PH 212: PHYSICS II

Lecture PowerPoints

CAPACITANCE

Topics Covered

- Capacitor
- Charging and Discharging Capacitor
- Charging and Discharging Processes
- Capacitors and A.C. Circuits
- Capacitance Definition and Units
- Parallel Plate Capacitor
- Capacitance of Isolated Sphere
- Capacitors in series and parallel
- Charging and discharging a capacitor in C-R circuit
- Energy stored in a capacitor
- Energy and Q— V Graph, Heat Produced in Charging
- Connected Capacitors, Loss of Energy

Capacitor

Capacitor

- A capacitor is a device for storing charge.
- The earliest capacitor was invented almost accidentally by van Musschenbroek of Leyden, in about 1746 and became known as a Leyden jar.
- One form of it is shown in Figure 1(i);
  - J is a glass jar, FF are tin-foil coatings over the lower parts of its walls, and T is a knob connected to the inner coating.
  - Modern forms of capacitor are shown at (ii) and (iv) in the figure.
- Essentially *all capacitors consist of two metal plates separated by an insulator.*
  - The insulator is called the dielectric; in some capacitors it is polystyrene, oil or air.
- Figure 1 (iii) shows the circuit symbol for such a capacitor; T T are terminals joined to the plates.

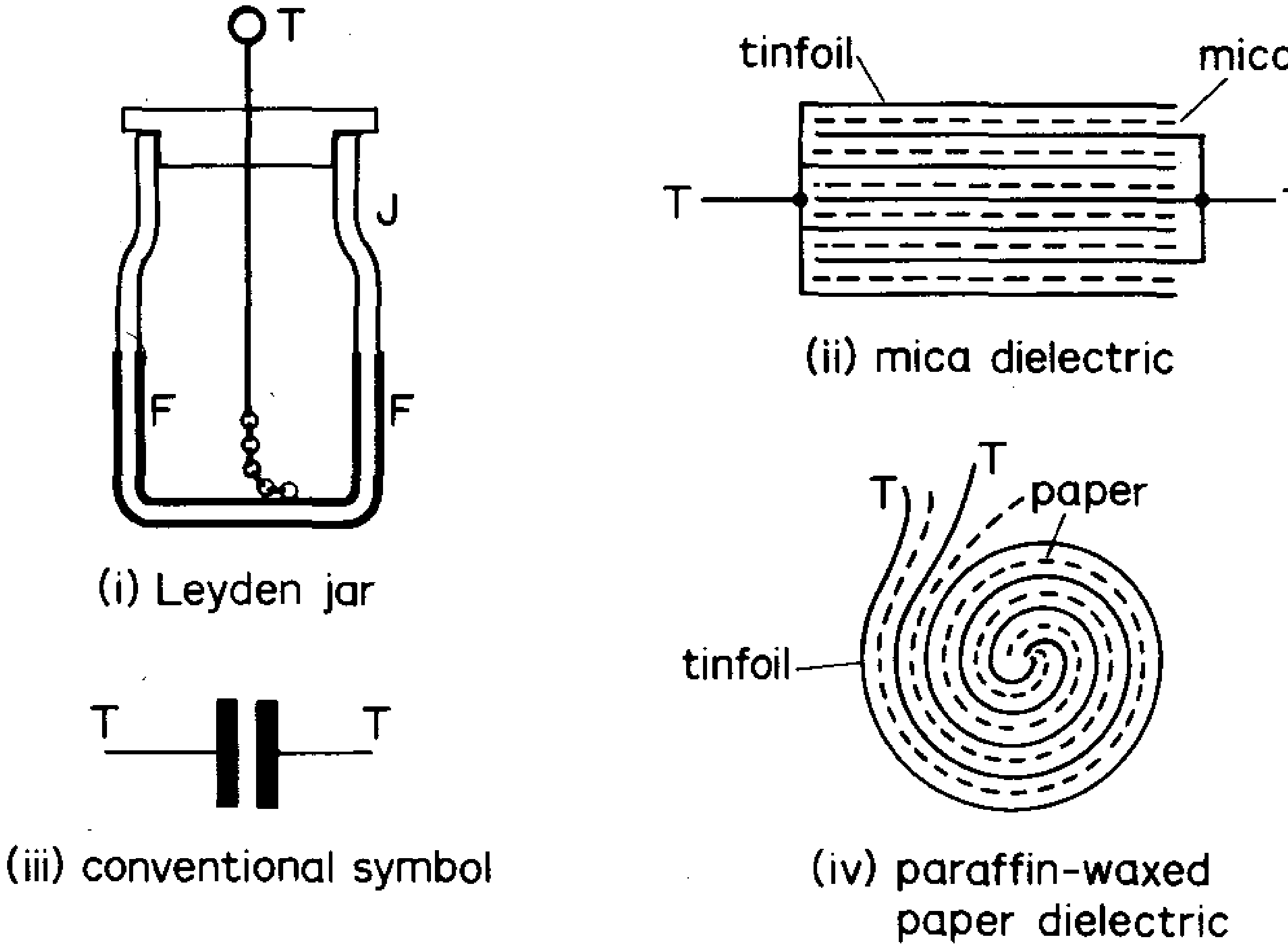

Figure 1: Types of capacitor

Charging and Discharging Capacitor

Charging and Discharging Capacitor (1)

- Figure 2 (i) shows a circuit which may be used to study the action of a capacitor.
  - C is a large capacitor such as 500 microfarad,
  - R is a large resistor such as 100 kiloOhms (10^5 Ω),
  - A is a current meter reading up to 100 microamperes (100 μA),
  - K is a two-way key, and D is a 6 V d.c. supply.
- When the battery is connected to C by contact at X,
  - The current *I* in the meter A is seen to be initially about 60 μA
  - Then as shown in Figure 2 (ii), it slowly decreases to zero.
- So current flows to *C* for a short time when the battery is connected to it, even though the capacitor plates are separated by an insulator.
- We can disconnect the battery from *C* by opening *X*.

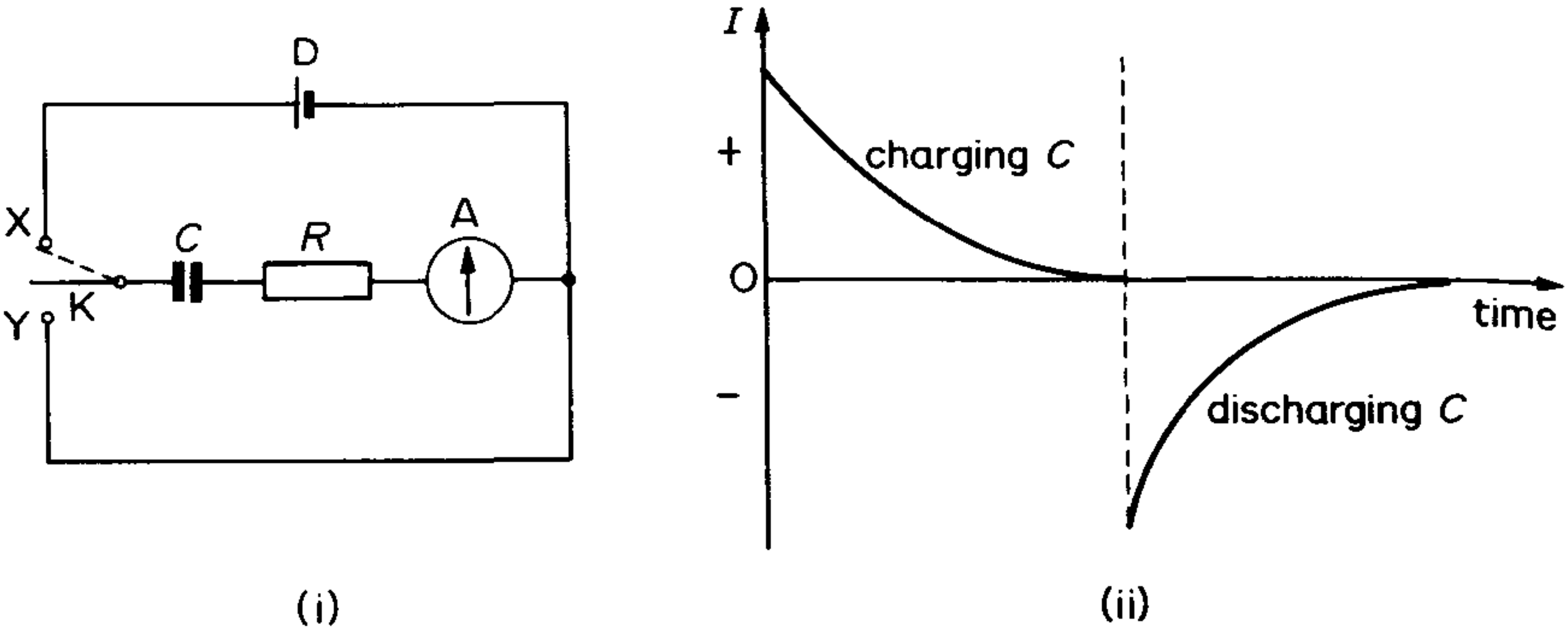

Figure 2: Charging and discharging capacitor

Charging and Discharging Capacitor (2)

- If contact with *Y* is now made, so that in effect the plates of *C* are joined together through *R* and *A*,
  - the current in the meter is observed to be about 60 μA initially in the opposite direction to before and then slowly decreases to zero, Figure 2 (ii).
- This current flow shows that *C* stored charge when it was connected to the battery originally.
- Generally, a capacitor is charged when a battery or p.d. is connected to it.
- When the plates of the capacitor are joined together, the capacitor becomes discharged.
- Large values of *C* and *R* in the circuit of Figure 2 (i) help to slow the current flow,
  - so that we can see the charging and discharging which occurs.

Charging and Discharging Capacitor (3)

- We can also show that a charged capacitor has stored energy by connecting the terminals by a piece of wire.
- A spark, a form of light and heat, passes just as the wire makes contact.

Charging and Discharging Processes

Charging and Discharging Processes (1)

- When we connect a capacitor to a battery,
  - electrons flow from the negative terminal of the battery on to the plate A of the capacitor connected to it (Figure 3).
- At the same rate, electrons flow from the other plate B of the capacitor towards the positive terminal of the battery.
  - Equal positive and negative charges therefore appear on the plates, and opposite the flow of electrons which causes them.
- As the charges increase, the potential difference between the plates increases,
  - and the charging current falls to zero when the potential difference becomes equal to the battery voltage V_0.
- The charges on the plates B and A are now +Q and –Q, and the capacitor is said to have stored a charge Q in amount.

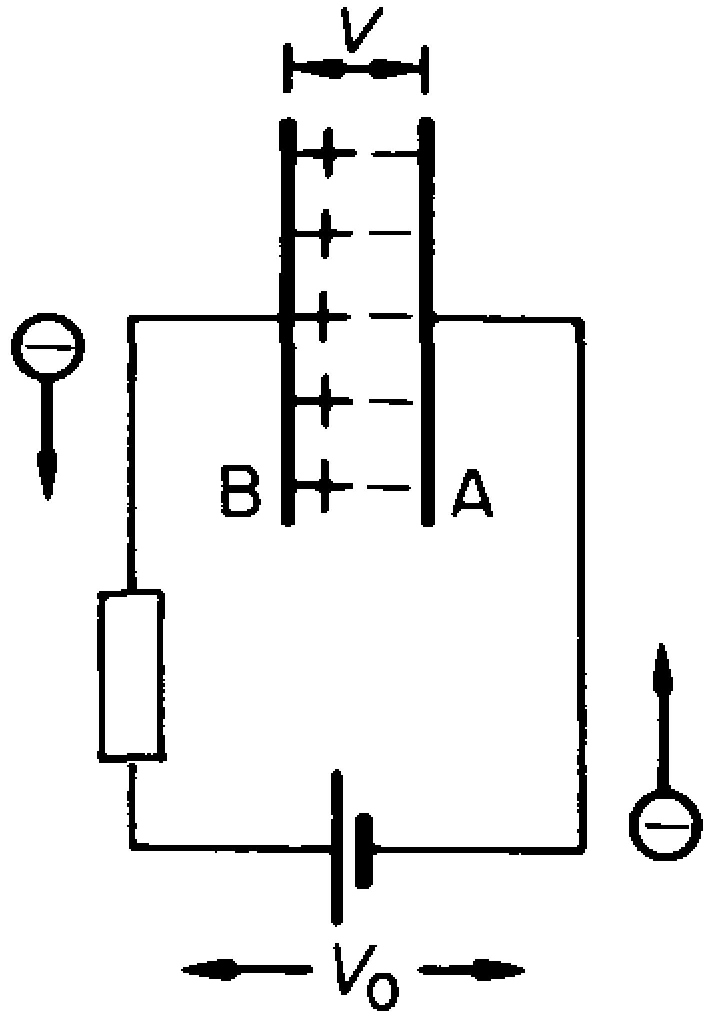

Figure 3: A capacitor charging (resistance is shown because some is always present, even if only that of the connecting wires)

Charging and Discharging Processes (2)

- Alternatively, if we think of the battery as an ‘electric pump’, it pushes electrons or negative charge from B round to A.
  - So when the electrons stop moving, A has a negative charge –Q and B is left with an equal positive charge +Q.
- When the battery is disconnected and the plates are joined by a wire,
  - electrons flow back from plate A to plate B until the positive charge on B is completely neutralized.
- So a current flows for a time in the wire, and at the end of the time the charges on the plates become zero.
  - So the capacitor is discharged.
    - Note that a charge Q flows from one plate to the other during the discharge.

Capacitors and A.C. Circuits

Capacitors and A.C. Circuits (1)

- Capacitors are widely used in alternating current and radio circuits,
  - because they can transmit alternating currents.
- To see how they do so, let us consider circuit of Figure 4, in which the capacitor D may be connected across either of the batteries X, Y.
- When the key is closed at A, current flows from battery X, and charges the plate D of the capacitor positively.
- If the key is now closed at B instead, current flows from the battery Y;
  - the plate D loses its positive charge and becomes negatively charged.

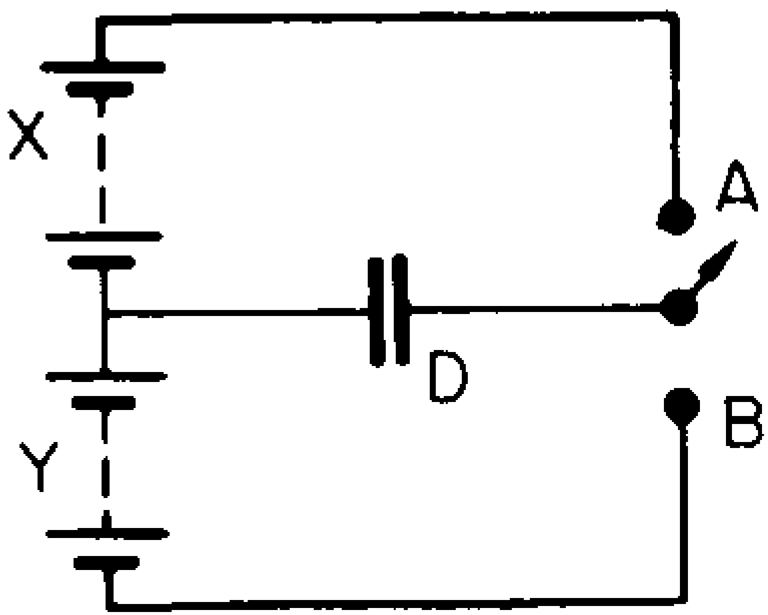

Figure 4: Reversals of voltage applied to capacitor

Capacitors and A.C. Circuits (2)

- So if the key is rocked rapidly between A and B,
  - current surges backwards and forwards along the wires connected to the capacitor.
- An alternating voltage, is one which reverses many times a second.
- When such a voltage is applied to a capacitor, therefore, an alternating current flows in the connecting wires,
  - even though the capacitor has an insulator between its plates.

Capacitance Definition and Units

Capacitance Definition and Units (1)

- Since $Q \propto V$, the ratio Q/V is a constant for the capacitor.
- The ratio of the charge on either plate to the potential difference between the plate is called the capacitance, C, of the capacitor:

  $C = Q/V$, so **$Q = CV$** and **$V = Q/C$**
- When Q is in coulombs (C) and V in volts (V), the capacitance C is in farads (F).
  - One farad (1F) is the capacitance of a very large capacitor.
- In practical circuits, such as in radio receivers, the capacitance of capacitors used are therefore expressed in microfarads (μF).
- One microfarad is one millionth part of a farad, i.e., 1 μF $= 10^{-6}$ F.

Capacitance Definition and Units (2)

- It is also quite usual to express small capacitors, such as those used on hi-fi systems, in picofarads (pF).
- A picofarad is one millionth part of a microfarad, i.e., 1pF = 10^{-6} μF = $l0^{-12}$ F.
- A nanofarad (nF) = 10^{-9}F.1 μF = 10^{-6} F, 1 nF = 10^{-9} F, 1 pF = $l0^{-12}$ F

Parallel Plate Capacitor

Parallel Plate Capacitor (1)

- We now obtain a formula for the capacitance of a parallel-plate capacitor which is widely used.
- Suppose two parallel plates of a capacitor each have a charge numerically equal to Q, Figure 5.
- The surface density σ is then Q/A where A is the area of either plate and the field-strength between the plates, E, is given by,

  $$\mathbf{E = \sigma / \varepsilon = Q / (\varepsilon A)}$$

- Now E is numerically equal to the potential gradient V/d

  $$\mathbf{V/d = Q / (\varepsilon A)}$$

  $$\mathbf{Q/V = \varepsilon A / d}$$

  Therefore $\mathbf{C = \varepsilon_0 A / d}$

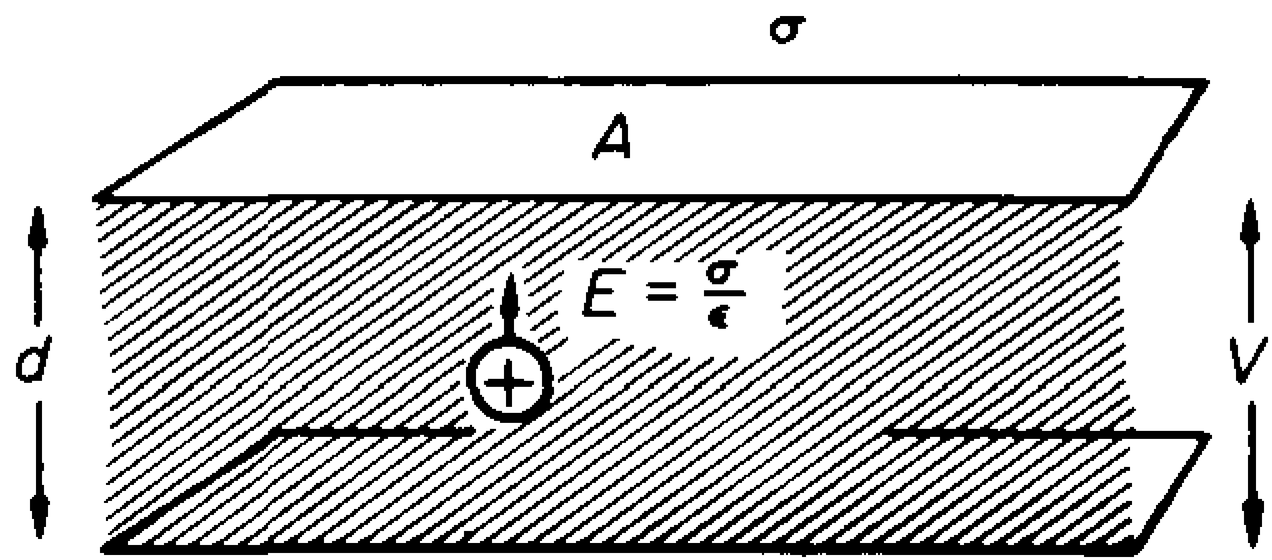

Figure 5: Parallel-plate capacitor

Parallel Plate Capacitor (2)

- So a capacitor with parallel plates, having a vacuum (or air, if we assume the permittivity of air is the same as a vacuum) between them, has a capacitance given by

  $C = \varepsilon_0 A / d$

where

C = capacitance in farads (F),

A = area of overlap of plates in metre^2,

d = distance between plates in metres and

$\varepsilon_0 = 8.854 \times 10^{-12}$ farads metre^{-1}.

Capacitance of Isolated Sphere

Capacitance of Isolated Sphere

- Suppose a sphere of radius r metres situated in air is given a charge of Q coulombs.
- We assume, that the charge on a sphere gives rise to potentials on and outside the sphere as if all the charge were concentrated at the centre.
- The surface of the sphere thus has a potential relative to that 'at infinity' (or, in practice, to that of the earth) given by

  $V = Q / (4\pi\varepsilon_0 r)$

  Therefore $Q/V = 4\pi\varepsilon_0 r$

  Capacitance, $C = 4\pi\varepsilon_0 r$
- The other 'plate' of the capacitor is the earth.
- Suppose $r = 10$ cm $= 0.1$ m.
  - Then $C = 4\pi\varepsilon_0 r = 4\pi \times 8.85 \times 10^{-12} \times 0.1$ F $= 11 \times 10^{-12}$ F (approx.) = 11 pF

Capacitors in series and parallel

Capacitors in series and parallel (1)

- In radio circuits, capacitors are used in arrangements whose total capacitance C must be known.
- To find C, we need the equations

  $\mathbf{C = Q/V, \ V = Q/C, Q = CV}$
- *Capacitors In Parallel*.
  - Figure 6 shows three capacitors, having all their left-hand plates connected, and also all their right-hand plates.
  - They are said to be connected in parallel across the same potential difference V.
  - The charges on the individual capacitors are respectively

    $Q_1=C_1V, \ Q_2=C_2V, \ Q_3=C_3V.$
  - The total charge on the system of capacitors is

    $Q= Q_1 + Q_2 + Q_3 = (C_1+ C_2 + C_3) V$

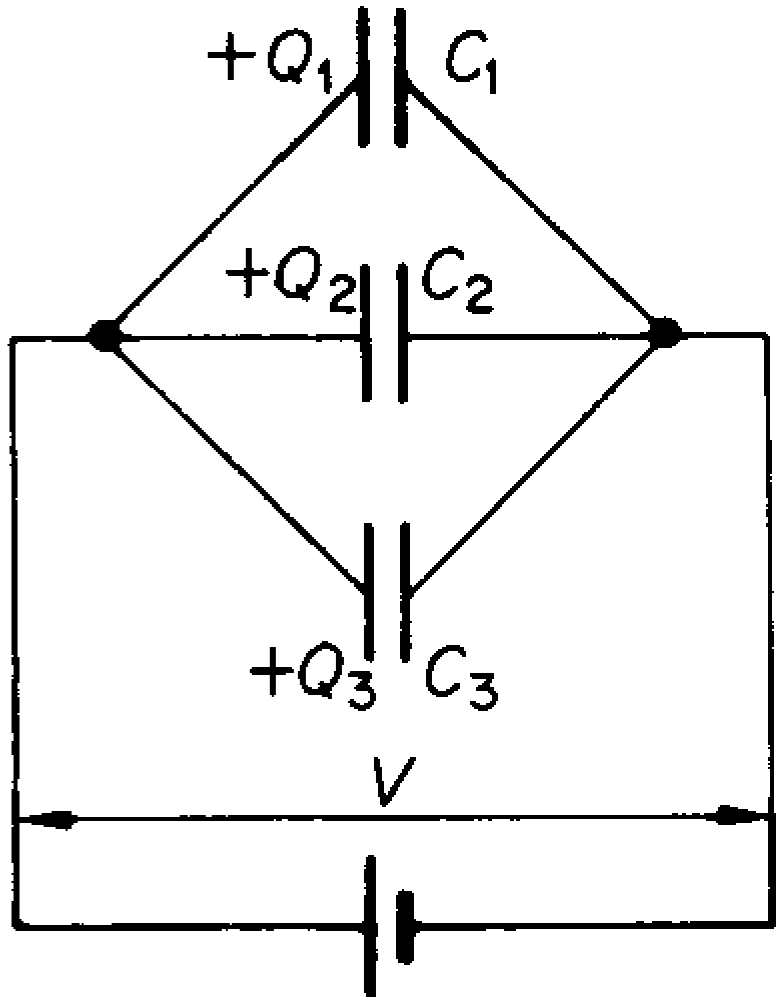

Figure 6: Capacitors in parallel

Capacitors in series and parallel (2)

  - The system is equivalent to a single capacitor, of capacitance

    $\boldsymbol{C = Q/V = C_1 + C_2 + C_3}$
  - So when capacitors are connected in parallel, their resultant capacitance C is the *sum* of their individual capacitances.
  - C is greater than the greatest individual one.
- *Capacitors In Series*
  - Figure 7 shows three capacitors having the right-hand plate or one connected to the left-hand plate of the next, and so on – connected in *series.*
- When a cell is connected across the ends of the system,
  - a charge *Q* is transferred from the plate H to the plate A, a charge –*Q* being left on H.
  - This charge induces a charge +*Q* on plate G; similarly, charges appear on all the other capacitor plates, as shown in the figure.

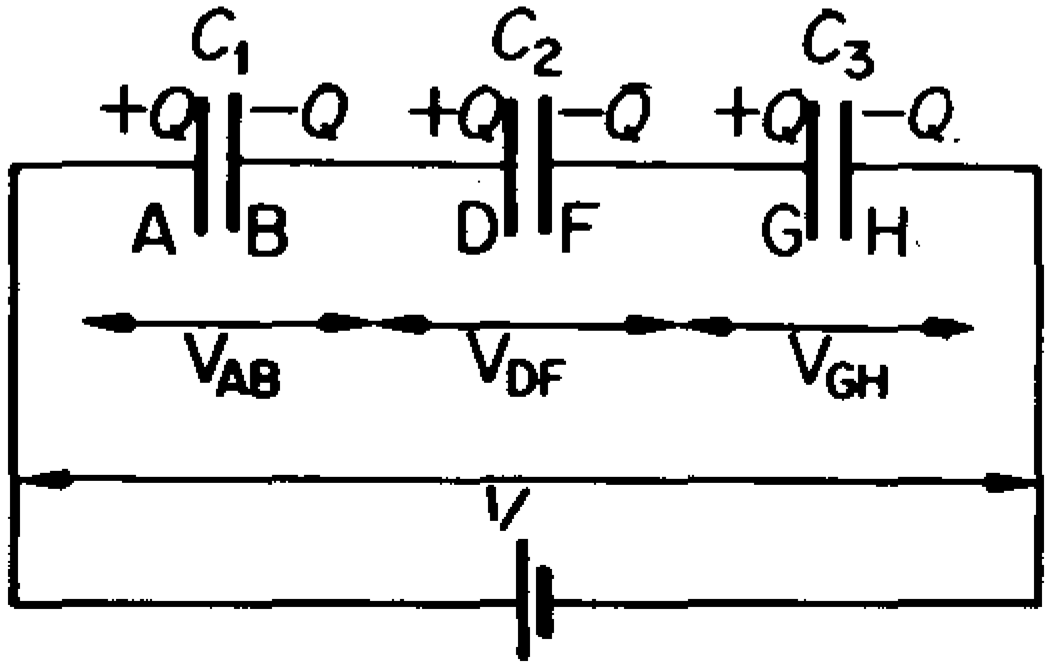

Figure 7: Capacitors in series

Capacitors in series and parallel (3)

- The induced and inducing charges are equal because the capacitor plates are very large and very close together; in effect, either may be said to enclose the other.
- The potential differences across the individual capacitors are, therefore, given by

$V_{AB} = Q/C_1$, $V_{DF} = Q/C_2$, $V_{GH} = Q/C_3$

- The sum of these is equal to the applied potential difference V
  - because the work done in taking a unit charge from H to A is the sum of the work done in taking it from H to G, from F to D, and from B to A.
- So **$V = V_{AB} + V_{DF} + V_{GH}$**

  $= Q\,(1/C_1 + 1/C_2 + 1/C_3)$

- The resultant capacitance of the system is the ratio of the charge stored to the applied potential difference, V.
- The charge stored is equal to *Q*, because, if the battery is removed, and the plates HA joined by a wire, a charge *Q* will pass through that wire, and the whole system will be discharged.

Capacitors in series and parallel (4)

– The resultant capacitance is therefore given by

$C = Q/V$ or **$1/C = V/Q$**

– So

$1/C = 1/C_1 + 1/C_2 + 1/C_3$

– So, to find the resultant capacitance C of capacitors in series,

  - we must add the reciprocals of their individual capacitances.

– C is less than the smallest individual.

Comparison of Series and Parallel Arrangements

- Let us compare Figures 6 and 7.
- In Figure 7, where the capacitors are in *series*,
  - all the capacitors have the same charge, which is equal to the charge carried by the system as a whole *Q*.
- So to find the charge *Q* on each capacitor, use

  $\boldsymbol{Q = CV}$

  - where *C* is the resultant or total capacitance given by the 1/C in the equation for the resultant capacitance.
- The potential difference applied to the system is divided amongst the capacitors, in inverse proportion to their capacitances.
- In Figure 6, where the capacitors are in *parallel*,
  - they all have the same potential difference. The charge stored is divided amongst them, in direct proportion to the capacitances.

Examples on Capacitors in Series and Parallel (1)

1. In Figure 8(i), C_1(3 μF) and C_2 (6 μF) are in series across a 90 V d.c. supply. Calculate the charges on C_1 and C_2 and the p.d. across each.

- Total capacitance *C* is given by $1/C = 1/C_1 + 1/C_2$

  1/C = 1/3 + 1/6 = 3/6

  Thus C = 2 μF

- The charges on C_1 and C_2 are the same and equal to *Q* on *C*.
- So $Q = CV = 2 \times 10^{-6} x90 = 180 \times 10^{-6}\ C$
- Then $V_1 = Q/C_1 = 180 \times 10^{-6} / 3 \times 10^{-6} = 60V$
- and $V_2 = Q/C_2 = 180 \times 10^{-6} / 6 \times 10^{-6} = 30V$

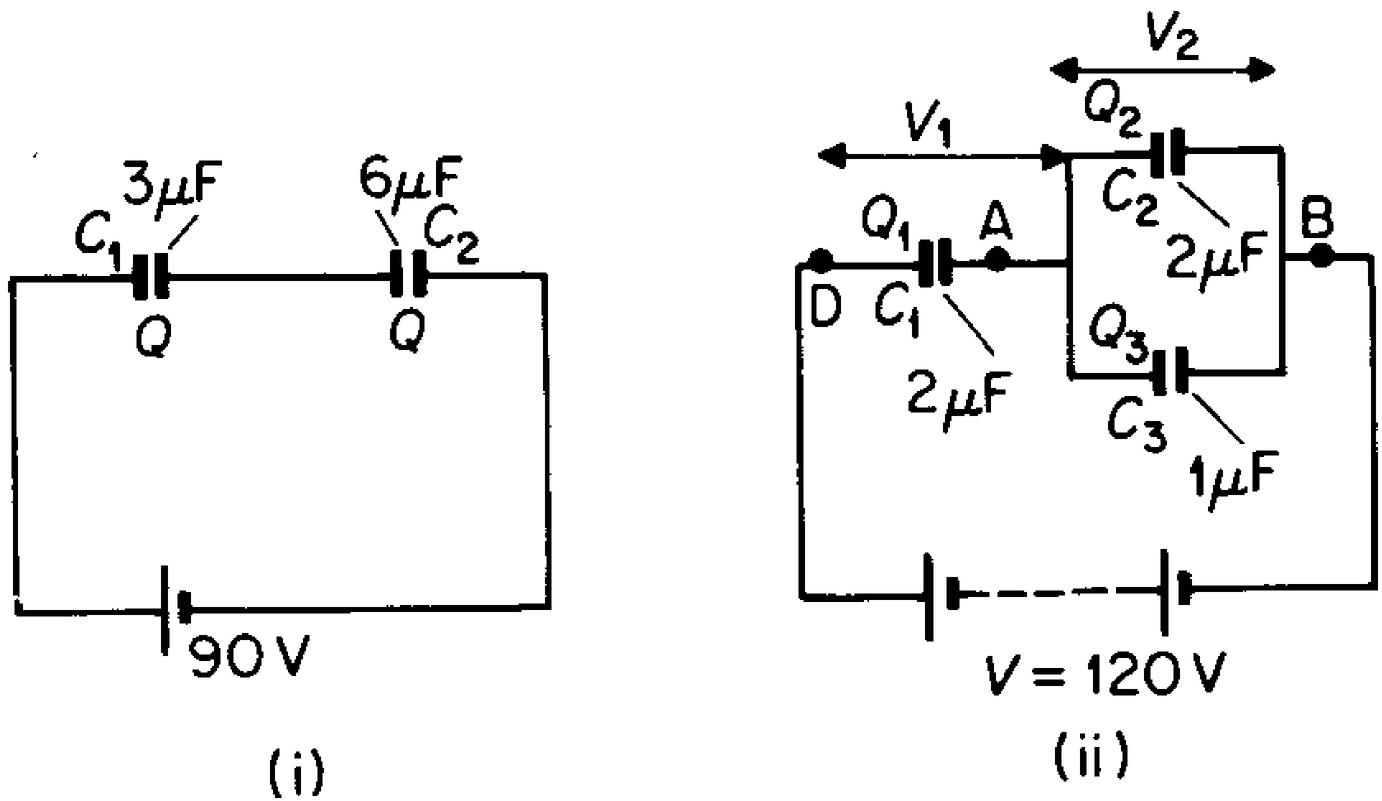

Figure 8: Examples on capacitors

Examples on Capacitors in Series and Parallel (2)

2. Find the charges on the capacitors in Figure 8 (ii) and the potential differences across them.

- Capacitance between A and B,

  $C' = C_2 + C_3 = 3\mu F$

- Overall capacitance B to D, since C1 and C' are in series, is, from $1/C = 1/C_1 + 1/C'$,

  $C = C_1C'/(C_1+C') = (2 \times 3)/(2 + 3) = 1.2\mu F$

- Charge stored in this capacitance $C = Q_2 + Q_3 = CV = 1.2 \times 10^{-6} \times 120 = 144 \times 10^{-6}\ C$

  Therefore $V_1 = Q_1/C_1 = 144 \times 10^{-6} / (2 \times 10^{-6}) = 72\ V$

- So $V_2 = V - V_1 = 120 - 72 = 48\ V$

  $Q_2 = C_2V_2 = 2 \times 10^{-6} \times 48 = 96 \times 10^{-6}\ C$

  $Q_3 = C_3V_2 = 10^{-6} \times 48 = 48 \times 10^{-6}\ C$

Charging and discharging a capacitor in C-R circuit

Discharge in C –R Circuit (1)

- We now consider in more detail the *discharge* of a capacitor *C* through a resistor *R* which is widely used in electronic circuits.
- Suppose the capacitor is initially charged to a p.d. V_0 so that its charge is then $Q = CV_0$.
- At a time *t* after the discharge through *R* has begun, the current *I* flowing = V/R_0 where V is the p.d. across *C*, Figure 9(i).
- Now $V = Q/C$ and $I = -dQ/dt$ (the minus shows *Q* decreases with increasing *t*).
- So, from $I = V/R$, we have

$$-\frac{dQ}{dt} = \frac{1}{CR}Q$$

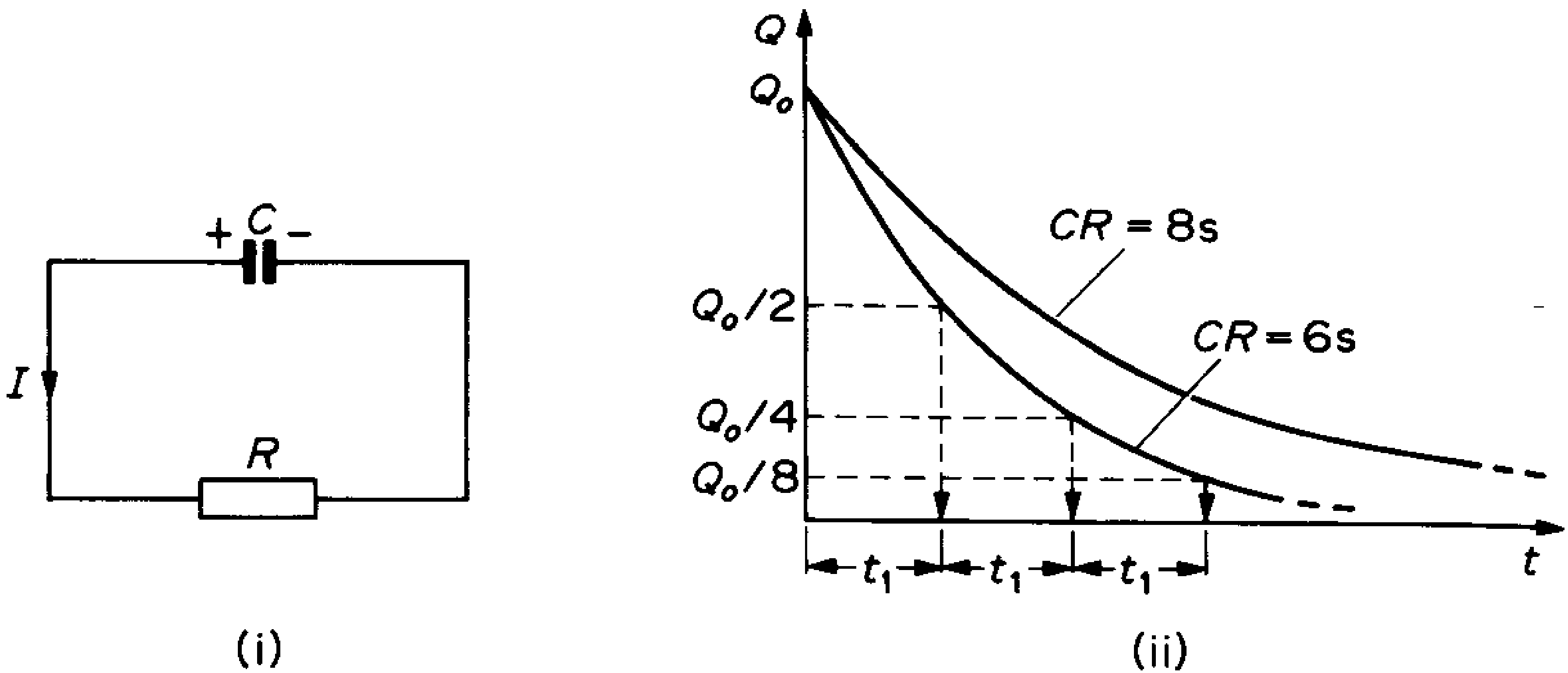

Figure 9: Discharge in C—R circuit

Discharge in C –R Circuit (2)

- Integrating,

$$\int_{Q_0}^{Q} \frac{\mathrm{dQ}}{\mathrm{Q}} = -\frac{1}{CR}\int_0^t \mathrm{dt}$$

$$\therefore \ln\left(\frac{\mathrm{Q}}{\mathrm{Q_0}}\right) = -\frac{\mathrm{t}}{\mathrm{CR}} \quad \therefore \mathrm{Q} = \mathrm{Q_0 e^{-t/CR}}$$

- So *Q* decreases exponentially with time t, Figure 9(ii).
- Since the p.d. *V* across *C* is proportional to *Q*,
  - it follows that $V = V_0\, e^{-t/CR}$.
- Further, since the current *I* in the circuit is proportional to *V*, then $I = V = I_0\, e^{-t/CR}$,
  - where I_0 is the initial current value, V_0/R.

Discharge in C –R Circuit (3)

- From the equation for *Q*, *Q* decreases from Q_0 to half its value, $Q_0/2$, in a time t given by

$$e^{-t/(CR)} = \frac{1}{2} = 2^{-1}$$

- Taking logs to the base e, $-t/CR = -\ln 2$
- So $t = CR\ln 2$
- Similarly, *Q* decreases from $Q_0/2$ to half this value, $Q_0/4$, in a time $t = CR\ln 2$.
  - This is the same time from Q_0 to $Q_0/2$.
- So the time for a charge to diminish to half its initial value, no matter what the initial value may be, is always the same. See Figure 9(ii).

Discharge in C –R Circuit (4)

- This is true for fractions other than one-half.
- It is typical of an exponential variation or ‘decay’ which also occurs in radioactivity.

Time Constant

- The *time constant T* of the discharge circuit is defined as *CR* seconds, where *C* is in farads and R is in ohms.
- So if $C = 4\ \mu F$ and $R = 2\ M\Omega$,
  - then $T = (4 \times 10^{-6}) \times (2 \times 10^{6}) = 8$ *seconds*.
- Now, from the equation $Q = Q_0\, e^{-t/CR}$,
  - if $t = CR$, then, using e = 2.72 (approx)
- $Q = Q_0\, e^{-1} = 1/eQ_0 = 0.37Q_0$ (approx.)

Charging C through R (1)

- Consider now the *charging* of a capacitor *C* through a resistance *R* in series,
  - and suppose the applied battery has an emf E and a negligible internal resistance, Figure 10(i).
- At the instant of making the circuit, there is no charge on *C* and so no p.d.
  - then the initial current flowing, $I_0 = E/R$.
- Suppose *I* is the current flowing after a time t. Then, V_C is the p.d. now across *C*. So

$$I = \frac{E - V_C}{R}$$

- Now $I = dQ/dt$ and $V_C = Q/C$. Substituting in the above equation and simplifying.

$$\mathrm{CR}\,\frac{\mathrm{dQ}}{\mathrm{dt}} = \mathrm{CE} - \mathrm{Q} = \mathrm{Q}_0 - \mathrm{Q}$$

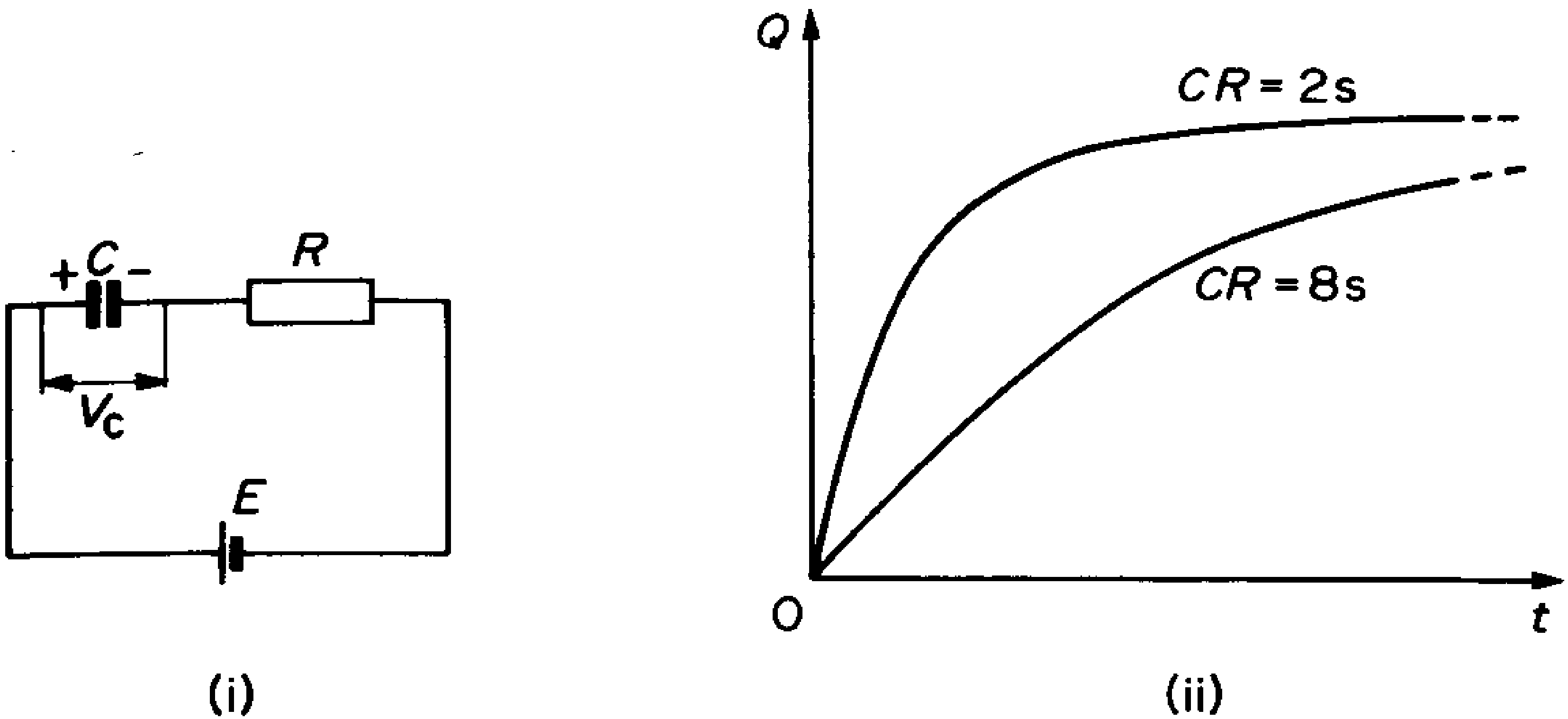

Figure 10: Charging in C—R circuit

Charging C through R (2)

- Where $Q_0 = CE$ = final charge on C, when no further current flows. Integrating,

$$\frac{1}{CR}\int_0^t dt = \int_0^Q \frac{dQ}{Q_0 - Q}$$

$$\therefore \frac{t}{CR} = -\ln\left(\frac{Q_0 - Q}{Q_0}\right) \qquad \therefore Q = Q_0\left(1 - e^{-t/(CR)}\right)$$

- In the case of the discharge circuit,
  - the *time constant T* is defined as *CR* in seconds with *C* in farads and *R* in ohms.
- If *T* is high, it takes a long time for *C* to reach its final charge, i.e, *C* charges slowly.
  - If *T* is small, *C* charges rapidly. See Figure 10 (ii).
- The voltage *V* follows the same variation as *Q* since *V* is proportional to *Q*.

Rectangular Pulse Voltage and C-R Circuit (1)

- Let us find how the voltages across a capacitor *C* and resistor *R* vary when a *rectangular pulse voltage*, shown in Figure 11(i) is applied to a C R series circuit.
  - This type of circuit is used in analogue computers.
- On one half of a cycle, the p.d. is constant along AB at a value E say.
- We can therefore consider that this is similar to the case of charging a C-R circuit by a battery of e.m.f. E.
- The p.d. V_C across the capacitor hence rises along an exponential curve, Figure 11(ii).
- During the same time, the p.d. across R, V_R falls exponentially as shown in Figure 11(iii).

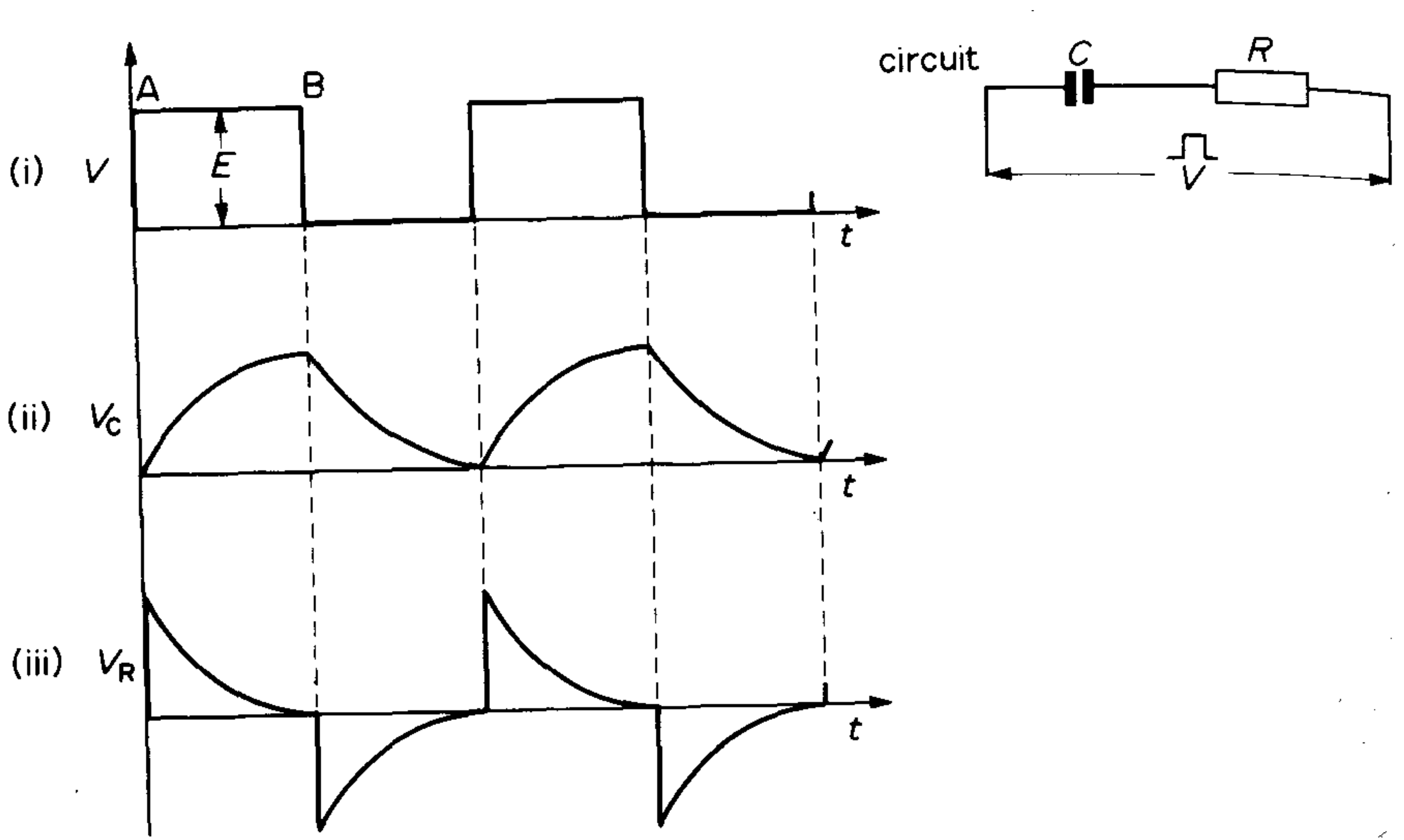

Figure 11: Rectangular pulse voltage and C—R circuit

Rectangular Pulse Voltage and C—R Circuit (2)

- Since $V_R = E - V$, the curves for V_R and V together add up to the straight line graph AB in Figure 11(i).
- Similarly, during the time when V = 0, the curves for V_C and V_R add up to zero.
- This helps to check the drawings of the two curves.

Energy stored in a capacitor

Energy stored in a capacitor (1)

- A charged capacitor is a store of electrical energy,
  - as we may see from the vigorous spark it can give on discharge.
- This can also be shown by charging a large electrolytic capacitor *C*, such as 10000 μF, to a p.d. of 6 V,
  - and then discharging it through a small or toy electric motor A, Figure 12(i).
- A small mass M such as 10 g, suspended from a thread tied round the motor wheel, now rises as the motor functions.
- Some of the stored energy in the capacitor is then transferred to gravitational potential energy of the mass;
  - the remainder is transferred to kinetic energy and heat in a motor

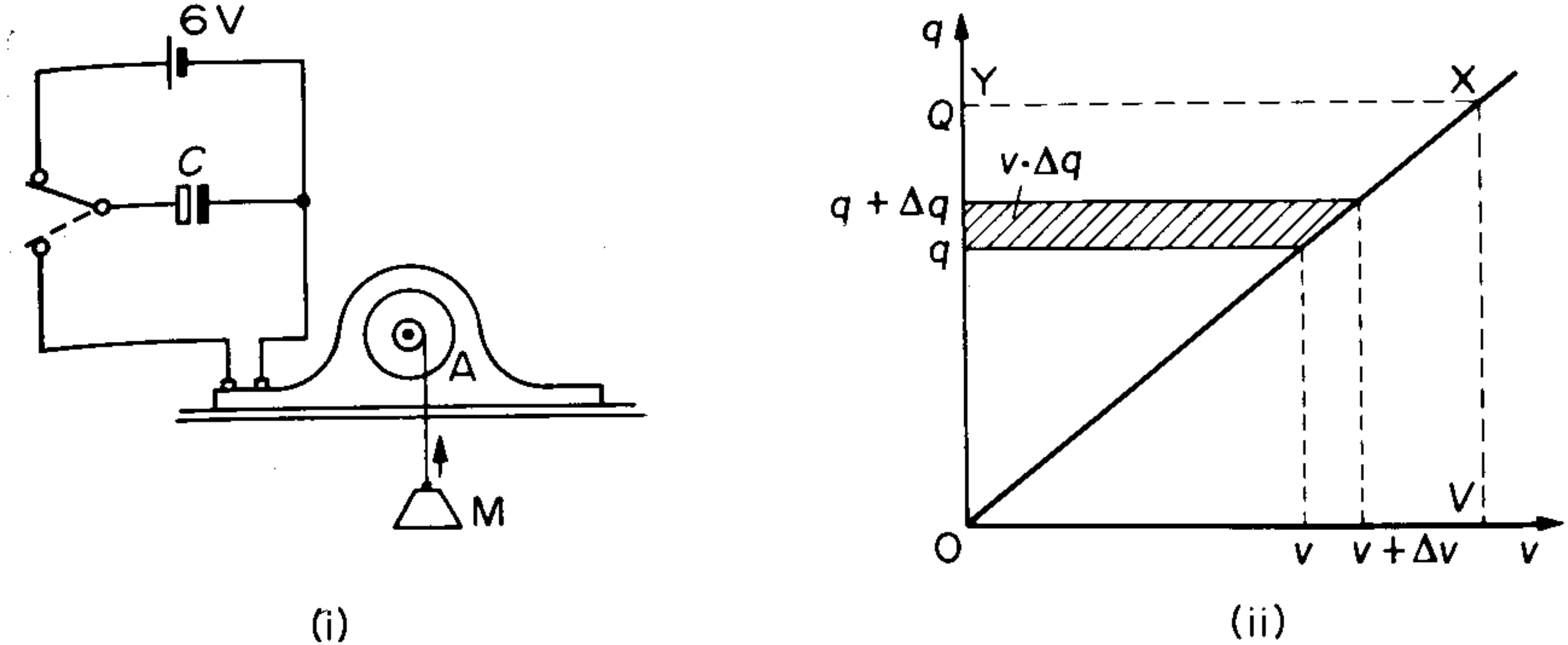

Figure 12: Energy in charged capacitor

Energy stored in a capacitor (2)

- To find the energy stored in the capacitor,
  - since *q* (charge) $\propto$ *v* (pd. across the capacitor) at any instant, the graph OX showing how *q* varies with *v* is a straight line, Figure 12(ii).
- We may therefore consider that the final charge *Q* on the capacitor moved from one plate to the other through an *average* p.d. equal to ½ (0 + V),
  - since there is zero p.d. across plates at the start and a p.d. *V* at the end.
- So work done, W = energy stored = charge x p.d. = Q x ½ V
- So $W = ½\, Q\, V$
- From $Q = CV$, other expressions for energy stored are

Energy stored in a capacitor (3)

$$W = \frac{1}{2} C V^2 = \frac{Q^2}{2C}$$

$$\text{Energy } \mathrm{W} = \frac{1}{2}\mathrm{CV}^2 = \frac{1}{2}\frac{\mathrm{Q}^2}{\mathrm{C}} = \frac{1}{2}\mathrm{QV}$$

- If C is measured in farads, Q in coulombs and V in volts, then the formulae will give the energy W in joules.

Alternative Proof of Energy Formulae (1)

- We can also calculate the energy stored in a charged capacitor by a calculus method.
- At any instant of the charging process, suppose the charge on the plates is q and the p.d. across the plates is then *v*.
- If an additional tiny charge Δq now flows from the negative to the positive plate, we may say that the charge Δq has moved through a p.d. equal to *v*.
- So work done in displacing the charge Δq = v Δq

$$\text{total work done} = \text{energy stored} = \int_0^Q \mathrm{v}\,\mathrm{dq}$$

  - where the limits are $q = Q$, final charge, and $q = 0$, as shown.
- To integrate, we substitute $v = q/C$.

Alternative Proof of Energy Formulae (2)

- Then

$$\text{Energy stored W} = \int_0^Q \frac{q\,dq}{C} = \frac{1}{C}\left[\frac{q^2}{2}\right]_0^Q = \frac{Q^2}{2C}$$

- Using $Q = CV$, other expressions for W are

$$W = \frac{1}{2}CV^2 \text{ or } W = \frac{1}{2}QV$$

Energy and Q— V Graph, Heat Produced in Charging

Energy and Q-V Graph, Heat Produced in Charging (1)

- Figure 12 (ii) shows the variation of the charge *q* on the capacitor and its corresponding p.d. *v* while the capacitor is charged to a final value *Q*.
- The small shaded area shown = v. Δq.
- So the area represents the small amount of work done or energy stored during a change from q to q + Δq.
- It therefore follows that the total energy stored by the capacitor is represented by the area of the triangle OXY.
- This area = ½ QV, as previously obtained.
- If a high resistor *R* is included in the charging circuit,
  - the rate of charging is slowed.

Energy and Q- V Graph, Heat Produced in Charging (2)

- When the charging current ceases to flow, the final charge *Q* on the capacitor is the same as if negligible resistance was present in the circuit,
  - since the whole of the applied p.d. *V* is the p.d. across the capacitor when the current in the resistor is zero.
- So the energy stored in the capacitor is ½ Q V whether the resistor is large or small.
- It is important to note that the energy in the capacitor comes from the battery.
- This supplies an amount of energy equal to QV during the charging process.
- Half of the energy, ½ QV, goes to the capacitor.
- The other half is transferred to heat in a circuit resistance

Energy and Q- V Graph, Heat Produced in Charging (3)

- If this is a high resistance, the charging current is low and the capacitor gains its final charge after a long time.
- If it is a low resistance, the charging current is higher and the capacitor gains its final charge in a quicker time.
- In both cases, however, the total amount of heat produced is the same, ½ Q V.

Connected Capacitors, Loss of Energy

Connected Capacitors, Loss of Energy (1)

- Consider a capacitor C_1 of 2 μF charged to a p.d. of 50 V, and a capacitor C_2 of 3 μF charged to a p.d. of 100 V, Figure 13(i).
- Then charge Q_1 on $C_1 = C_1V_1 = 2 \times 10^{-6} \times 50 = 10^{-4}$ C and charge Q_2 on $C_2 = C_2V_2 = 3 \times 10^{-6} \times 100 = 3 \times 10^{-4}$C.
- Therefore total charge = 4×10^{-4}C
- Suppose the capacitors are now joined with plates of like charges connected together, Figure 13(ii).
- Then some charges will flow from C_1 to C_2 until the p.d across each capacitor becomes equal to some value V.
- Further, since charge is conserved, the total charge on C_1 and C_2 after connection = the total charge before connection.

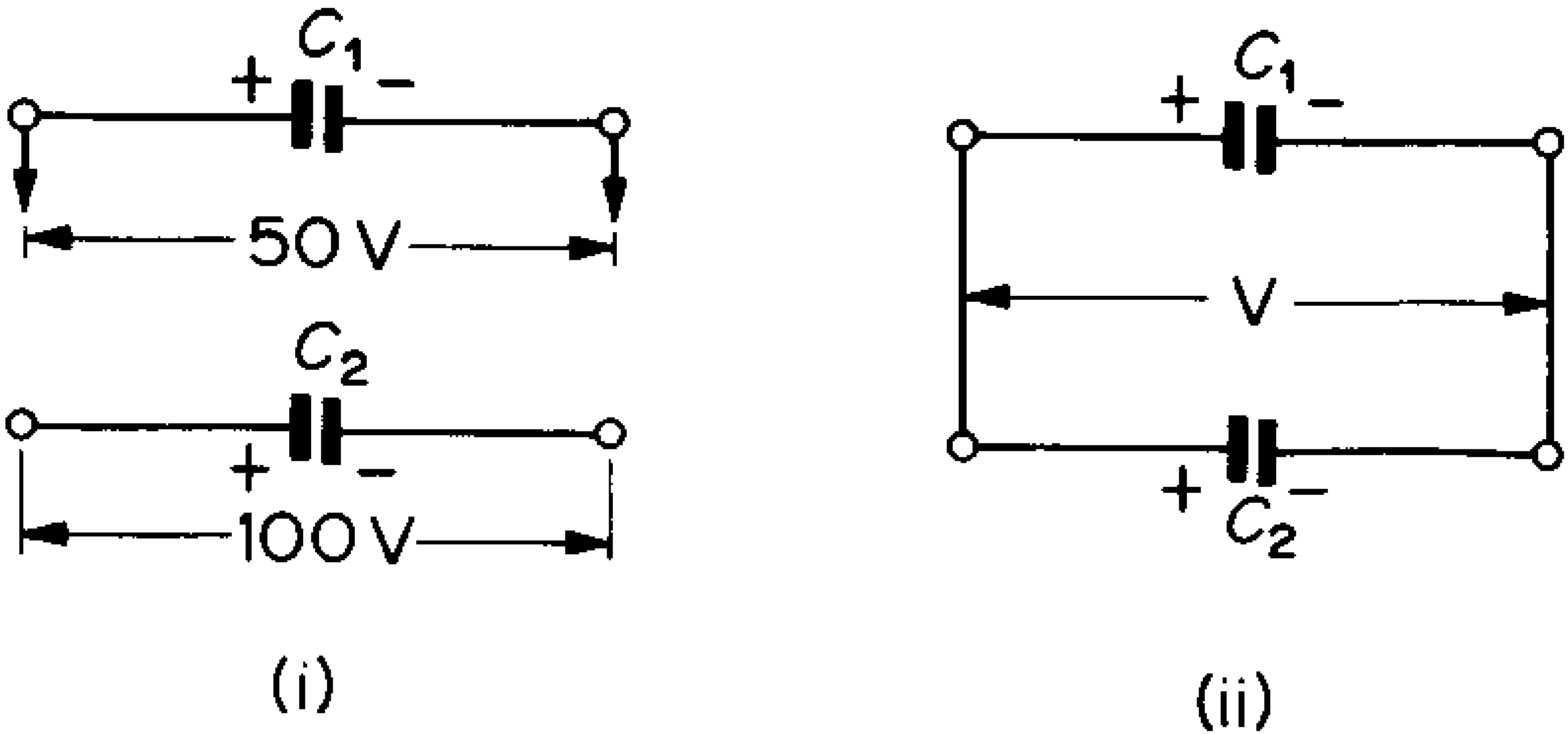

Figure 13: Loss of energy in connected capacitors

Connected Capacitors, Loss of Energy (2)

- Now after connection,
  - total charge = $C_1V + C_2V = (C_1 + C_2)V = 5 \times 10^{-6} \times V$
- From total charge = 4×10^{-4}C, $5 \times 10^{-6}\ V = 4 \times 10^{-4}$.
  - Therefore V = 80V.
- Total energy of C_1 and C_2 after connection

  $= ½ (C_1 + C_2)V^2 = ½ \times 5 \times 10^{-6} \times 80^2 = 0.016$J
- Total energy of C_1 and C_2 before connection

  $= ½C_1 V_1^2 + ½C_2 V_2^2 = ½ \times 2 \times 10^{-6} \times 50^2 + ½ \times 3 \times 10^{-6} \times 100^2$

  $= 0.0025 + 0.015 = 0.0175$ J
- Comparing the energies, we can see that a loss of energy occurs when the capacitors are connected.
- This loss of energy is transferred to heat in the meeting wires.