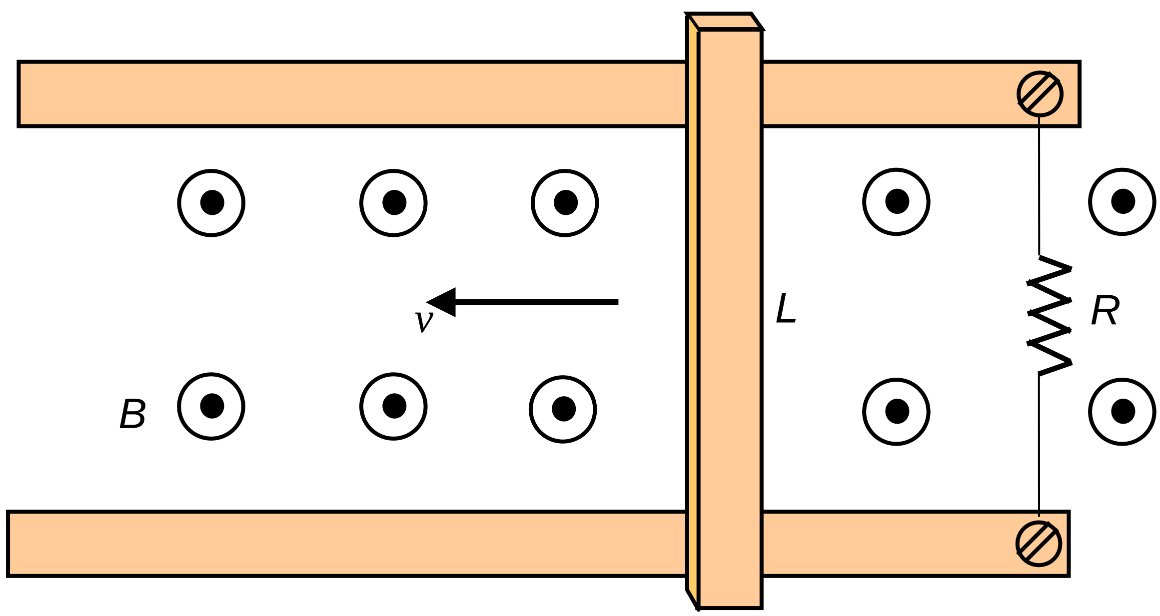



**Fig. Q.7.1**

Before answering the following questions, draw a diagram showing the polarization of the rod, and the direction of the Coulomb electric field inside the rod.

a) Which of the following statements is true ?

i) The top of the moving rod is positive.

ii) The top of the moving rod is negative.
iii) The right side of the moving rod is positive.
iv) The right side of the moving rod is negative.

b) After the initial transient, what is the magnitude of the net force on a mobile electron inside the rod ?

c) What is the magnitude of the electric force on a mobile electron inside the rod ?

d) What is the magnitude of the magnetic force on a mobile electron inside the rod ?

e) What is the magnitude of the potential difference across the rod ?

f) In what direction must you exert a force to keep the rod moving at constant speed ?

## Chapter 8

**Q.8.1*** The Fig. Q.8.1 shows a circuit consisting of a battery and a long wire, part of which is in a uniform magnetic field pointing out of the page.

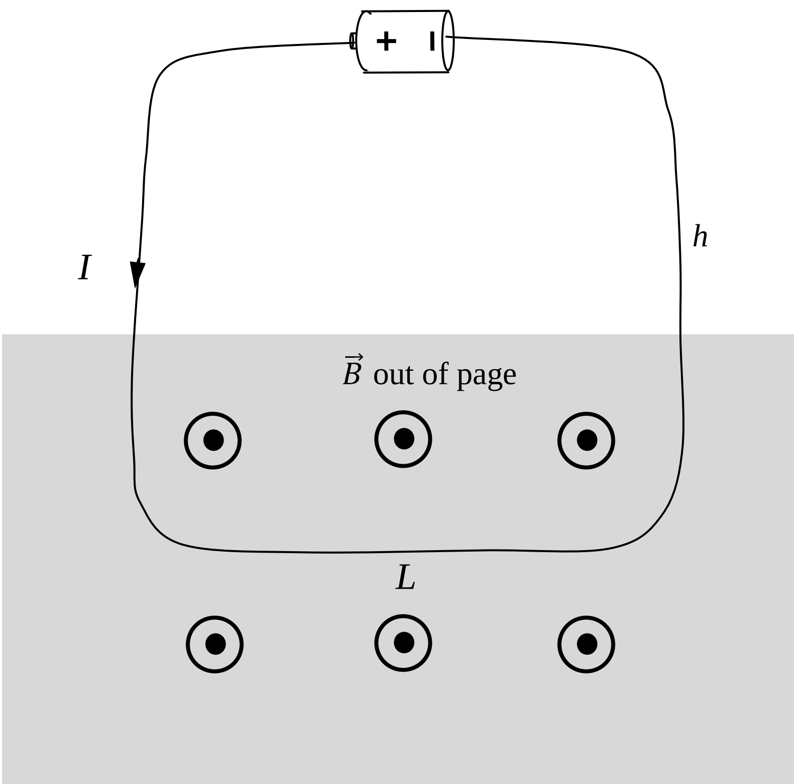



**Fig. Q.8.1** Magnetic forces on a loop of wire carrying conventional current *I*.

a) Sketch the direction of the magnetic force on each of the 3 segments of the long wire (2 vertical segments and one horizontal segment in the uniform magnetic field).

b) Using a different arrow symbol, sketch the net force on the wire. Describe the effect of the individual component of the force on each segment of the loop.

c) What is the magnitude of the net force on the wire in terms of the magnetic field $B$, current $I$, height $h$, and length $L$.

d) Using the formula of part (c), assuming $B$ = 1 tesla, $I$ = 10 amperes, $h$ = 50 cm, and $L$ = 10 cm, calculate the net force. How does it compare with the force exerted by the gravitational field on an apple.

**Q.8.2*** A nichrome wire has the shape of two quarter-circles of radius $a$ and $b$, connected by straight sections as shown in Fig. Q.8.2.

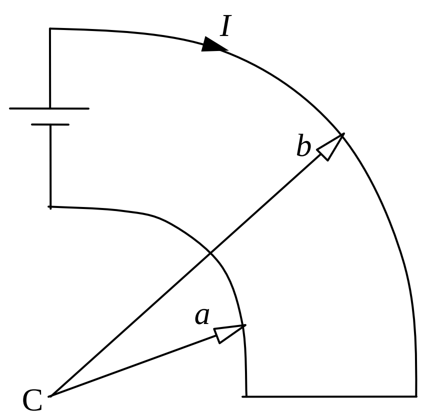



**Fig. Q.8.2** A circuit produces a magnetic field and affects a moving electron

The wire carries a conventional current $I$ in the direction shown.

a) Calculate the direction and magnitude of the magnetic field at point C, the center of the quarter-circles. Briefly explain your work, including a diagram.

b) At a particular instant, an electron is at point C, traveling to the right with speed $v$. Calculate the direction and magnitude of the magnetic force on the electron. Briefly explain your work, including a diagram.

## Chapter 9

**Q.9.1** Two silicon diodes Type 1N4007 are connected as shown in Fig. Q.9.1. Assume that the circuit is in room temperature.

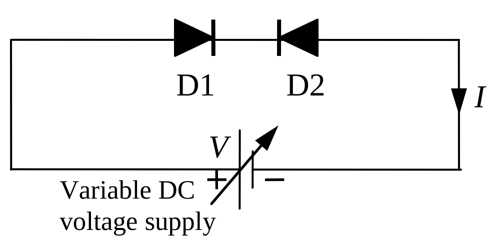



**Fig. Q.9.1** A circuit with two diodes.

Assume $V$ = 5 volts for questions (a) to (i).

a) On a sketch of a magnified view of the circuit with the wires shown by two parallel lines, the bulk regions and depletion region of the *p-n* junctions of the two diodes, draw field vectors with relative strengths represented using thin and thick arrows at several locations. Pay attention to the direction of arrows when marking them in the depletion regions. The sketch will be useful in answering the following questions.

b) Will diode D1 be forward-biased or reverse biased ? Explain.

c) Will the diode D2 be forward-biased or reverse biased ? Explain.

d) Will the conventional current $I$ with direction indicated be positive or negative ? Explain.

e) We can identify two distinct conduction processes in a *p-n* junction diode: i) the current due to recombination of an electron with a hole, which is called the "recombination" current. ii) a current due to the drift of liberated electrons and holes in an electric field when hole-electron pairs are generated, which is called the "generation" current. Usually both are present simultaneously in the diode though with different intensities.
Identify the dominant type of current in the diodes D1 and D2 in the Fig. Q.9.1.

f) What is the order of current you expect will flow in the circuit ? Which diode would you say determined the magnitude ? Explain.

g) What is the magnitude and direction of the current ? Assume conventional current flow direction and mark it in a sketch of the figure. If necessary, refer to the table below Fig. 9.41.

h) Make a sketch of the *V-I* characteristics of each diode (assume that they have identical characteristics) and on them mark approximately the operating point.

i) What should the voltage drop across each diode sum up to ? Explain.

j) Roughly indicate the voltage drops across each diode. Explain how you determined the voltage drops.

k) What is the maximum voltage that can be applied to the circuit before circuit breakdown ? Give reasons and backup your answer with component specification data (Refer Section 9.9 and the table below Fig. 9.41.)

**Q.9.2** Two identical silicon *p-n* diodes with a maximum current rating of 1 Ampere are connected in parallel as shown in Fig. Q.9.2.

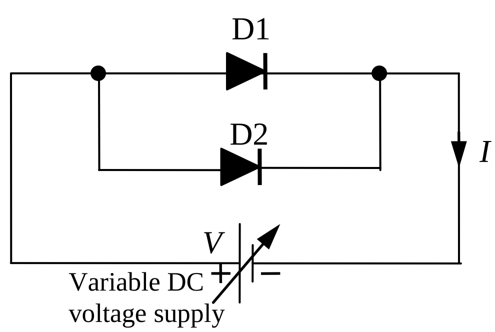



**Fig. Q.9.2** Two identical silicon diodes connected in parallel

On a sketch of a magnified view of the circuit with the wires shown by two parallel lines, the bulk regions and depletion region of the *p-n* junctions of the two diodes, draw field vectors with relative strengths represented using thin and thick arrows at several locations. This will assist in answering the following questions.

a) If a small voltage ($V$ = 0.4 volts) were to be applied will the diodes conduct ? And, will they conduct simultaneously ? Explain.

b) Mark current arrows with labels $I_1$ and $I_2$ in each of the diode branches. Write an expression for $I$ using $I_1$ and $I_2$. Are the currents in the two diodes different ? If the voltage is increased will the currents be different in the two diodes ?

c) Assuming that the diodes are identical 1N4007 diodes (Refer Section 9.9 and the table below Fig. 9.41), and if the variable DC voltage is adjusted such that $I$ = 5 milliamps, will the voltage be less than or greater than the cut-in voltage ?

d) What is the order of the maximum voltage that can be applied to the circuit before circuit breakdown ? Give reasons.

e) Treating both the parallel connected diodes as a single component unit, sketch the combined *V-I* characteristic.

f) Diode D2 is changed to a different type, say a 1N914 with a maximum current rating of 10 milliamperes.

i) What will be the effect on the currents $I_1$ and $I_2$ ? Explain.

ii) Will the voltage across the diodes change ? Explain.

iii) Is the voltage drop different across the two diodes ? If yes, then what effect do the two diodes make to themselves to ensure steady-state.

iv) What is the order of the maximum voltage that can be applied to the circuit before circuit breakdown ? Give reasons.

## Chapter 10

**Q.10.1*** If the magnetic field in a particular pulse has a magnitude of $1 \times 10^{-5}$ tesla (comparable to the earth's magnetic field), what is the magnitude of the associated electric field ? Is the field radiative or inductive or electrostatic ?

**Q.10.2*** A pulse of radiation propagates with velocity $v = \langle 0, c, 0 \rangle$. The electric field in the pulse is $\langle 0, 0, 1 \times 10^6 \rangle$ N/C. Is the field radiative or inductive or electrostatic ? What is the magnetic field (vector) in the pulse ?

Hint: Using Eqs. (9) and (10) in Chapter 10, obtain a relation between E, B and $v$. Then, use $v = c$.

**What led Einstein to the postulates of the Theory of Special Relativity**

If you were to move at a speed *c* with a beam of light, then you will observe a stationary wave of the beam whose electric and magnetic field components will be

$$\vec{E} = \sin(kx)\,\hat{j} \text{ and magnetic field } \vec{B} = \sin(kx)\,\hat{k}.$$

A wave being a function of both space and time then, due to the variation of *E* with both time *t* and space variable *x*, we may plot *E* as a function of *t* by keeping *x* constant and also make a plot of *E* as a function of *x* by keeping *t* constant.

A plot of *E* vs. *t* is the classic sinusoidal waveform and the plot of *E* vs. *x* is also a sinusoidal waveform as shown in Fig. Q.l0.2.

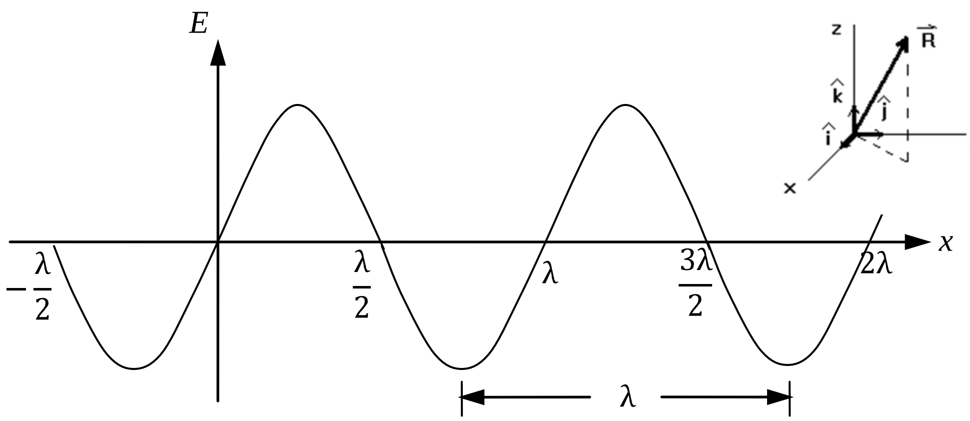



**Fig. Q.10.2** A plot of the spatial variation of electric field *E* of an electromagnetic wave.

See Ref. [32], for detailed descriptions and a plot of the electric and magnetic field spatial variations at one instant of time.

The reader is cautioned to view the variations in time and space as variation of the *strength* of the electric field in time and space. See Figs. 10.2 and 10.9 in the book.

Such a waveform has wavelength (λ) = 2π/*k* and the em wave travels in the direction of the *x*-axis (the direction of unit vector $\hat{\imath}$).

For such a waveform $\nabla \times \vec{E} = k\cos(kx)\,\hat{k}$ and $\frac{\partial \vec{B}}{\partial t} = 0$.

{**Note** $\nabla \times \vec{E} = \begin{vmatrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ 0 & \sin(kx) & 0 \end{vmatrix} = 0\hat{\imath} + 0\hat{\jmath} + kcos(kx)\hat{k} - 0\hat{\imath} - 0\hat{\jmath} - 0\hat{k} = k\cos(kx)\,\hat{k}$}.

This conflicts with Faraday's Law which is one of Maxwell's equations, $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$. And, $\frac{\partial \vec{B}}{\partial t} = 0$ would have meant that the beam no longer propagates, which is incorrect and so, the speedy observer with the beam can't exist.

This led Einstein to pronounce the postulates (Section F.5, Appendix F) of the Theory of Special Relativity, according to which, Maxwell's equations hold unaltered in every inertial reference frame (as do all laws of nature) and the equations also predict that the vacuum speed of light is always *c* in such a frame.

Observers in two different spaceships moving towards each other either head on or in orthogonal directions will record the speed of a beam of light emitted by one of them to be *c*; the color of the light is different for the two observers but the speed is the same viz. *c* (see Ref.[41]).

Also see "Doppler shift" in the links_to_animations_articles file in the CD.

**Q.10.3*** An electron is traveling at nonrelativistic (far less than the speed of light) speed along the z-axis in the +z direction in a region of nearly zero fields (Fig. Q.10.3).

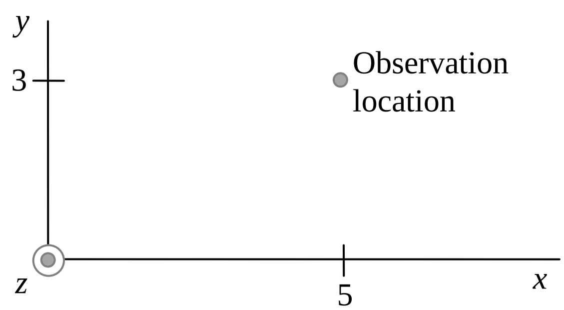



**Fig. Q.10.3** An electron enters a region of electric field

At $t = 0$, it reaches the origin $\langle 0, 0, 0\rangle$ and enters a region where the electric field is $\langle 0, 0, 2 \times 10^{16}\ \mathrm{V/m}\rangle$. You observe fields at location $\langle 5, 3, 0\rangle$ m. In the following, explain your work fully.

a) When do you first observe radiative fields ? Explain.

b) On the diagram, show the direction of the initial radiative electric field at your location. Explain.

c) On the diagram, show the direction of the initial radiative magnetic field at your location.

d) What is the magnitude of the initial radiative electric field at your location.

e) What is the magnitude of the initial radiative magnetic field at your location.

Hint:

Step – 1 Calculate the time it would take for light to propagate from the origin to the observation location.

Step – 2 Note the direction of the electric field (external) where the electron enters the region of the electric field.

Will the electron accelerate or decelerate because of the field ?
Mark the acceleration direction at the observation location using a circle with × in the center to indicate into the page or a circle with a · in the center to indicate out of the page.

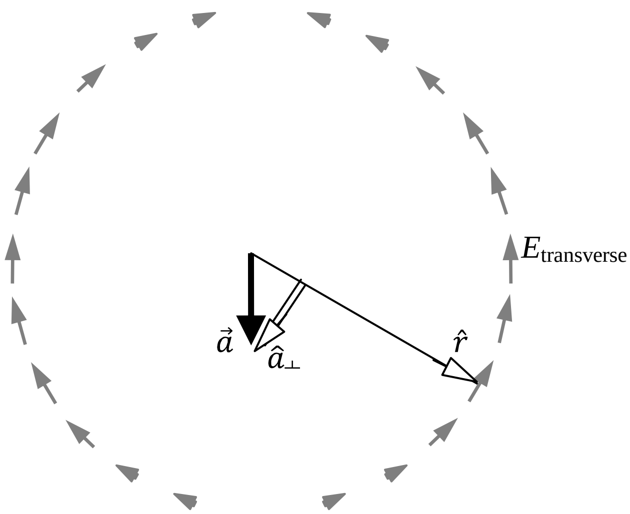
If the electron were to be motivated in the same direction you should expect an acceleration out of the page and if it were to be pulled back the acceleration would be in the opposite direction.

Step – 3 The direction of wave propagation is given by $\vec{E} \times \vec{B}$ which should be from the origin to the observation location.

Mark the direction of $\vec{B}$ at the observation location using this information. Note that the Biot-Savart predicts a direction opposite to the direction you would have obtained.

And, the magnitude given by the Biot-Savart law would be different from the magnitude predicted by a radiative field (proportionality with distance factor). Explain.

Step – 4 From the force equation $ma = eE/m$ where $m$ is the mass of the electron, $a$ it's acceleration and $E$ the electric field, obtain the acceleration $a$ of the electron. Strictly speaking the acceleration $a$ is the projected acceleration $\hat{a}_\perp$ as shown in the sketch.




However, because the speed of the electron is nonrelativistic, the projected acceleration $\hat{a}_\perp$ will be nearly equal to the acceleration.

Step – 6 Plug this into the equation (See Eq. 13, Chapter 10 with $\theta$ = 90°) to obtain the magnitude of the transverse electric field.

Step – 7 Using Eqs. 9 and 10 in Chapter 10, show that $\frac{E_t}{B_t} = c$. Calculate $B_t$ using this formula.

**Q.10.4*** This question is related to the speed of waves in matter.

**How does light *slow down* in a material ?**
In Section 10.5 we had discussed the index of refraction of a material and stated that the index is given by $c/v$, where $v$ is the speed of light in a material say, glass. But in fact the speed of light is a universal quantity, so to say that the "light travels more slowly in the glass" would be incorrect. The slowing down is *apparent* and for a description of how this is so, read an article by Prof. Bruce Sherwood, here https://brucesherwood.net/?p=95 .

a) Distinguish between the mechanism that causes the speed of a voltage wave to slow down in a transmission line and the mechanism which makes a light wave slow down in matter.

b) The index of refraction of water is 1.33. At what speed would a crest in a beam of visible light move through water ? Hint: See "Index of Refraction" in Chapter 10.

**Q.10.5*** A receiving antenna is oriented in three different ways (A, B, and C) as shown in Fig. Q.10.5.

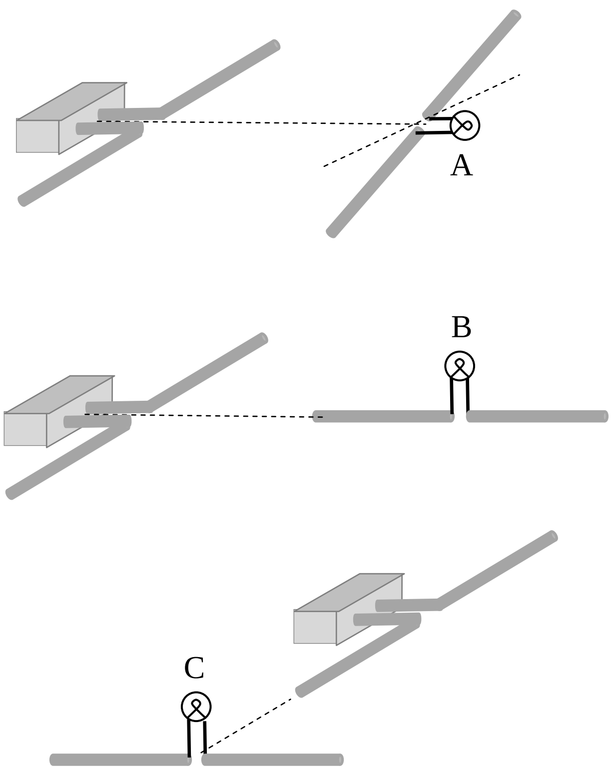



**Fig. Q.10.5** Antenna and receiver orientations

In each case, predict the brightness of the bulb and explain briefly.

Hint: Make simple sketches of the radiative electric field vectors (small arrows with correct direction) at the location of the receiving antenna. Then, sketch the components of the electric field along the length of the receiving antenna for different orientations. This should provide some clues about the amount of power delivered to the bulb by the transmitting antenna.