



Basic Electrical & Electronics Engineering

Complete study notes — from Ohm's law and circuit theorems to AC power, diodes, transistors, logic gates and safe hands-on measurement.

10

Modules

60+

Circuit diagrams &
tables

200+

Solved problems &
MCQs



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How to use these notes

Work through each module in order — every module builds on the one before. Solve the worked examples yourself before reading the solution, and finish each module's practice questions. Modules 1–3 are the foundation: master them before moving on.

Blue box — Key idea. The one thing to remember from that part.

Yellow box — Formula. Learn these; they appear in every problem.

Green box — Practical tip. How it works on the bench.

Orange box — Caution. Safety points and common mistakes.

Worked example. Try it first, then check the steps.

Practice.
Questions at the end of every module.

Electrical Fundamentals: Voltage, Current, and Resistance

What electricity actually is, the three quantities every circuit depends on, the water-pipe analogy, Ohm's law, and electrical power and energy.

1.1 Charge — where electricity begins

All matter is made of atoms. Each atom has a tiny, heavy **nucleus** containing positively charged **protons** (and neutral neutrons), surrounded by much lighter, negatively charged **electrons**. Electric charge is a basic property of these particles, like mass. Like charges repel; unlike charges attract.

The unit of charge is the **coulomb (C)**. One electron carries a charge of only 1.6×10^{-19} C, so one coulomb is the charge of about 6.25×10^{18} electrons — six and a quarter billion billion.

In metals such as copper and aluminium, the outermost electron of each atom is only loosely held. These **free electrons** drift randomly between atoms. When a voltage is applied, they drift in one direction — and that flow of charge is electric current.

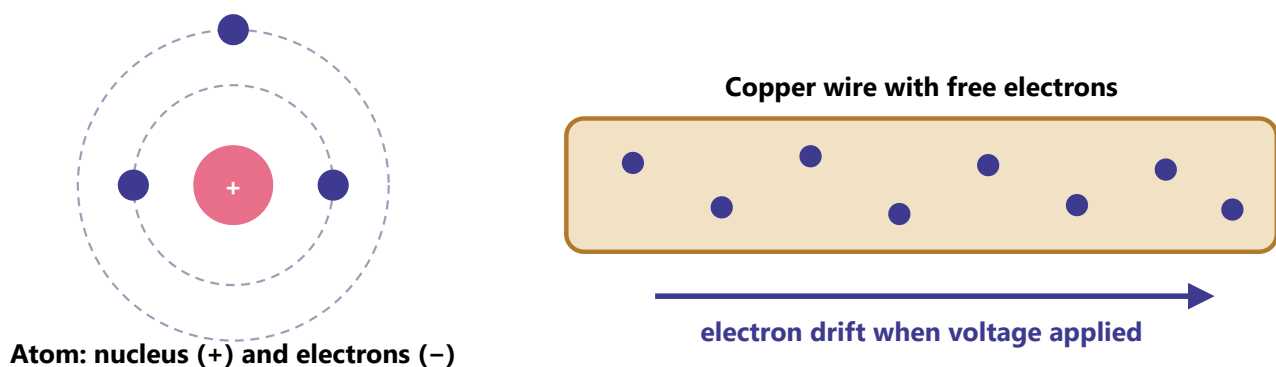


Figure 1.1 — Free electrons in a conductor drift in one direction when a voltage is applied.

1.2 Current (I)

Electric current is the rate of flow of charge — how many coulombs pass a point in the wire each second. Its unit is the **ampere (A)**: one ampere is one coulomb per second.

Formula — current

$$I = Q \div t$$

I in amperes (A), Q in coulombs (C), t in seconds (s). Smaller units: 1 mA = 10^{-3} A; 1 μ A = 10^{-6} A.

Worked example 1.1

A charge of 180 C passes through a lamp in 1 minute. Find the current.

$$I = Q \div t = 180 \div 60 = \mathbf{3\ A}.$$

Conventional current versus electron flow

Early scientists assumed current flowed from positive to negative before electrons were discovered. This direction — **conventional current** — is still used in all circuit diagrams and formulas. Electrons actually move the opposite way, from negative to positive. Both views give the same answers; just be consistent. In these notes, arrows show conventional current.

DC and AC

Direct current (DC) flows in one direction only — from batteries, solar cells and phone chargers. **Alternating current (AC)** reverses direction many times a second — 50 times a second on the Indian mains. Modules 5 and 6 cover AC.

1.3 Voltage (V)

Charges only flow if something pushes them. That push is the **voltage**, also called **potential difference (p.d.)** or, for a source, **electromotive force (EMF)**. Voltage is the energy given to (or used by) each coulomb of charge.

Formula — voltage

$$V = W \div Q$$

V in volts (V), W = energy in joules (J), Q in coulombs. One volt = one joule per coulomb.

Voltage is always measured **between two points**. When we say "the battery is 9 V", we mean the positive terminal is 9 V higher than the negative terminal. A single point has a voltage only relative to a reference, usually **ground (0 V)**.

Source

Typical voltage

AA / AAA cell	1.5 V
Lithium-ion phone cell	3.7 V (4.2 V full)
USB port	5 V
Car battery	12 V
Indian household supply	230 V AC (single-phase), 415 V between phases
Distribution lines	11 kV, 33 kV
Transmission lines	132 kV to 765 kV

1.4 Resistance (R)

Resistance is the opposition a material offers to the flow of current. As electrons drift, they collide with atoms, and this converts some electrical energy into heat. The unit is the **ohm (Ω)**. Larger units: $1 \text{ k}\Omega = 1,000 \Omega$; $1 \text{ M}\Omega = 1,000,000 \Omega$.

The resistance of a wire depends on four things:

- **Length (L):** longer wire $\rightarrow$ more resistance ($R \propto L$).
- **Cross-sectional area (A):** thicker wire $\rightarrow$ less resistance ($R \propto 1/A$).
- **Material:** described by its **resistivity ρ** (rho). Copper: $1.72 \times 10^{-8} \Omega\cdot\text{m}$; aluminium: $2.82 \times 10^{-8} \Omega\cdot\text{m}$; nichrome (heater wire): about $1.1 \times 10^{-6} \Omega\cdot\text{m}$.
- **Temperature:** for metals, resistance increases as temperature rises.

Formula — resistance of a conductor

$$R = \rho L \div A$$

ρ in $\Omega\cdot\text{m}$, L in metres, A in m^2 . ($1 \text{ mm}^2 = 10^{-6} \text{ m}^2$.)

Worked example 1.2

Find the resistance of 100 m of copper wire with a cross-section of 2.5 mm^2 .

$$R = (1.72 \times 10^{-8} \times 100) \div (2.5 \times 10^{-6}) = 1.72 \times 10^{-6} \div 2.5 \times 10^{-6} = \mathbf{0.688 \Omega}.$$

Effect of temperature

Formula — resistance at temperature T

$$R_T = R_0 [1 + \alpha (T - T_0)]$$

α = temperature coefficient of resistance; for copper ≈ 0.0039 per $^{\circ}\text{C}$ (at 20°C).

Worked example 1.3

A copper winding measures $10\ \Omega$ at 20°C . Find its resistance at 70°C .

$$R = 10 \times [1 + 0.0039 \times 50] = 10 \times 1.195 = \mathbf{11.95\ \Omega}.$$

Conductors, insulators and semiconductors

Type	Examples	Resistivity	Uses
Conductors	Silver, copper, aluminium, gold	Very low	Wires, busbars, contacts
Insulators	Rubber, PVC, glass, mica, porcelain, dry wood	Very high	Cable insulation, switch bodies, line insulators
Semiconductors	Silicon, germanium	In between; changes with temperature and doping	Diodes, transistors, ICs, solar cells

Conductance

The reciprocal of resistance is **conductance (G)**, measured in **siemens (S)**: $G = 1/R$. It is handy for parallel circuits (Module 2).

1.5 The water-pipe analogy

Electricity cannot be seen, so an analogy helps. Think of water flowing through pipes from a tank:

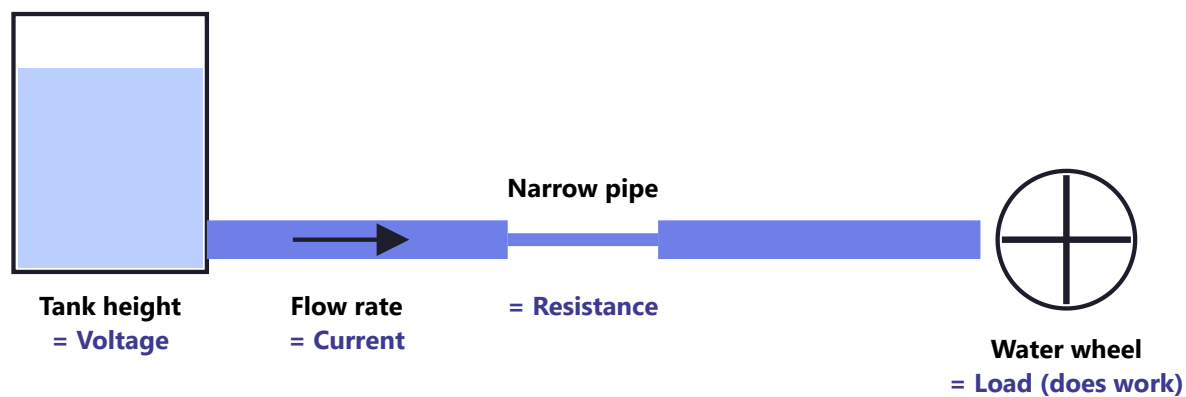


Figure 1.2 — The water analogy: pressure ↔ voltage, flow ↔ current, narrow pipe ↔ resistance.

Water system	Electric circuit
Water pressure (height of tank)	Voltage (V)
Flow rate (litres per second)	Current (A)
Narrowness / roughness of pipe	Resistance (Ω)
Pump	Battery / generator (source of EMF)
Water wheel / turbine	Load (lamp, motor, heater)
Valve	Switch
Amount of water	Charge (C)

More pressure pushes more water; a narrower pipe allows less. In exactly the same way, more voltage drives more current, and more resistance allows less. That relationship is Ohm's law.

1.6 Ohm's law

In 1827, Georg Simon Ohm discovered that for many conductors at constant temperature, the current is **directly proportional** to the voltage across them.

Ohm's law

$$V = I \times R \quad I = V \div R \quad R = V \div I$$

Cover the quantity you want in the triangle below to see the formula.

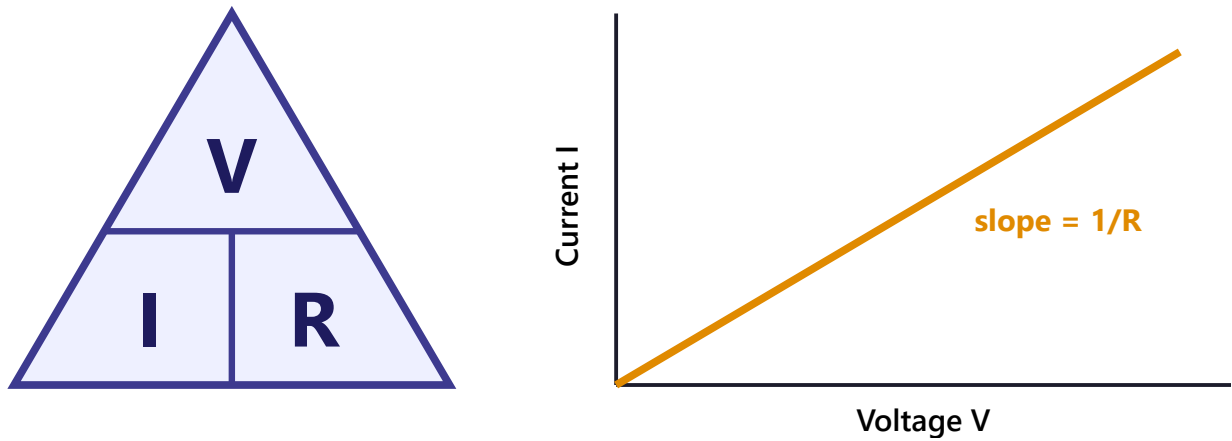


Figure 1.3 — The Ohm's-law triangle, and the straight-line V – I graph of an ohmic resistor.

Worked example 1.4

(a) A 12 V battery is connected to a $4\ \Omega$ resistor. Find the current.

$$I = V \div R = 12 \div 4 = \mathbf{3\ A}.$$

(b) A current of 0.5 A flows through a $220\ \Omega$ resistor. Find the voltage across it.

$$V = I \times R = 0.5 \times 220 = \mathbf{110\ V}.$$

(c) A lamp draws 0.26 A from 230 V. Find its (hot) resistance.

$$R = V \div I = 230 \div 0.26 = \mathbf{885\ \Omega}.$$

Components that obey Ohm's law (a straight-line V – I graph) are called **ohmic** — for example, metal-film resistors at constant temperature. **Non-ohmic** devices include filament lamps (resistance rises as they heat), diodes (current flows easily only one way) and thermistors.

1.7 Resistors in practice

Resistors are components made to have a specific resistance. They limit current, divide voltage, and set operating points in electronic circuits. Key ratings: **resistance value**, **tolerance** (e.g. $\pm 5\%$, $\pm 1\%$) and **power rating** ($\frac{1}{4}$ W, $\frac{1}{2}$ W, 1 W, 5 W...).

Colour code (4-band)

Colour	Digit	Multiplier	Colour	Digit	Multiplier
Black	0	$\times 1$	Green	5	$\times 100\ \text{k}$
Brown	1	$\times 10$	Blue	6	$\times 1\ \text{M}$
Red	2	$\times 100$	Violet	7	—

Orange	3	$\times 1 \text{ k}$	Grey	8	—
Yellow	4	$\times 10 \text{ k}$	White	9	—

Tolerance band: Gold $\pm 5\%$, Silver $\pm 10\%$, Brown $\pm 1\%$, Red $\pm 2\%$. Gold as multiplier = $\times 0.1$.

Memory aid: "**B B ROY of Great Britain had a Very Good Wife**" — Black, Brown, Red, Orange, Yellow, Green, Blue, Violet, Grey, White.



Yellow–Violet–Red–Gold = $47 \times 100 = 4,700 \, \Omega = 4.7 \text{ k}\Omega \pm 5\%$

Figure 1.4 — Reading a 4-band resistor colour code.

1.8 Electrical power

Power is the rate at which electrical energy is converted into another form (heat, light, motion). Its unit is the **watt (W)** = one joule per second.

Formulas — power

$$P = V \times I$$

$$P = I^2 \times R \quad P = V^2 \div R$$

The second and third forms come from substituting Ohm's law. Use whichever matches the quantities you know.

Worked example 1.5

(a) A 230 V kettle draws 8.7 A. Find its power. $P = 230 \times 8.7 = \mathbf{2,001 \text{ W} \approx 2 \text{ kW}}$.

(b) 2 A flows through a $50 \, \Omega$ resistor. Power = $I^2 R = 4 \times 50 = \mathbf{200 \text{ W}}$ — a small $\frac{1}{4}$ -W resistor would burn instantly.

(c) A $1 \text{ k}\Omega$ resistor is connected across 12 V. Power = $V^2/R = 144/1,000 = \mathbf{0.144 \text{ W}}$ → a $\frac{1}{4}$ -W resistor is fine.

Caution — power rating

If a resistor dissipates more than its power rating it overheats, changes value, burns, or can start a fire. As a rule, choose a power rating at least **twice** the calculated power.

1.9 Electrical energy and the electricity bill

Formula — energy

$$W = P \times t$$

In joules when P is in watts and t in seconds; in **kilowatt-hours (kWh)** when P is in kW and t in hours. $1 \text{ kWh} = 3.6 \times 10^6 \text{ J}$ = one "unit" on the bill.

Worked example 1.6 — monthly bill

A home uses: 5 LED bulbs of 10 W for 6 h/day, 3 fans of 70 W for 10 h/day, a 150 W fridge running 10 h/day, and a 2 kW geyser for 1 h/day. Find the monthly energy and cost at ₹6 per unit (30 days).

Bulbs: $5 \times 10 \times 6 = 300 \text{ Wh}$. Fans: $3 \times 70 \times 10 = 2,100 \text{ Wh}$. Fridge: $150 \times 10 = 1,500 \text{ Wh}$. Geyser: $2,000 \times 1 = 2,000 \text{ Wh}$.

Daily = 5,900 Wh = 5.9 kWh. Monthly = $5.9 \times 30 = \mathbf{177 \text{ kWh}}$. Cost = $177 \times 6 = \mathbf{₹1,062}$.

1.10 Efficiency

No machine converts all its input energy into useful output — some is lost as heat, noise or friction.

Formula — efficiency

$$\eta = \text{Output power} \div \text{Input power} \times 100\%$$

Worked example 1.7

A motor takes 1,000 W from the supply and delivers 850 W of mechanical power. Efficiency = $850 \div 1,000 \times 100 = \mathbf{85\%}$; losses = 150 W (heat in windings, friction).

1.11 Circuit basics and symbols

A **circuit** is a closed path for current. It needs a **source**, a **load**, **conductors**, and usually a **switch** and **protection** (fuse or circuit breaker). An **open circuit** has a break — no current flows. A **short circuit** is an unintended low-resistance path — a very large current flows, which is dangerous.

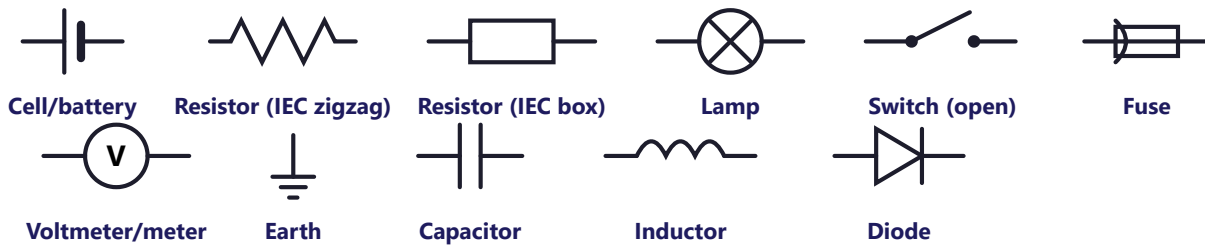


Figure 1.5 — Common circuit symbols used throughout these notes.

Module 1 — Summary

- Current is flow of charge: $I = Q/t$ (amperes).
- Voltage is energy per charge: $V = W/Q$ (volts), measured between two points.
- Resistance opposes current: $R = \rho L/A$ (ohms); rises with temperature in metals.
- Ohm's law: $V = IR$.
- Power: $P = VI = I^2R = V^2/R$ (watts). Energy: $W = Pt$; 1 kWh = 1 unit.
- Efficiency $\eta = \text{output} \div \text{input}$.

Practice questions — Module 1

1. A current of 2.5 A flows for 4 minutes. How much charge passes? (Ans: 600 C)
2. Find the resistance of 50 m of aluminium wire of area 4 mm^2 . (Ans: 0.3525Ω)
3. A 9 V battery drives 30 mA through an LED circuit. Find the total resistance. (Ans: 300Ω)
4. Decode: Brown–Black–Orange–Gold. (Ans: $10 \text{ k}\Omega \pm 5\%$)
5. A 100Ω resistor carries 0.2 A. Find the power. Is a $\frac{1}{2}$ -W resistor suitable? (Ans: 4 W; no)
6. A 1.5 kW heater runs 3 h a day for 30 days. Find the cost at ₹7/unit. (Ans: 135 kWh, ₹945)
7. Explain the difference between an open circuit and a short circuit.
8. A pump takes 1.2 kW and delivers 0.9 kW. Find its efficiency. (Ans: 75%)

DC Circuit Analysis: Series and Parallel

Combining resistors, voltage and current dividers, series-parallel networks, power in resistors, and real sources with internal resistance.

2.1 Series circuits

Components are in **series** when they are connected end to end, forming a single path, so **the same current flows through every one of them**. The source voltage is shared between them.

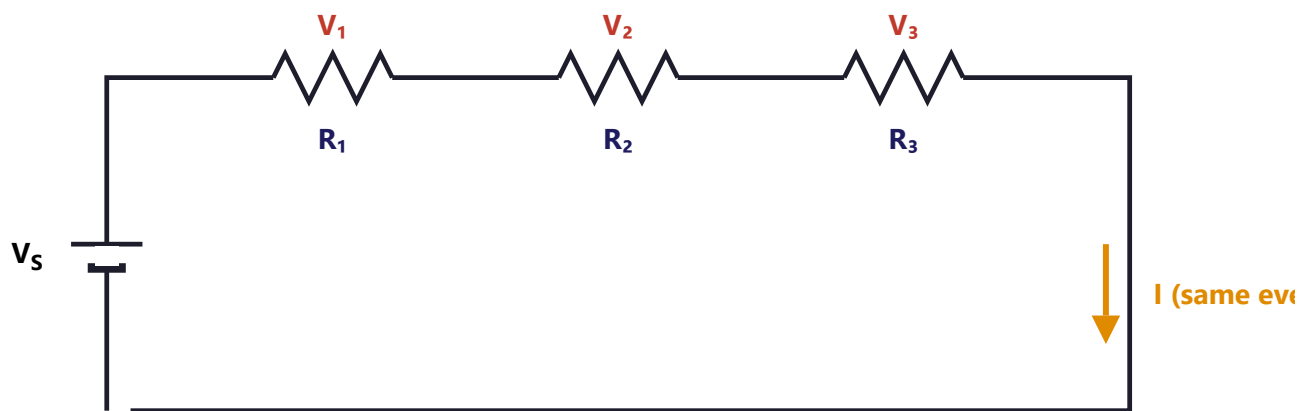


Figure 2.1 — Three resistors in series. One current I ; the voltages add up to V_S .

Series rules

$$I = I_1 = I_2 = I_3$$

$$V_S = V_1 + V_2 + V_3$$

$$R_T = R_1 + R_2 + R_3 + \dots$$

Total resistance in series is always **larger** than the largest individual resistor.

Worked example 2.1

Resistors of $10\ \Omega$, $20\ \Omega$ and $30\ \Omega$ are in series across 12 V . Find R_T , I , each voltage and each power.

$$R_T = 10 + 20 + 30 = 60\ \Omega. I = 12 \div 60 = \mathbf{0.2\text{ A}}.$$

$$V_1 = 0.2 \times 10 = 2\text{ V}; V_2 = 0.2 \times 20 = 4\text{ V}; V_3 = 0.2 \times 30 = 6\text{ V}. \text{ Check: } 2 + 4 + 6 = 12\text{ V } \checkmark.$$

$$P_1 = 0.2^2 \times 10 = 0.4\text{ W}; P_2 = 0.8\text{ W}; P_3 = 1.2\text{ W}; \text{ total} = 2.4\text{ W} = 12 \times 0.2\ \checkmark.$$

Properties of series circuits

- If one component fails open, current stops everywhere (old-style serial decoration lights).
- The largest resistor gets the largest share of voltage and dissipates the most power.
- Adding more resistors in series reduces the current.

2.2 The voltage divider

Two series resistors split a voltage in proportion to their resistances. This is one of the most used circuits in electronics — for example, to scale a sensor voltage down for a microcontroller input.

Voltage-divider rule

$$V_2 = V_S \times R_2 \div (R_1 + R_2)$$

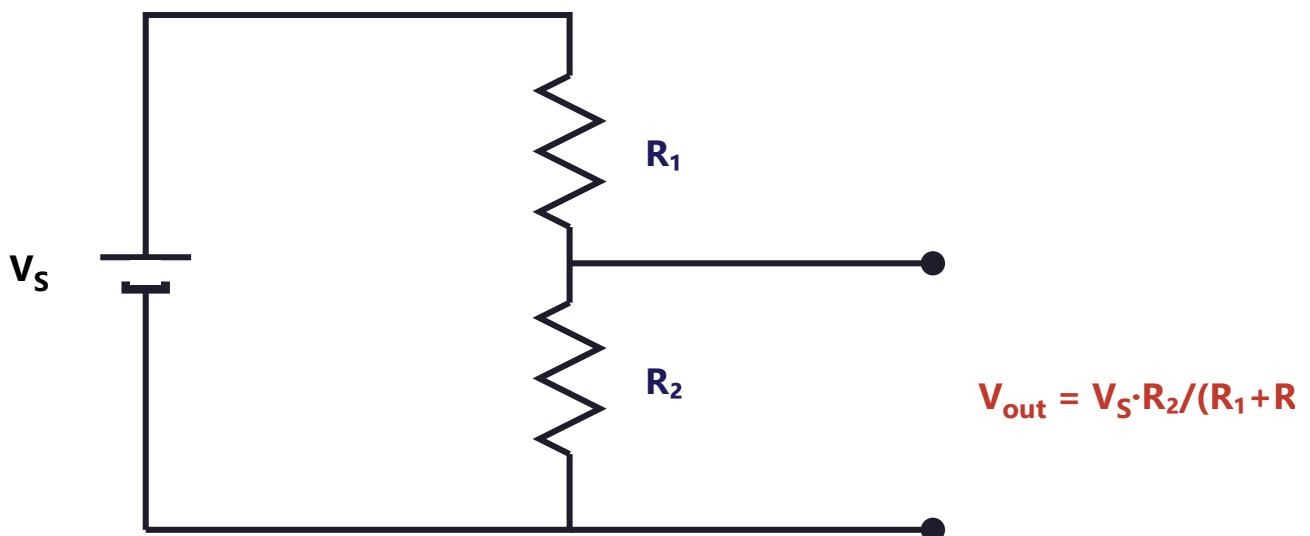


Figure 2.2 — Voltage divider.

Worked example 2.2

A 9 V supply, $R_1 = 10\text{ k}\Omega$, $R_2 = 5\text{ k}\Omega$. Find V_{out} across R_2 .

$$V_{\text{out}} = 9 \times 5 \div 15 = \mathbf{3\text{ V}}.$$

Loading effect: if a $5\text{ k}\Omega$ load is connected across R_2 , the lower part becomes $5 \parallel 5 = 2.5\text{ k}\Omega$, so $V_{\text{out}} = 9 \times 2.5 \div 12.5 = \mathbf{1.8\text{ V}}$. A divider's output drops when loaded — keep the load resistance at least 10 times larger than R_2 .

2.3 Parallel circuits

Components are in **parallel** when they are connected across the same two points, so **the same voltage appears across each**. The total current divides between the branches. All the sockets and lights in your home are connected in parallel across the 230 V supply.

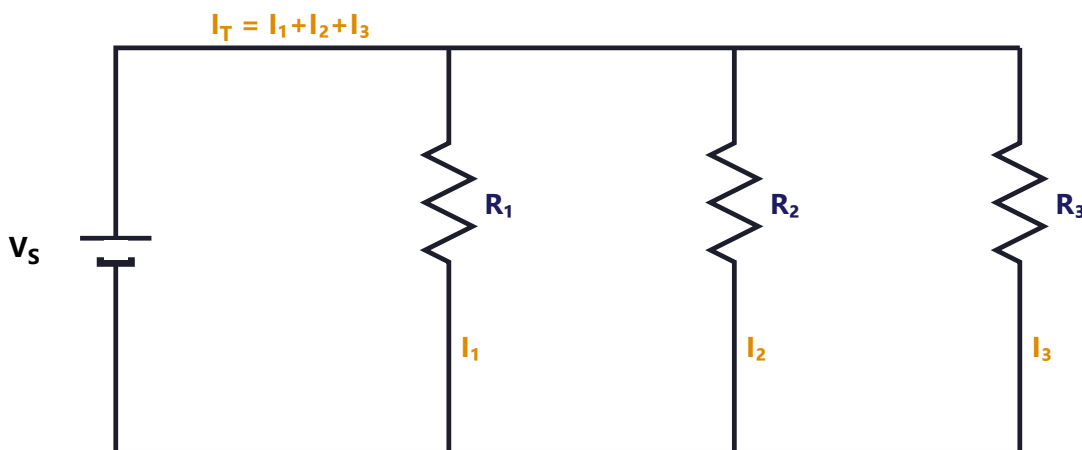


Figure 2.3 — Three resistors in parallel: same voltage, currents add.

Parallel rules

$$V = V_1 = V_2 = V_3$$

$$I_T = I_1 + I_2 + I_3$$

$$1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \dots$$

Two resistors: $R_T = (R_1 \times R_2) \div (R_1 + R_2)$ ("product over sum")

Total resistance in parallel is always **smaller** than the smallest branch. n equal resistors R in parallel give R/n .

Worked example 2.3

Resistors of $6\ \Omega$, $12\ \Omega$ and $4\ \Omega$ are in parallel across 24 V . Find R_T , each current and total current.

$$1/R_T = 1/6 + 1/12 + 1/4 = 2/12 + 1/12 + 3/12 = 6/12 \rightarrow R_T = \mathbf{2\ \Omega}.$$

$$I_1 = 24/6 = 4\text{ A}; I_2 = 24/12 = 2\text{ A}; I_3 = 24/4 = 6\text{ A}. I_T = \mathbf{12\text{ A}} = 24/2\ \checkmark.$$

Properties of parallel circuits

- Each branch works independently — if one lamp fails, the others stay on.
- Adding more branches **increases** the total current drawn from the source (and can overload a circuit — which is why too many heaters trip the MCB).
- The smallest resistance takes the largest current.

2.4 The current divider

Current-divider rule (two branches)

$$I_1 = I_T \times R_2 \div (R_1 + R_2) \quad I_2 = I_T \times R_1 \div (R_1 + R_2)$$

Note: each branch current uses the **other** branch's resistance on top.

Worked example 2.4

A 9 A current splits between $3\ \Omega$ and $6\ \Omega$ in parallel. $I(3\ \Omega) = 9 \times 6 \div 9 = \mathbf{6\text{ A}}$; $I(6\ \Omega) = 9 \times 3 \div 9 = \mathbf{3\text{ A}}$. The smaller resistor carries more current $\checkmark$.

2.5 Series–parallel (compound) circuits

Real circuits combine series and parallel parts. The method is always the same: **simplify step by step** from the part farthest from the source, replacing each series or parallel group with its equivalent, until one resistor remains. Then work back to find individual currents and voltages.

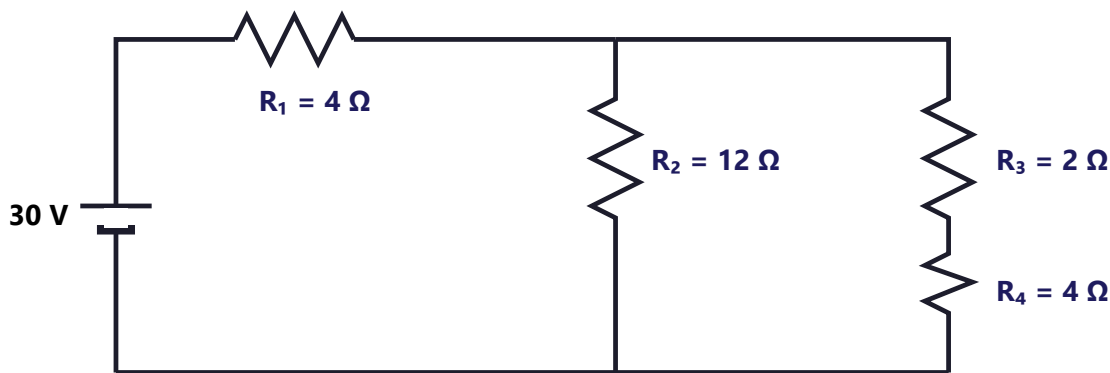


Figure 2.4 — A series-parallel network.

Worked example 2.5

For Figure 2.4 find the total resistance, the supply current, and the current in R_2 .

Step 1: R_3 and R_4 are in series: $2 + 4 = 6\ \Omega$.

Step 2: That $6\ \Omega$ is in parallel with $R_2 = 12\ \Omega$: $(12 \times 6)/(12 + 6) = 72/18 = 4\ \Omega$.

Step 3: Add R_1 in series: $R_T = 4 + 4 = 8\ \Omega$.

Step 4: $I_T = 30 \div 8 = 3.75\ \text{A}$.

Step 5: Voltage across $R_1 = 3.75 \times 4 = 15\ \text{V}$, so the parallel section has $30 - 15 = 15\ \text{V}$.

Step 6: $I(R_2) = 15 \div 12 = 1.25\ \text{A}$; $I(R_3+R_4) = 15 \div 6 = 2.5\ \text{A}$. Check: $1.25 + 2.5 = 3.75\ \checkmark$.

2.6 Power dissipation and ratings

Every resistor converts electrical energy into heat at the rate $P = I^2R$. The total power delivered by the source always equals the sum of the powers in all the resistors — energy is conserved.

Worked example 2.6

In Example 2.5, find the power in each resistor and check the total.

$P_1 = 3.75^2 \times 4 = 56.25\ \text{W}$; $P_2 = 1.25^2 \times 12 = 18.75\ \text{W}$; $P_3 = 2.5^2 \times 2 = 12.5\ \text{W}$; $P_4 = 2.5^2 \times 4 = 25\ \text{W}$.

Total = $112.5\ \text{W}$. Source: $30 \times 3.75 = 112.5\ \text{W}\ \checkmark$.

2.7 Real sources: EMF and internal resistance

A real battery is not a perfect voltage source. Inside it there is some **internal resistance (r)**. When current flows, part of the EMF is "lost" across r , so the **terminal voltage** falls as the load

current rises. This is why a car's headlights dim when the starter motor cranks.

Formula — terminal voltage

$$V_{\text{terminal}} = E - I r \quad I = E \div (R + r)$$

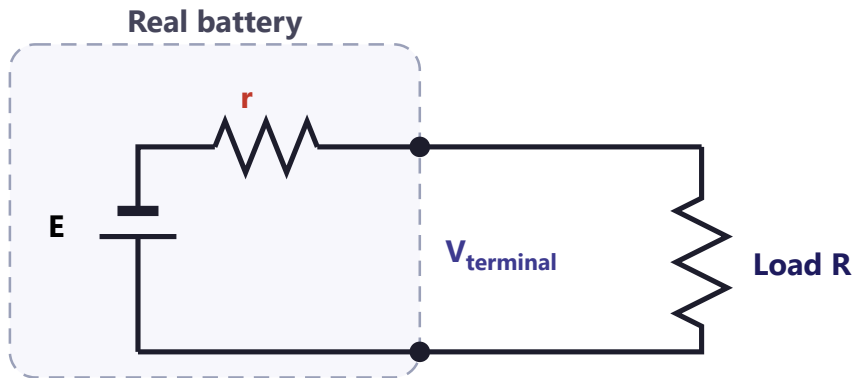


Figure 2.5 — A real source modelled as an ideal EMF E in series with internal resistance r .

Worked example 2.7

A battery has $E = 12.6 \text{ V}$ and $r = 0.05 \Omega$. It supplies a load of 2.95Ω .

$$I = 12.6 \div (2.95 + 0.05) = 12.6 \div 3 = \mathbf{4.2 \text{ A}}. \quad V_{\text{terminal}} = 12.6 - 4.2 \times 0.05 = \mathbf{12.39 \text{ V}}.$$

If the load is short-circuited ($R = 0$): $I = 12.6 \div 0.05 = \mathbf{252 \text{ A}}$ — enough to melt thin wires. This is why batteries need fuses.

2.8 Maximum power transfer

A source delivers the **maximum power** to a load when the load resistance equals the source's internal resistance: $R_L = r$. At that point the efficiency is only 50% (half the power is lost inside the source), so power systems never operate this way — but it matters in electronics and communications, for example matching a speaker to an amplifier or an antenna to a receiver. Module 3 revisits this with Thevenin's theorem.

Formula — maximum power

$$P_{\text{max}} = E^2 \div (4 r) \quad \text{when } R_L = r$$

2.9 Cells in series and parallel

- **Series:** EMFs add and internal resistances add. Six 1.5 V cells $\rightarrow$ 9 V.
- **Parallel (identical cells):** EMF stays the same; internal resistance is divided by the number of cells; capacity (and maximum current) increases.

2.10 Practical applications

Application	Circuit idea
House wiring	All loads in parallel across 230 V, so each works independently at full voltage
LED current-limiting resistor	Series resistor sets the LED current: $R = (V_S - V_{LED}) \div I$
Volume control / potentiometer	Adjustable voltage divider
Sensor interface (LDR, thermistor)	Divider converts changing resistance into changing voltage
Ammeter shunt	Low-value resistor in parallel with a meter to extend its current range
Voltmeter multiplier	High-value resistor in series with a meter to extend its voltage range

Worked example 2.8 — LED resistor

A red LED ($V_F = 2$ V, $I = 20$ mA) is powered from 5 V. $R = (5 - 2) \div 0.02 = \mathbf{150\ \Omega}$. Power $= 0.02^2 \times 150 = 0.06$ W $\rightarrow$ a 1/4-W resistor is fine.

Module 2 — Summary

- Series: same current; voltages add; $R_T = \Sigma R$.
- Parallel: same voltage; currents add; $1/R_T = \Sigma(1/R)$; two resistors: product/sum.
- Voltage divider: $V_2 = V_S R_2 / (R_1 + R_2)$. Current divider: $I_1 = I_T R_2 / (R_1 + R_2)$.
- Solve compound networks by simplifying step by step, then working back.
- Real sources: $V = E - Ir$. Max power transfer when $R_L = r$.

Practice questions — Module 2

1. Find R_T for $47\ \Omega$, $100\ \Omega$ and $220\ \Omega$ in series. (Ans: $367\ \Omega$)
2. Find R_T for $10\ \Omega$ and $40\ \Omega$ in parallel. (Ans: $8\ \Omega$)
3. Three $30\ \Omega$ resistors are in parallel across $15\ \text{V}$. Find total current. (Ans: $1.5\ \text{A}$)
4. Design a divider giving $3.3\ \text{V}$ from $5\ \text{V}$ with $R_2 = 20\ \text{k}\Omega$. (Ans: $R_1 \approx 10.3\ \text{k}\Omega$; use $10\ \text{k}\Omega$)
5. A $12\ \text{A}$ current divides between $4\ \Omega$ and $8\ \Omega$. Find each current. (Ans: $8\ \text{A}$, $4\ \text{A}$)
6. $R_1 = 5\ \Omega$ in series with $(10\ \Omega \parallel 10\ \Omega)$ across $20\ \text{V}$. Find the supply current and current in each $10\ \Omega$. (Ans: $2\ \text{A}$; $1\ \text{A}$ each)
7. A cell of EMF $1.5\ \text{V}$ and $r = 0.5\ \Omega$ supplies $2.5\ \Omega$. Find current and terminal voltage. (Ans: $0.5\ \text{A}$; $1.25\ \text{V}$)
8. Find the resistor for a white LED ($3.2\ \text{V}$, $15\ \text{mA}$) from $12\ \text{V}$. (Ans: $\approx 587\ \Omega \rightarrow 560$ or $620\ \Omega$)

Kirchhoff's Laws and Network Theorems

Tools for circuits too complex for series/parallel rules: KCL, KVL, mesh and nodal analysis, superposition, Thevenin's and Norton's theorems, and maximum power transfer.

3.1 Why we need more tools

Series and parallel rules work only when a circuit can be reduced step by step. Many practical networks — circuits with two or more sources, bridges, or cross-connections — cannot be simplified that way. In 1845, Gustav Kirchhoff stated two laws that apply to **every** circuit, however complicated. Together with Ohm's law, they can solve any linear DC network.

Some useful terms

- **Node (junction):** a point where two or more components connect.
- **Branch:** a path between two nodes containing one or more elements.
- **Loop:** any closed path through the circuit.
- **Mesh:** a loop that contains no other loop inside it ("window" of the circuit).

3.2 Kirchhoff's Current Law (KCL)

KCL

The algebraic sum of currents at any node is zero. In other words: **total current entering a node = total current leaving it.**

$$\Sigma I_{\text{in}} = \Sigma I_{\text{out}}$$

KCL is a statement of **conservation of charge**: charge cannot pile up at a point or disappear from it. Water analogy: the water flowing into a pipe junction must equal the water flowing out.

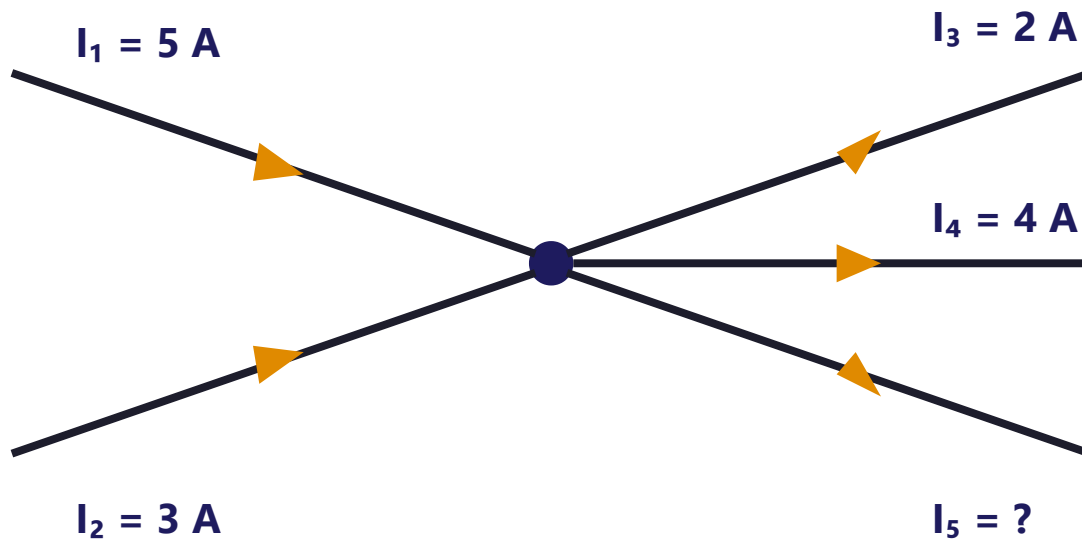


Figure 3.1 — KCL at a node: $5 + 3 = 2 + 4 + I_5$, so $I_5 = 2$ A.

3.3 Kirchhoff's Voltage Law (KVL)

KVL

Around any closed loop, the algebraic sum of all voltages is zero. In other words: **the sum of the EMFs = the sum of the voltage drops (IR) around the loop.**

$$\Sigma E = \Sigma I R$$

KVL is a statement of **conservation of energy**: a charge travelling around a loop and returning to its starting point must end with the same energy it started with.

Sign convention (follow it every time)

1. Choose a direction to go round the loop (clockwise is usual).
2. For a source: going from $-$ to $+$ is a **rise** (+E); from $+$ to $-$ is a **drop** (−E).
3. For a resistor: going in the **same** direction as the assumed current is a drop (−IR); going against it is a rise (+IR).
4. If a current comes out negative in the answer, it simply flows the opposite way to your assumption.

3.4 Solving a two-source circuit with Kirchhoff's laws

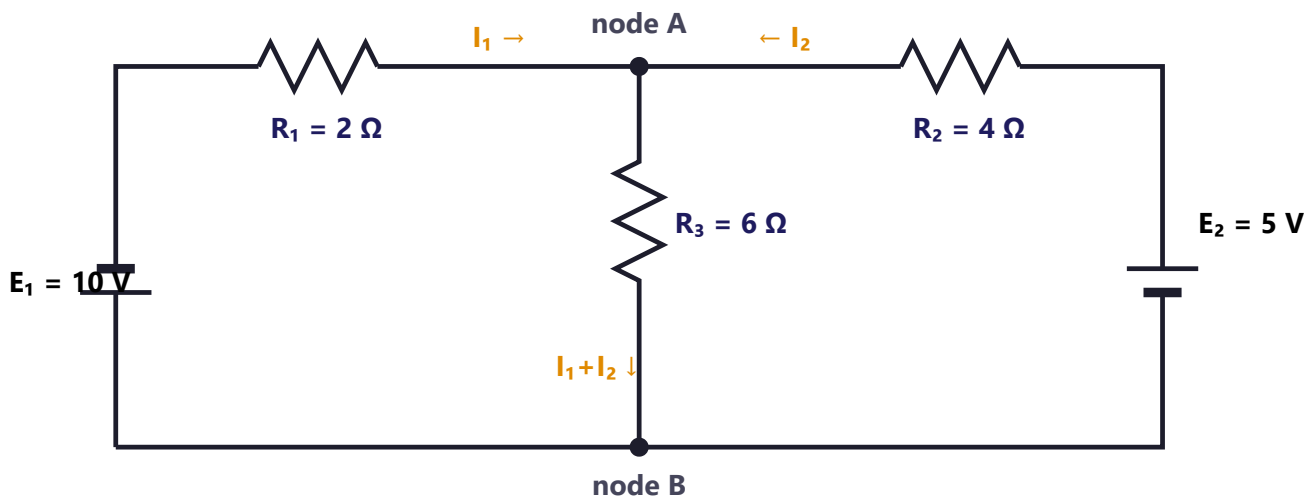


Figure 3.2 — Two sources feeding a common load R_3 . (Both batteries have + at the top.)

Worked example 3.1

Find the current in each branch of Figure 3.2.

KCL at node A: current down through $R_3 = I_1 + I_2$.

KVL, left loop ($E_1 \rightarrow R_1 \rightarrow R_3$): $10 = 2 I_1 + 6 (I_1 + I_2) \rightarrow 10 = 8 I_1 + 6 I_2 \dots (1)$

KVL, right loop ($E_2 \rightarrow R_2 \rightarrow R_3$): $5 = 4 I_2 + 6 (I_1 + I_2) \rightarrow 5 = 6 I_1 + 10 I_2 \dots (2)$

Solve: Multiply (1) by 5 and (2) by 3: $50 = 40 I_1 + 30 I_2$; $15 = 18 I_1 + 30 I_2$. Subtract: $35 = 22 I_1 \rightarrow I_1 = \mathbf{1.591 \text{ A}}$.

From (1): $6 I_2 = 10 - 8(1.591) = -2.727 \rightarrow I_2 = \mathbf{-0.455 \text{ A}}$.

The negative sign means I_2 actually flows the other way — the 10 V source is **charging** the 5 V battery through R_2 .

Current in $R_3 = 1.591 - 0.455 = \mathbf{1.136 \text{ A}}$ (downwards). Check: $V(R_3) = 6.82 \text{ V}$; left loop: $10 - 2(1.591) = 6.82 \text{ V} \checkmark$.

3.5 Mesh (loop-current) analysis

Mesh analysis is a tidy, systematic version of KVL. Instead of branch currents, we assign an imaginary **mesh current** circulating clockwise in each window of the circuit. A resistor shared by two meshes carries the **difference** of their mesh currents.

1. Assign clockwise mesh currents $I_a, I_b, \dots$ to each mesh.

2. Write KVL for each mesh: (sum of resistances in the mesh) $\times$ own current – (shared resistance) $\times$ neighbour's current = sum of source EMFs in the mesh (taken positive if they push current clockwise).
3. Solve the simultaneous equations.

Worked example 3.2 — same circuit by mesh analysis

Mesh a (left, clockwise): $(2 + 6) I_a - 6 I_b = 10$.

Mesh b (right, clockwise): E_2 has + at the top; going clockwise down through E_2 goes + to –, so it opposes: $-6 I_a + (4 + 6) I_b = -5$.

From these: $8 I_a - 6 I_b = 10$ and $-6 I_a + 10 I_b = -5$.

Solving: $I_a = 1.591 \text{ A}$, $I_b = 0.455 \text{ A}$. Current in $R_3 = I_a - I_b = \mathbf{1.136 \text{ A}}$ ✓ (same answer).

3.6 Nodal analysis

Nodal analysis applies KCL at each node, using node voltages as the unknowns. Choose one node as the **reference (0 V)**. For each other node, write: sum of currents leaving the node = 0, with each current written as $(V_{\text{node}} - V_{\text{other}}) \div R$.

Worked example 3.3 — same circuit by nodal analysis

Take node B as 0 V; let node A = V.

Currents leaving A: through R_1 towards E_1 : $(V - 10)/2$; through R_2 towards E_2 : $(V - 5)/4$; through R_3 : $V/6$.

$(V - 10)/2 + (V - 5)/4 + V/6 = 0$. Multiply by 12: $6V - 60 + 3V - 15 + 2V = 0 \rightarrow 11V = 75 \rightarrow \mathbf{V = 6.818 \text{ V}}$.

$I(R_3) = 6.818/6 = \mathbf{1.136 \text{ A}}$ ✓. Only **one** equation was needed — nodal analysis is often the quickest method.

Which method should I use?

Count the unknowns. Mesh analysis needs one equation per mesh; nodal analysis needs one equation per node (minus the reference). Choose the method with fewer equations. Circuits with many parallel branches usually favour nodal analysis.

3.7 The superposition theorem

Superposition theorem

In a linear circuit with several sources, the current in any branch equals the **sum of the currents produced by each source acting alone**, with every other source replaced by its internal resistance (ideal voltage sources **short-circuited**, ideal current sources **open-circuited**).

Worked example 3.4 — superposition on Figure 3.2

E₁ alone (E₂ shorted): $R_2 \parallel R_3 = (4 \times 6)/10 = 2.4 \, \Omega$; total = $2 + 2.4 = 4.4 \, \Omega$; $I = 10/4.4 = 2.273 \, \text{A}$. Current divider into R_3 : $2.273 \times 4/10 = \mathbf{0.909 \, \text{A}}$ (down).

E₂ alone (E₁ shorted): $R_1 \parallel R_3 = (2 \times 6)/8 = 1.5 \, \Omega$; total = $4 + 1.5 = 5.5 \, \Omega$; $I = 5/5.5 = 0.909 \, \text{A}$. Into R_3 : $0.909 \times 2/8 = \mathbf{0.227 \, \text{A}}$ (down).

Total in $R_3 = 0.909 + 0.227 = \mathbf{1.136 \, \text{A}}$ ✓.

Caution

Superposition works for currents and voltages, but **not for power**, because power depends on I^2 (a non-linear quantity). Find the total current first, then calculate power.

3.8 Thevenin's theorem

Thevenin's theorem

Any linear two-terminal network, however complex, can be replaced — as far as a load connected to its terminals is concerned — by a single voltage source **V_{TH}** in series with a single resistance **R_{TH}**.

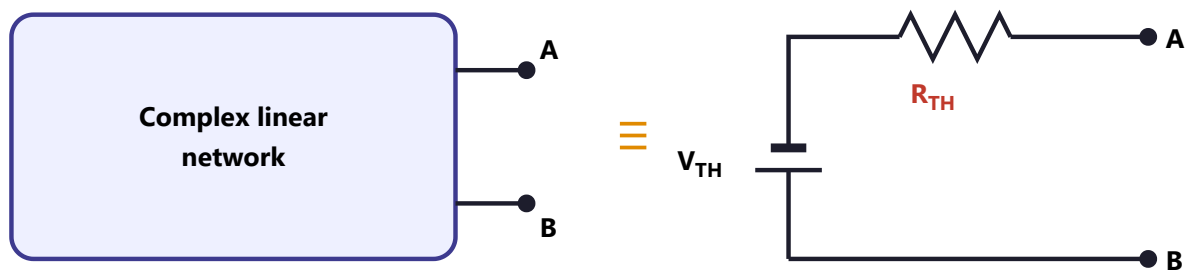


Figure 3.3 — Thevenin equivalent: one source and one series resistance.

Steps to find the Thevenin equivalent

1. Remove the load resistor from terminals A–B.
2. V_{TH} = open-circuit voltage across A–B.
3. R_{TH} = resistance seen from A–B with all sources replaced by their internal resistances (voltage sources shorted, current sources opened).
4. Reconnect the load: $I_L = V_{TH} \div (R_{TH} + R_L)$.

The great advantage: once you have the Thevenin equivalent, you can find the current for **any** load value instantly, without re-solving the whole network.

Worked example 3.5 — Thevenin on Figure 3.2, with R_3 as the load

Remove R_3 . The remaining circuit is E_1 (10 V) and R_1 (2 Ω) in a loop with E_2 (5 V) and R_2 (4 Ω). Net EMF = 10 – 5 = 5 V driving current round the loop: $I = 5/(2 + 4) = 0.833$ A.
 $V_{TH} = V_{AB} = 10 - 0.833 \times 2 = \mathbf{8.333\text{ V}}$ (check: $5 + 0.833 \times 4 = 8.333$ ✓).

R_{TH} (sources shorted) = $R_1 \parallel R_2 = (2 \times 4)/6 = \mathbf{1.333\ \Omega}$.

Load current in $R_3 = 6\ \Omega$: $I = 8.333/(1.333 + 6) = \mathbf{1.136\text{ A}}$ ✓ — the same answer a fourth way.

If R_3 changes to 2 Ω : $I = 8.333/3.333 = 2.5\text{ A}$ — found in one line.

3.9 Norton's theorem

Norton's theorem

Any linear two-terminal network can be replaced by a **current source I_N** in **parallel** with a resistance **R_N** .

I_N = short-circuit current between A and B. $R_N = R_{TH}$ (found the same way).

Converting between Thevenin and Norton

$$I_N = V_{TH} \div R_{TH} \quad V_{TH} = I_N \times R_N \quad R_N = R_{TH}$$

Worked example 3.6

For Example 3.5: $I_N = 8.333 \div 1.333 = \mathbf{6.25 \text{ A}}$, in parallel with 1.333Ω .

Check directly: short A–B: current from $E_1 = 10/2 = 5 \text{ A}$; from $E_2 = 5/4 = 1.25 \text{ A}$; total short-circuit current = $6.25 \text{ A} \checkmark$.

Load current by current divider: $6.25 \times 1.333/(1.333 + 6) = \mathbf{1.136 \text{ A} \checkmark}$.

3.10 Maximum power transfer theorem

Maximum power transfer

A load receives maximum power from a network when its resistance equals the network's Thevenin resistance: $R_L = R_{TH}$. Then $P_{\max} = V_{TH}^2 \div (4 R_{TH})$.

Worked example 3.7

For the network above, the maximum power any load can receive is when $R_L = 1.333 \Omega$:

$$P_{\max} = 8.333^2 \div (4 \times 1.333) = 69.44 \div 5.333 = \mathbf{13.02 \text{ W}}.$$

With the actual 6Ω load: $P = 1.136^2 \times 6 = 7.75 \text{ W}$ — less than the maximum, as expected.

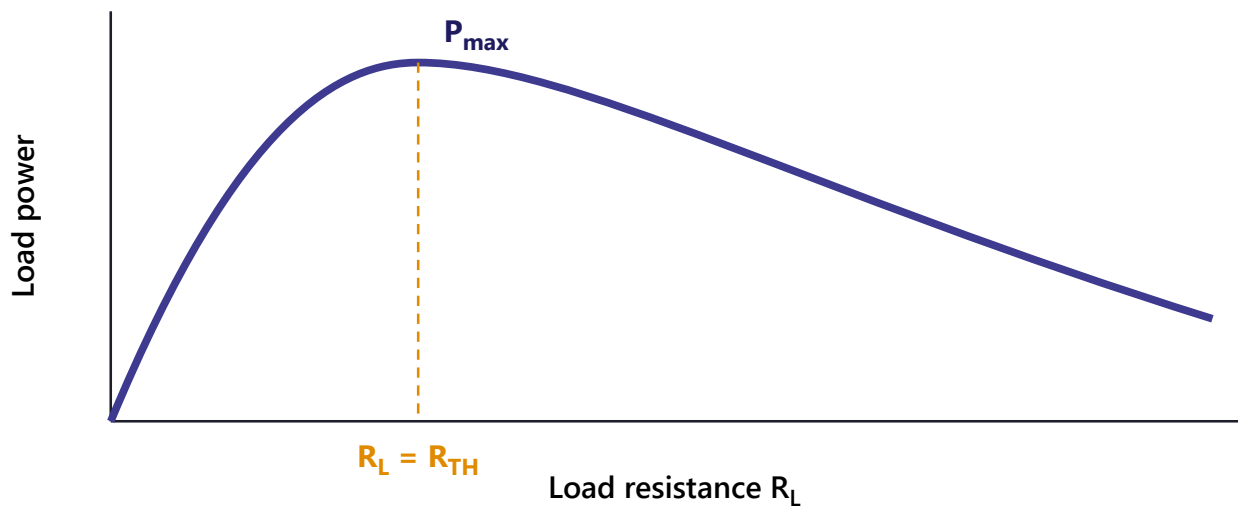


Figure 3.4 — Load power peaks when the load matches the source's Thevenin resistance.

3.11 The Wheatstone bridge

The **Wheatstone bridge** is four resistors in a diamond, with a sensitive meter (galvanometer) across the middle. When the bridge is **balanced**, no current flows through the meter. This is used to measure an unknown resistance very precisely, and in sensor circuits such as strain gauges and temperature sensors.

Balance condition

$$R_1 \div R_2 = R_3 \div R_x \rightarrow R_x = R_2 \times R_3 \div R_1$$

Worked example 3.8

A bridge balances with $R_1 = 100 \, \Omega$, $R_2 = 470 \, \Omega$, $R_3 = 250 \, \Omega$. $R_x = 470 \times 250 \div 100 = 1,175 \, \Omega$.

3.12 Star–delta (Y–Δ) transformation

Some networks contain three resistors connected as a **delta (Δ)** triangle or a **star (Y)** that can be neither series nor parallel. Converting one form to the other often unlocks the simplification.

Delta → Star

$$R_a = R_{ab} R_{ca} \div (R_{ab} + R_{bc} + R_{ca}) \quad (\text{and similarly for } R_b, R_c)$$

Star → Delta: $R_{ab} = R_a + R_b + R_a R_b / R_c$. For three equal resistors: $R_Y = R_{\Delta} / 3$.

Module 3 — Summary

- KCL: $\sum I_{in} = \sum I_{out}$ at a node (charge conservation).
- KVL: $\sum E = \sum IR$ around a loop (energy conservation).
- Mesh analysis (loop currents) and nodal analysis (node voltages) organise KVL/KCL systematically.
- Superposition: add effects of each source acting alone (not for power).
- Thevenin: V_{TH} (open-circuit) + series R_{TH} ; Norton: I_N (short-circuit) $\parallel R_N$; $I_N = V_{TH} / R_{TH}$.
- Max power when $R_L = R_{TH}$; $P_{max} = V_{TH}^2 / 4R_{TH}$.
- Wheatstone bridge balance: $R_1 / R_2 = R_3 / R_x$.

Practice questions — Module 3

1. State KCL and KVL, and name the conservation law behind each.
2. At a node, 8 A and 3 A enter; 6 A leaves by one wire. Find the current in the other wire. (Ans: 5 A leaving)
3. Use nodal analysis: $E_1 = 12$ V with $R_1 = 3 \Omega$ and $E_2 = 6$ V with $R_2 = 6 \Omega$ both feed node A, which connects to $R_3 = 2 \Omega$ to ground. Find V_A . (Ans: 5.0 V)
4. Using superposition, find the current in R_3 for Q3. (Ans: 2.5 A)
5. A network has $V_{TH} = 20$ V and $R_{TH} = 5 \Omega$. Find the load current for $R_L = 5, 15$ and 35Ω . (Ans: 2 A, 1 A, 0.5 A)
6. Convert the network in Q5 into its Norton equivalent. (Ans: 4 A $\parallel$ 5 Ω)
7. Find the maximum power the network in Q5 can deliver. (Ans: 20 W)
8. Three 30Ω resistors in delta are converted to star. Find each star resistance. (Ans: 10 Ω)

Capacitors, Inductors, and Transient Response

How capacitors store energy in electric fields and inductors in magnetic fields, how to combine them, and what happens in the first moments after a switch closes — RC and RL charging curves and the time constant.

4.1 The capacitor

A **capacitor** is two conducting plates separated by an insulator called the **dielectric**. When a voltage is applied, electrons pile up on one plate and leave the other, so one plate becomes negative and the other positive. No current flows *through* the dielectric, but charge builds up on the plates and an **electric field** forms between them. The capacitor stores energy in this field.

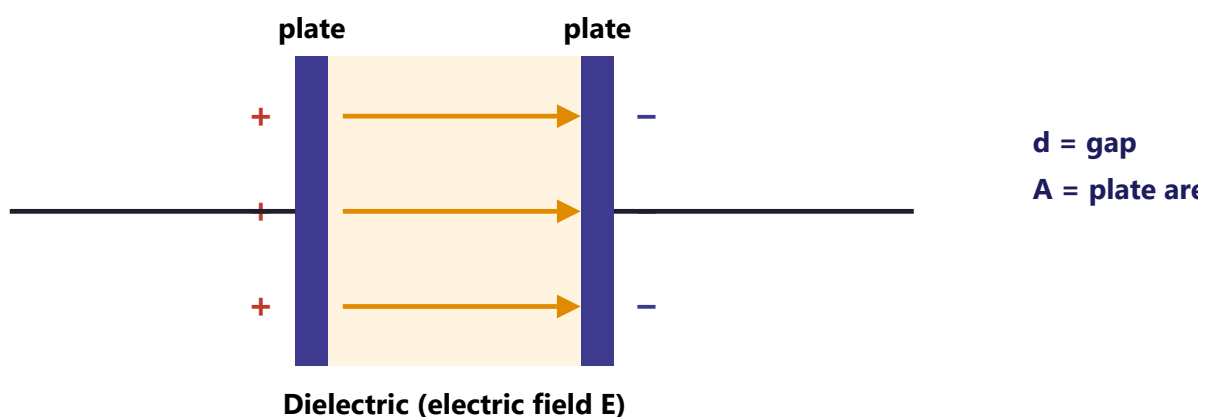


Figure 4.1 — A parallel-plate capacitor stores charge on its plates and energy in the field between them.

Capacitance

Capacitance (C) is the charge stored per volt. Its unit is the **farad (F)**. One farad is very large, so practical values are in μF (10^{-6}), nF (10^{-9}) and pF (10^{-12}).

Formulas — capacitance

$$C = Q \div V \quad Q = C V$$

$$\text{Parallel-plate: } C = \epsilon_0 \epsilon_r A \div d$$

$\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$ (permittivity of free space); ϵ_r = relative permittivity of the dielectric (air ≈ 1 , paper $\approx 2\text{--}4$, mica ≈ 6 , ceramic up to thousands).

So capacitance increases with larger plates, a smaller gap and a better dielectric.

Worked example 4.1

(a) A 470 μF capacitor is charged to 12 V. Charge stored: $Q = CV = 470 \times 10^{-6} \times 12 =$
5.64 mC.

(b) Two plates of 0.01 m^2 are 0.1 mm apart with mica ($\epsilon_r = 6$): $C = 8.854 \times 10^{-12} \times 6 \times$
 $0.01 \div 10^{-4} =$ **5.31 nF.**

Energy stored

Formula — capacitor energy

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

Worked example 4.2

A camera flash capacitor of 200 μF is charged to 330 V. $W = \frac{1}{2} \times 200 \times 10^{-6} \times 330^2 =$
10.9 J — released in about a millisecond, giving a bright flash (and a painful shock if touched).

Caution — capacitors can bite

Capacitors can hold a dangerous charge long after the power is switched off — especially in TVs, microwave ovens, inverters and power supplies. Always discharge large capacitors safely through a suitable resistor before touching, and check with a meter.

4.2 Types of capacitor

Type	Typical values	Features	Uses
Ceramic	1 pF – 10 μF	Small, cheap, non-polarised	Decoupling, high-frequency filters
Film (polyester, polypropylene)	1 nF – 100 μF	Stable, low loss, non-polarised	Audio, timing, AC motor run, power factor correction
Aluminium electrolytic	1 μF – 100,000 μF	Polarised , large value, limited life	Power supply smoothing, bulk storage

Tantalum	0.1 – 1,000 μF	Polarised, compact, stable	Compact electronics
Supercapacitor	0.1 – 3,000 F	Very large capacity, low voltage per cell	Backup power, energy recovery

Caution — polarity

An electrolytic capacitor connected the wrong way round, or above its rated voltage, can overheat and burst. The negative lead is marked with a stripe and is usually the shorter lead.

4.3 Capacitors in series and parallel

Capacitors combine the **opposite way** to resistors:

Combination rules

$$\text{Parallel: } C_T = C_1 + C_2 + C_3 \dots$$

$$\text{Series: } 1/C_T = 1/C_1 + 1/C_2 + \dots \quad (\text{two: } C_1 C_2 / (C_1 + C_2))$$

In parallel, the plate areas effectively add. In series, the gaps effectively add. In series every capacitor has the same charge, and the smallest capacitor takes the largest voltage.

Worked example 4.3

(a) 10 μF , 22 μF and 47 μF in parallel: $C_T = \mathbf{79 \mu F}$.

(b) 6 μF and 3 μF in series across 90 V: $C_T = 18/9 = 2 \mu\text{F}$; $Q = 2 \mu\text{F} \times 90 = 180 \mu\text{C}$; $V(6 \mu\text{F}) = 180/6 = \mathbf{30 V}$; $V(3 \mu\text{F}) = 180/3 = \mathbf{60 V}$.

4.4 Charging a capacitor: the RC circuit

When a capacitor is connected to a DC source through a resistor, it does not charge instantly. At the moment the switch closes, the capacitor is empty (0 V), so the full supply voltage appears across the resistor and a large current $I_0 = V/R$ flows. As charge builds up, the capacitor voltage rises, the voltage across R falls, and the current falls. Charging slows down and the voltage approaches the supply voltage along an **exponential curve**.

Formulas — RC charging

Time constant $\tau = R \times C$ (seconds)

$$v_C(t) = V (1 - e^{-t/\tau})$$

$$i(t) = (V/R) e^{-t/\tau}$$

Discharging through R: $v_C(t) = V_0 e^{-t/\tau}$.

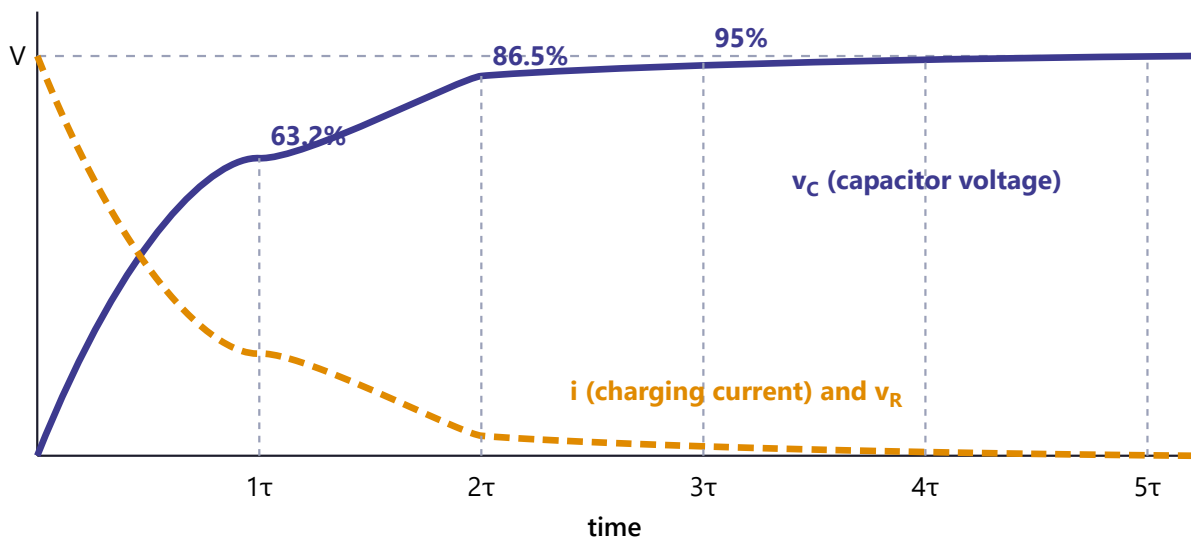


Figure 4.2 — RC charging: the capacitor voltage reaches 63.2% of V in one time constant and is practically full after 5τ .

Time	1τ	2τ	3τ	4τ	5τ
v_C while charging (% of V)	63.2%	86.5%	95.0%	98.2%	99.3%
Current / v_C while discharging (% of initial)	36.8%	13.5%	5.0%	1.8%	0.7%

Key idea — the 5τ rule

After about **five time constants** a capacitor is considered fully charged (or discharged). A capacitor **opposes sudden changes in voltage**: its voltage cannot jump instantly. In steady DC it behaves like an **open circuit** (no current).

Worked example 4.4

A 100 k Ω resistor and 47 μ F capacitor are connected to 10 V.

$\tau = 100 \times 10^3 \times 47 \times 10^{-6} = \mathbf{4.7 \text{ s}}$. Initial current = 10/100 k = **0.1 mA**.

After 4.7 s: $v_C = 6.32 \text{ V}$. After 10 s: $v_C = 10 (1 - e^{-10/4.7}) = 10 (1 - 0.119) = \mathbf{8.81 \text{ V}}$.

Fully charged after about $5 \times 4.7 = \mathbf{23.5 \text{ s}}$.

4.5 Uses of capacitors

- **Smoothing** the output of rectifiers in power supplies (Module 7).
- **Timing circuits:** RC time constants set delays and oscillator frequencies (e.g. the 555 timer).
- **Coupling** AC signals between amplifier stages while blocking DC.
- **Decoupling / bypass:** small capacitors near ICs absorb supply noise.
- **Filters:** with resistors and inductors, to pass or block certain frequencies.
- **Motor start/run capacitors** in single-phase motors (fans, pumps, compressors).
- **Power factor correction** in factories (Module 6).
- **Energy storage:** camera flash, defibrillators, supercapacitor backup.

4.6 Magnetism and electromagnetism — background for inductors

A current flowing in a wire creates a **magnetic field** around it. Winding the wire into a coil concentrates the field, and adding an iron core strengthens it greatly. This is the principle of electromagnets, relays, motors and transformers.

In 1831, Michael Faraday discovered the reverse effect: a **changing** magnetic field through a coil induces a voltage in it. This is **electromagnetic induction**.

Faraday's and Lenz's laws

$$e = -N \, d\Phi/dt$$

The induced EMF equals the rate of change of magnetic flux linkage (N = number of turns, Φ = flux in webers). The minus sign (**Lenz's law**) means the induced EMF always acts to **oppose the change** that causes it.

4.7 The inductor

An **inductor** is a coil of wire, often wound on an iron or ferrite core. When the current through it changes, its own changing magnetic field induces a voltage in the coil that opposes the change — this is **self-inductance**. The unit is the **henry (H)**.

Formulas — inductance

$$v_L = L \times di/dt$$

$$\text{Coil: } L = \mu_0 \mu_r N^2 A \div l$$

$$\text{Energy stored: } W = \frac{1}{2} L I^2$$

Inductance rises with the square of the number of turns, with core permeability μ_r and area A , and falls with coil length l . $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$.

Worked example 4.5

(a) The current in a 0.5 H coil rises from 0 to 2 A in 10 ms. Induced voltage = $0.5 \times 2/0.01$ = **100 V**.

(b) Energy stored at 2 A: $W = \frac{1}{2} \times 0.5 \times 2^2 = \mathbf{1 \text{ J}}$.

Key idea

An inductor **opposes sudden changes in current**: its current cannot jump instantly. In steady DC it behaves like a **short circuit** (just the resistance of its wire). Compare: a capacitor opposes sudden changes in *voltage*.

Inductors in series and parallel

With no magnetic coupling between them, inductors combine like resistors: series $L_T = L_1 + L_2 + \dots$; parallel $1/L_T = 1/L_1 + 1/L_2 + \dots$

4.8 RL circuits — current rise and decay

When a DC voltage is switched onto a coil through a resistance, the current does not jump; it rises exponentially, because the coil's back-EMF opposes the change. The shape is exactly the same as the RC charging curve, but now it is the **current** that rises.

Formulas — RL circuit

$$\tau = L \div R$$

$$\text{Rise: } i(t) = (V/R)(1 - e^{-t/\tau}) \quad \text{Decay: } i(t) = I_0 e^{-t/\tau}$$

$$v_L(t) = V e^{-t/\tau}$$

Worked example 4.6

A relay coil has $L = 0.2 \text{ H}$ and $R = 40 \Omega$ and is connected to 12 V .

$\tau = 0.2/40 = \mathbf{5 \text{ ms}}$. Final current = $12/40 = \mathbf{0.3 \text{ A}}$. After 5 ms : $i = 0.3 \times 0.632 = 0.19 \text{ A}$. Fully energised after about 25 ms .

4.9 Inductive kick and the flyback diode

If the current through an inductor is suddenly switched off, di/dt is huge, so $v = L di/dt$ produces a very large voltage spike — hundreds or thousands of volts. This **inductive kick** can arc across switch contacts or destroy the transistor driving a relay. The standard solution is a **flyback (freewheeling) diode** across the coil, which gives the current a safe path to decay (Module 7). The same principle is used deliberately in car ignition coils and in boost converters.

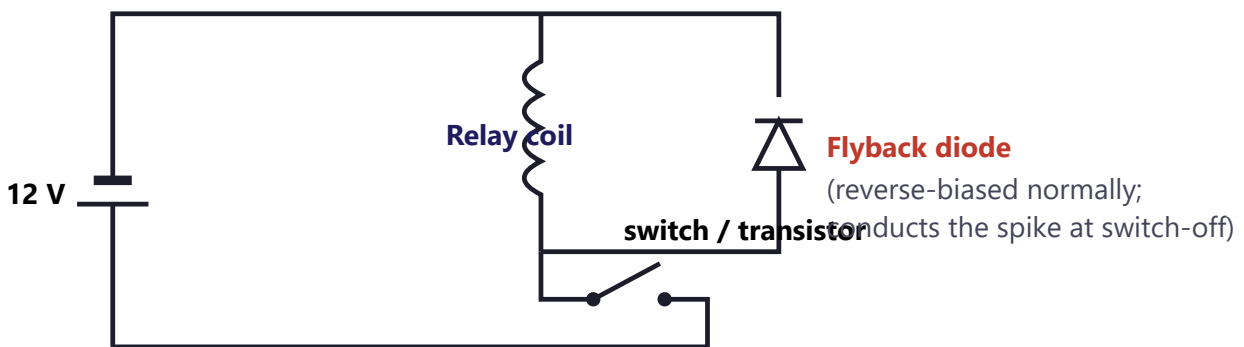


Figure 4.3 — A flyback diode across an inductive load absorbs the switch-off voltage spike.

4.10 Capacitor versus inductor — comparison

Property	Capacitor	Inductor
Stores energy in	Electric field	Magnetic field

Energy formula	$\frac{1}{2} C V^2$	$\frac{1}{2} L I^2$
Opposes sudden change in	Voltage	Current
Behaviour in steady DC	Open circuit	Short circuit (wire resistance)
Time constant	$\tau = RC$	$\tau = L/R$
Series combination	Reciprocals add	Values add
Parallel combination	Values add	Reciprocals add
In AC, opposition	Falls as frequency rises	Rises as frequency rises

Module 4 — Summary

- $Q = CV$; $C = \epsilon_0 \epsilon_r A/d$; $W = \frac{1}{2} CV^2$. Parallel C add; series reciprocals add.
- RC: $\tau = RC$; $v_C = V(1 - e^{-t/\tau})$; 63.2% at 1τ ; full at 5τ .
- Faraday: $e = -N d\Phi/dt$; Lenz: induced EMF opposes the change.
- $v_L = L di/dt$; $W = \frac{1}{2} LI^2$; RL: $\tau = L/R$.
- Capacitor opposes voltage change (open in DC); inductor opposes current change (short in DC).
- Use flyback diodes across relay coils and other inductive loads.

Practice questions — Module 4

1. A 220 μF capacitor holds 4.4 mC. Find its voltage. (Ans: 20 V)
2. Find the energy in a 1,000 μF capacitor at 50 V. (Ans: 1.25 J)
3. Find C_T for 4 μF and 12 μF in (a) parallel (b) series. (Ans: 16 μF ; 3 μF)
4. $R = 10 \text{ k}\Omega$, $C = 100 \mu F$, $V = 5 \text{ V}$. Find τ and v_C after 2 s. (Ans: 1 s; 4.32 V)
5. How long does the capacitor in Q4 take to charge fully? (Ans: $\approx 5 \text{ s}$)
6. Current in a 50 mH coil changes by 4 A in 2 ms. Find the induced EMF. (Ans: 100 V)
7. An RL circuit has $L = 2 \text{ H}$, $R = 100 \Omega$, $V = 20 \text{ V}$. Find τ and the final current. (Ans: 20 ms; 0.2 A)
8. Explain why a diode is connected across a relay coil in transistor circuits.

Alternating Current (AC) Fundamentals

How AC is generated, the sine wave and its measurements — amplitude, frequency, period, phase — and why the RMS value, not the peak, is printed on every appliance.

5.1 Why the world runs on AC

The electricity in homes and industries is **alternating current**: its direction reverses many times a second. AC won over DC for power distribution (the famous "war of the currents" between Edison and Tesla/Westinghouse in the 1880s–1890s) mainly because:

- **Transformers** can easily step AC voltage up or down. Power can then be transmitted at very high voltage and low current, which drastically reduces the I^2R losses in long lines, and stepped down again for safe use.
- AC **generators (alternators)** are simple and robust.
- AC **induction motors** are cheap, rugged and need almost no maintenance.
- AC is easier to interrupt safely, because the current passes through zero every half-cycle.

Today, high-voltage DC (HVDC) is used for some very long transmission links, and electronics use DC internally — but generation, distribution and most appliances are based on AC.

5.2 Generating an alternating voltage

When a coil rotates at a steady speed in a uniform magnetic field, the magnetic flux through it changes continuously. By Faraday's law (Module 4), an EMF is induced. As the coil turns, this EMF rises to a maximum, falls to zero, reverses, reaches a negative maximum and returns to zero — once every revolution. The shape of this voltage is a **sine wave**.

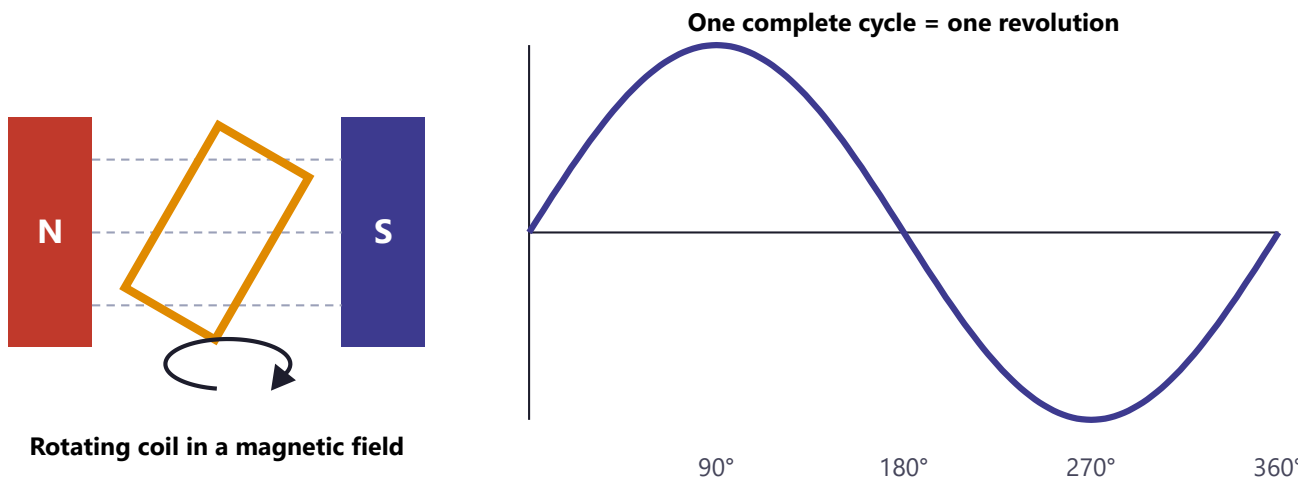


Figure 5.1 — A coil rotating in a magnetic field generates a sinusoidal EMF.

Formula — instantaneous value of a sine wave

$$v = V_m \sin(\omega t) = V_m \sin(2\pi ft)$$

v = instantaneous voltage; V_m = maximum (peak) value; ω = angular frequency (rad/s) = $2\pi f$; t = time (s).

5.3 Describing a sine wave

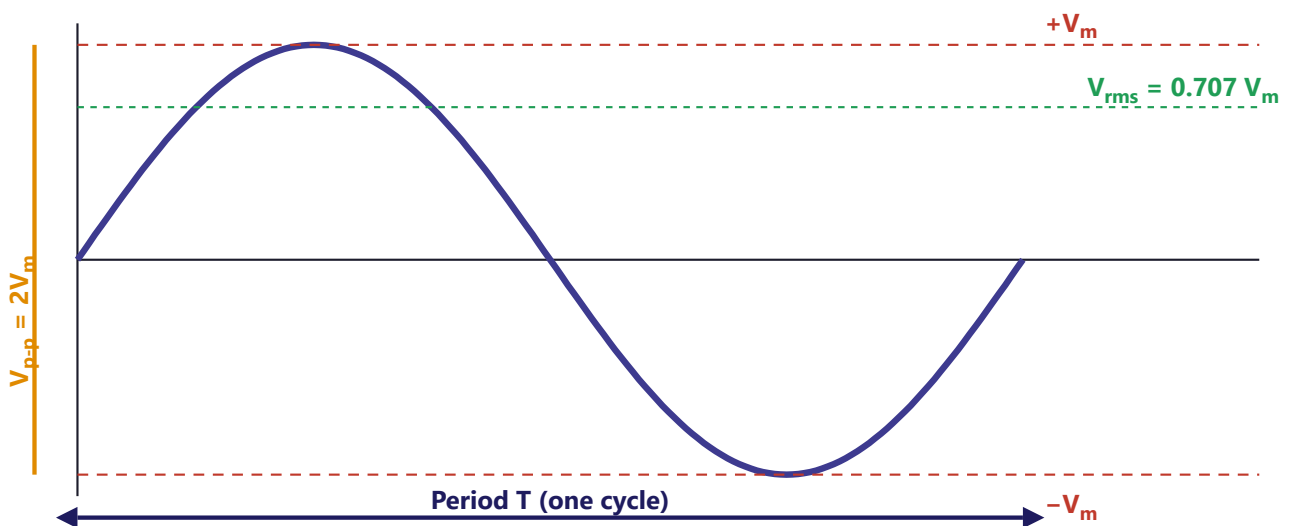


Figure 5.2 — Peak, peak-to-peak, RMS and period of a sine wave.

Term	Symbol	Meaning
Cycle	—	One complete set of positive and negative values
Period	T	Time for one cycle (seconds)

Frequency	f	Cycles per second, in hertz (Hz): $f = 1/T$
Angular frequency	ω	$\omega = 2\pi f$ (rad/s)
Peak (maximum) value / amplitude	V_m, I_m	Highest value reached in a half-cycle
Peak-to-peak value	V_{p-p}	From positive peak to negative peak = $2V_m$
Average value	V_{avg}	Average over one half-cycle = $0.637 V_m$ (over a full cycle it is zero)
RMS (effective) value	V_{rms}	The equivalent DC value that produces the same heating = $0.707 V_m$

Formulas — frequency and period

$$f = 1 \div T \quad T = 1 \div f \quad \omega = 2\pi f$$

India, Europe, most of Asia and Africa: 50 Hz ($T = 20$ ms). USA, Canada, parts of Japan: 60 Hz.

Worked example 5.1

The Indian supply is 50 Hz. Find T and ω .

$T = 1/50 = 0.02$ s = **20 ms**. $\omega = 2\pi \times 50 =$ **314.16 rad/s**. The current reverses direction 100 times every second.

Frequency of a generator

Formula — alternator frequency

$$f = P N \div 120$$

P = number of poles; N = speed in rpm. A 2-pole alternator must spin at 3,000 rpm for 50 Hz; a 4-pole at 1,500 rpm; hydro generators with many poles turn slowly.

5.4 RMS — the value that matters

If AC keeps changing, what single number describes its "strength"? The average over a whole cycle is zero, which is useless. Instead we ask: **what steady DC voltage would produce the same heating effect in a resistor?** That DC value is the **root-mean-square (RMS)** value. The

name describes the calculation: square the instantaneous values, take their mean, then the square root.

Formulas — sine-wave values

$$V_{\text{rms}} = V_m \div \sqrt{2} = 0.707 V_m$$

$$V_{\text{avg}} = 2V_m \div \pi = 0.637 V_m$$

$$\text{Form factor} = V_{\text{rms}} \div V_{\text{avg}} = 1.11 \quad \text{Crest (peak) factor} = V_m \div V_{\text{rms}} = 1.414$$

Key idea — "230 V" is an RMS value

Every AC voltage and current on appliance labels, meters and bills is an **RMS** value, unless stated otherwise. The Indian 230 V supply actually swings between +325 V and -325 V (peak) — which is why insulation and components must be rated for the peak.

Worked example 5.2

(a) Find the peak of 230 V RMS: $V_m = 230 \times 1.414 = \mathbf{325 \text{ V}}$; peak-to-peak = **650 V**.

(b) A current $i = 14.14 \sin(314t)$ A. Find I_{rms} , f and the value at $t = 2.5$ ms.

$I_{\text{rms}} = 14.14 \times 0.707 = \mathbf{10 \text{ A}}$. $f = 314/(2\pi) = \mathbf{50 \text{ Hz}}$. At $t = 2.5$ ms: $\omega t = 314 \times 0.0025 = 0.785$ rad (45°); $i = 14.14 \times \sin 45^\circ = \mathbf{10 \text{ A}}$.

Worked example 5.3 — why RMS works for power

A 2 kW heater (resistance $R = 230^2/2,000 = 26.45 \Omega$) on 230 V RMS AC gives exactly the same heat as on 230 V DC. If we wrongly used the peak (325 V): $P = 325^2/26.45 = 3,993$ W — double the true value. RMS is the correct "equivalent DC" for power.

5.5 Phase and phase difference

Two sine waves of the same frequency may not reach their peaks at the same moment. The time (or angle) between them is the **phase difference (ϕ)**, measured in degrees or radians.

- If wave A reaches its peak before wave B, A **leads** B.
- If A reaches its peak after B, A **lags** B.
- If they peak together, they are **in phase**; if $\phi = 180^\circ$, they are in **antiphase**.

Formula — waves with a phase shift

$$v = V_m \sin(\omega t) \quad i = I_m \sin(\omega t \pm \varphi)$$

$+\varphi$: i leads v ; $-\varphi$: i lags v . Time shift = $\varphi(\text{degrees})/360 \times T$.

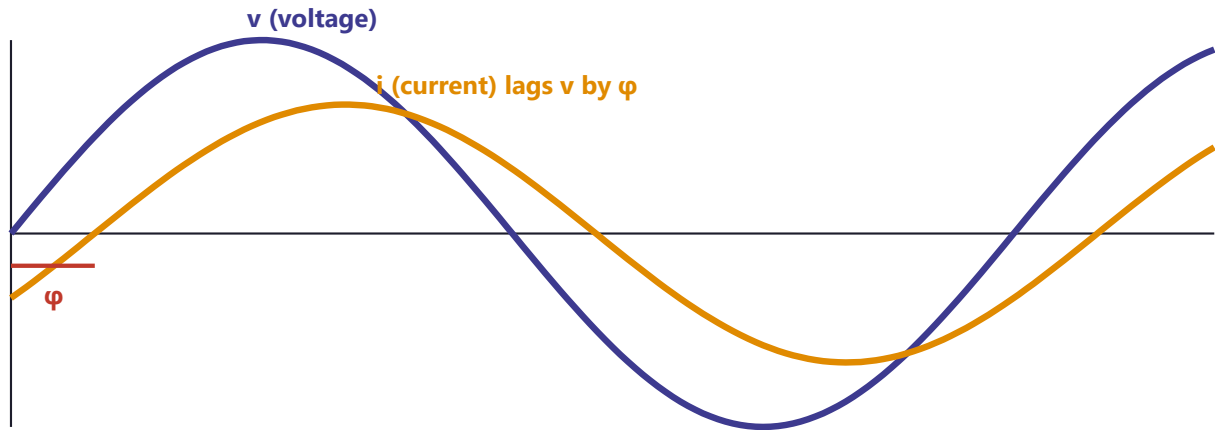


Figure 5.3 — Current lagging voltage by a phase angle φ (typical of inductive loads such as motors).

5.6 Phasors — a simpler way to picture AC

Adding sine waves point by point is tedious. Engineers use **phasors**: arrows whose **length** represents the RMS value and whose **angle** represents the phase. Imagine the arrow rotating anticlockwise at ω ; its vertical projection traces the sine wave. Phasors of the same frequency can be added like vectors (head to tail), which makes AC circuit calculations much easier (Module 6).

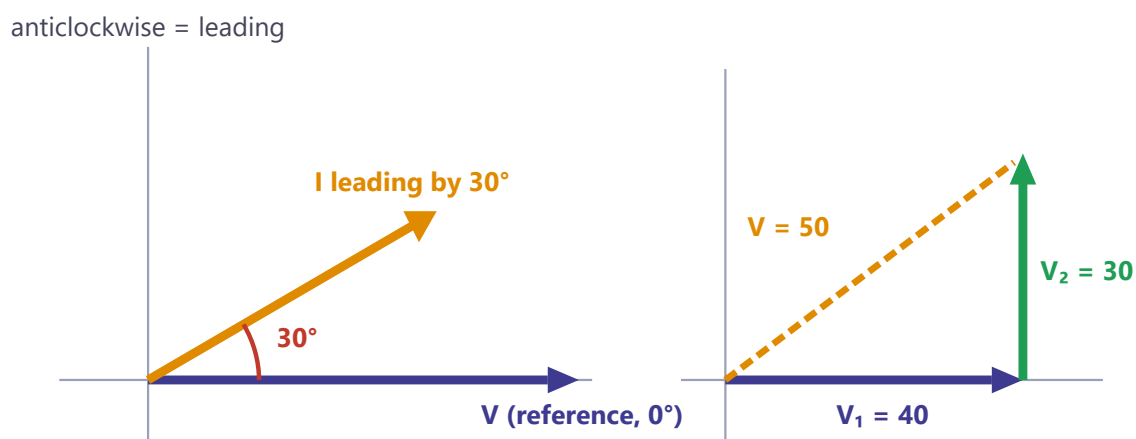


Figure 5.4 — Left: a phasor diagram. Right: adding two voltages 90° apart — 40 V and 30 V give 50 V, not 70 V.

Worked example 5.4 — adding phasors

In an AC circuit, two voltages of 40 V and 30 V are 90° out of phase. Their sum is not 70 V but $\sqrt{40^2 + 30^2} = \mathbf{50\ V}$, at an angle $\tan^{-1}(30/40) = \mathbf{36.9^\circ}$ to the first. This "voltages don't simply add" effect appears in every AC circuit with inductors or capacitors.

5.7 Non-sinusoidal waveforms

Waveform	RMS value	Where you meet it
Sine	$0.707 \times \text{peak}$	Mains supply, generators
Square (symmetrical $\pm V_m$)	V_m (RMS = peak)	Digital clocks, simple inverters
Triangular	$0.577 \times \text{peak}$	Signal generators, PWM carriers
Half-wave rectified sine	$0.5 \times \text{peak}$	Simple rectifiers
Full-wave rectified sine	$0.707 \times \text{peak}$	Bridge rectifiers

Practical tip — "True RMS" meters

Cheap multimeters assume a pure sine wave and scale the average reading by 1.11. With distorted waveforms (from inverters, LED drivers, variable-speed drives) they give wrong readings. A **true-RMS** meter calculates the real RMS value for any waveform.

5.8 Single-phase and three-phase supply

A **single-phase** supply has one live (phase) wire and a neutral. Homes in India typically get 230 V single-phase. Larger homes, shops and industries get a **three-phase** supply: three live wires (R, Y, B), each carrying a sine wave **120° apart**, plus a neutral.

- **Phase voltage** (line to neutral): 230 V.
- **Line voltage** (between any two lines): $\sqrt{3} \times 230 = \mathbf{400\text{--}415\ V}$.
- Three-phase delivers smooth, constant total power, and three-phase motors are simpler and more efficient than single-phase ones.
- Three-phase transmission needs less conductor material for the same power.

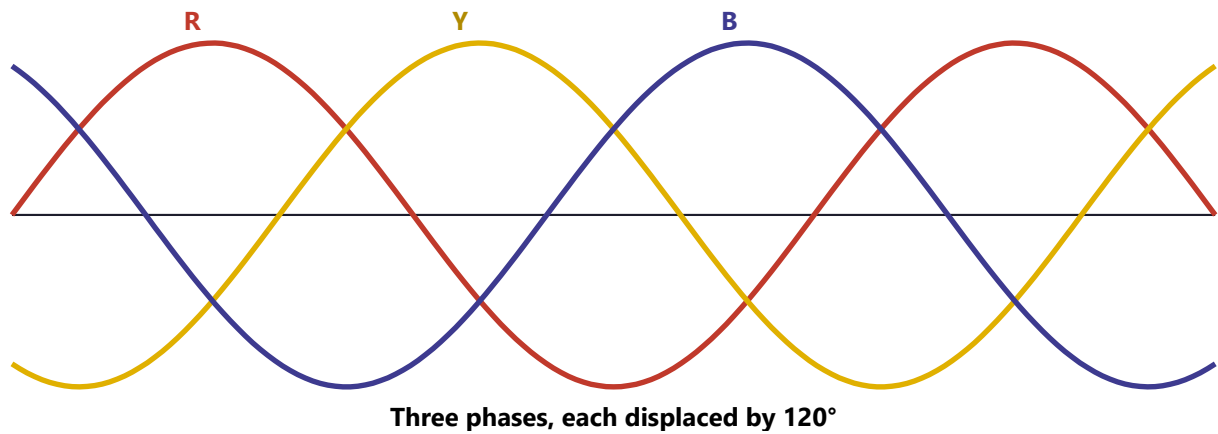


Figure 5.5 — A three-phase supply: R, Y and B phases 120° apart.

Module 5 — Summary

- AC is used because transformers make high-voltage, low-loss transmission easy.
- $v = V_m \sin(2\pi ft)$; $f = 1/T$; $\omega = 2\pi f$. India: 50 Hz, $T = 20$ ms.
- $V_{rms} = 0.707 V_m$; $V_{avg} = 0.637 V_m$; form factor 1.11; crest factor 1.414.
- Appliance ratings are RMS values; 230 V RMS = 325 V peak.
- Phase difference: leading/lagging; phasors add like vectors.
- Three-phase: 120° apart; line voltage = $\sqrt{3} \times$ phase voltage (≈ 400 – 415 V).

Practice questions — Module 5

1. Give three reasons why AC is used for power distribution.
2. Find the period of a 60 Hz supply. (Ans: 16.67 ms)
3. An AC voltage has a peak of 170 V. Find RMS, average and peak-to-peak values. (Ans: 120.2 V; 108.3 V; 340 V)
4. $v = 311 \sin(314t)$. Find V_{rms} , f and v at $t = 5$ ms. (Ans: 220 V; 50 Hz; 311 V)
5. A 4-pole alternator must supply 50 Hz. At what speed must it run? (Ans: 1,500 rpm)
6. Two currents of 6 A and 8 A are 90° apart. Find the resultant. (Ans: 10 A)
7. Explain why RMS rather than average value is used to rate AC supplies.
8. The phase voltage of a three-phase supply is 240 V. Find the line voltage. (Ans: ≈ 415.7 V)

AC Circuits: Impedance and Power

How resistors, inductors and capacitors behave with AC, reactance and impedance, series RL/RC/RLC circuits, resonance, and real, reactive and apparent power with power factor.

6.1 Three basic AC elements

With DC, only resistance limits current (after transients die out, inductors are shorts and capacitors are open). With AC, inductors and capacitors are constantly storing and releasing energy, so they too limit the current — and they shift its phase. Their opposition is called **reactance (X)**, measured in ohms.

Pure resistor

Current and voltage are **in phase**. Ohm's law applies directly with RMS values: $I = V/R$. All power is converted to heat.

Pure inductor — inductive reactance X_L

An inductor opposes changes in current, so the current **lags the voltage by 90°**. The faster the current changes (higher frequency), the more it opposes.

Formula — inductive reactance

$$X_L = 2\pi f L = \omega L \quad I = V \div X_L$$

X_L is proportional to frequency: zero at DC, very large at high frequency.

Pure capacitor — capacitive reactance X_C

A capacitor's current depends on how fast its voltage changes, so the current **leads the voltage by 90°**. Higher frequency → more charging and discharging per second → more current → less opposition.

Formula — capacitive reactance

$$X_C = 1 \div (2\pi f C) = 1 \div (\omega C) \quad I = V \div X_C$$

X_C is inversely proportional to frequency: infinite at DC (open circuit), very small at high frequency.

Memory aid — "CIVIL"

In a **C**apacitor, **I** leads **V**; **V** leads **I** in an inductor (**L**). C-I-V ... V-I-L.

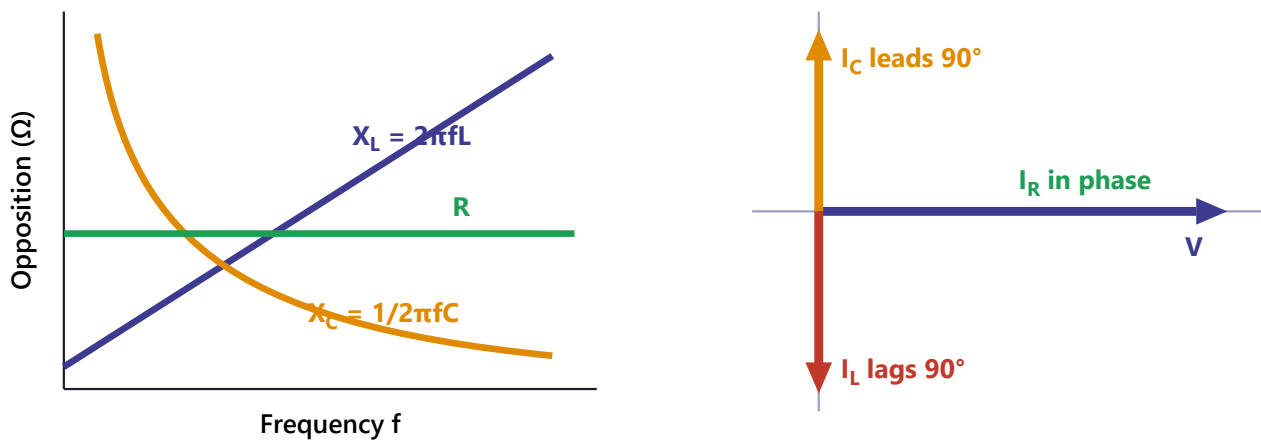


Figure 6.1 — Left: how R , X_L and X_C change with frequency. Right: current phase in R , L and C .

Worked example 6.1

- (a) A 0.1 H inductor on 230 V, 50 Hz: $X_L = 2\pi \times 50 \times 0.1 = \mathbf{31.4\ \Omega}$; $I = 230/31.4 = \mathbf{7.32\ A}$, lagging V by 90° .
- (b) A 10 μF capacitor on the same supply: $X_C = 1/(2\pi \times 50 \times 10 \times 10^{-6}) = \mathbf{318.3\ \Omega}$; $I = 230/318.3 = \mathbf{0.723\ A}$, leading V by 90° .
- (c) At 1 kHz, the same capacitor: $X_C = 15.9\ \Omega$ — a capacitor "passes" high frequencies easily.

6.2 Impedance

Most real circuits combine resistance and reactance. The total opposition to AC is the **impedance (Z)**, measured in ohms. Because the voltages across R and X are 90° apart, they add as phasors, not as simple numbers — the **impedance triangle**.

Formula — impedance

$$Z = \sqrt{R^2 + X^2} \quad I = V \div Z$$

$$\text{Phase angle } \phi = \tan^{-1}(X \div R) \quad \cos \phi = R \div Z$$

For series RLC, the net reactance is $X = X_L - X_C$.

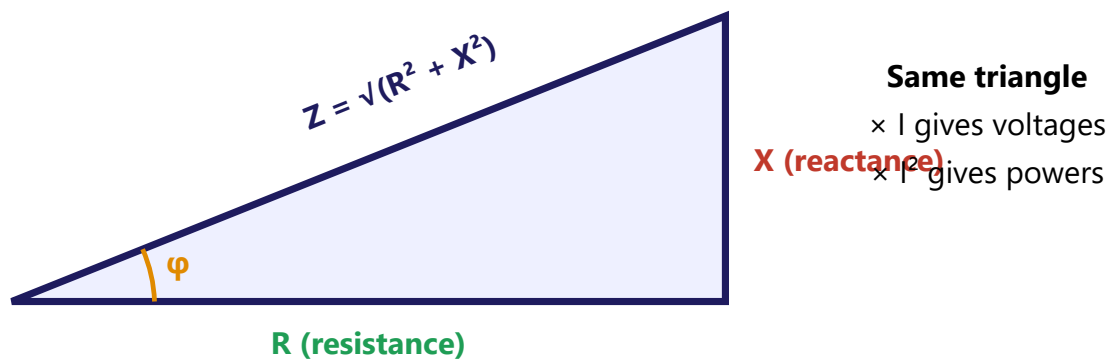


Figure 6.2 — The impedance triangle. Scaling it by I gives the voltage triangle; by I^2 gives the power triangle.

6.3 Series RL circuit

Typical of motors, fans, transformers, fluorescent chokes — most loads in industry. Current lags the supply voltage by ϕ (between 0° and 90°).

Worked example 6.2 — a series RL circuit

A coil with $R = 30\ \Omega$ and $L = 0.127\text{ H}$ is connected to 230 V , 50 Hz . Find X_L , Z , I , ϕ , V_R and V_L .

$$X_L = 2\pi \times 50 \times 0.127 = \mathbf{39.9\ \Omega \approx 40\ \Omega}.$$

$$Z = \sqrt{30^2 + 40^2} = \mathbf{50\ \Omega}. I = 230/50 = \mathbf{4.6\text{ A}}.$$

$$\phi = \tan^{-1}(40/30) = \mathbf{53.1^\circ \text{ lagging}}.$$

$$V_R = 4.6 \times 30 = 138\text{ V}; V_L = 4.6 \times 40 = 184\text{ V}.$$

Check: $\sqrt{138^2 + 184^2} = 230\text{ V} \checkmark$ — note $138 + 184 = 322\text{ V} \neq 230\text{ V}$. AC voltages add as phasors!

6.4 Series RC circuit

Current leads the voltage. RC circuits are used as filters, phase-shifters and timing networks.

Worked example 6.3

$R = 100\ \Omega$ in series with $C = 20\ \mu\text{F}$ on 230 V , 50 Hz .

$$X_C = 1/(2\pi \times 50 \times 20 \times 10^{-6}) = \mathbf{159.2\ \Omega}. Z = \sqrt{100^2 + 159.2^2} = \mathbf{188\ \Omega}.$$

$$I = 230/188 = \mathbf{1.22\text{ A}}, \text{ leading by } \phi = \tan^{-1}(159.2/100) = \mathbf{57.9^\circ}.$$

6.5 Series RLC circuit and resonance

In a series RLC circuit, the inductor's voltage and the capacitor's voltage are 180° apart, so they partly **cancel**. The net reactance is $X_L - X_C$. If $X_L > X_C$ the circuit is inductive (current lags); if $X_C > X_L$ it is capacitive (current leads).

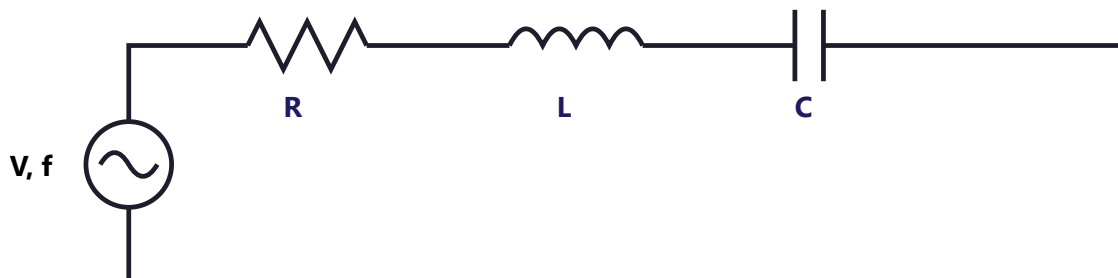


Figure 6.3 — Series RLC circuit.

Formulas — series RLC

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$\text{Resonance when } X_L = X_C: f_r = 1 \div (2\pi\sqrt{LC})$$

$$\text{At resonance: } Z = R \text{ (minimum), } I = V/R \text{ (maximum), } \phi = 0^\circ$$

$$\text{Quality factor } Q = X_L \div R = (1/R)\sqrt{L/C} \quad \text{Bandwidth} = f_r \div Q$$

Worked example 6.4 — resonance

$R = 10 \, \Omega$, $L = 0.1 \, \text{H}$, $C = 10 \, \mu\text{F}$, supply $100 \, \text{V}$ variable frequency.

$$f_r = 1/(2\pi\sqrt{0.1 \times 10 \times 10^{-6}}) = 1/(2\pi \times 0.001) = \mathbf{159.2 \, \text{Hz}}.$$

$$\text{At resonance } I = 100/10 = \mathbf{10 \, \text{A}}. \quad X_L = 2\pi \times 159.2 \times 0.1 = 100 \, \Omega.$$

$$V_L = V_C = 10 \times 100 = \mathbf{1,000 \, \text{V}} \text{ — ten times the supply voltage! } Q = 100/10 = 10.$$

$$\text{Bandwidth} = 159.2/10 \approx 15.9 \, \text{Hz}.$$

Caution — voltage magnification

At series resonance, the voltages across L and C can be many times the supply voltage (Q times). Components must be rated for this. Resonance is useful in radio tuning circuits, but dangerous if it happens accidentally in power systems.

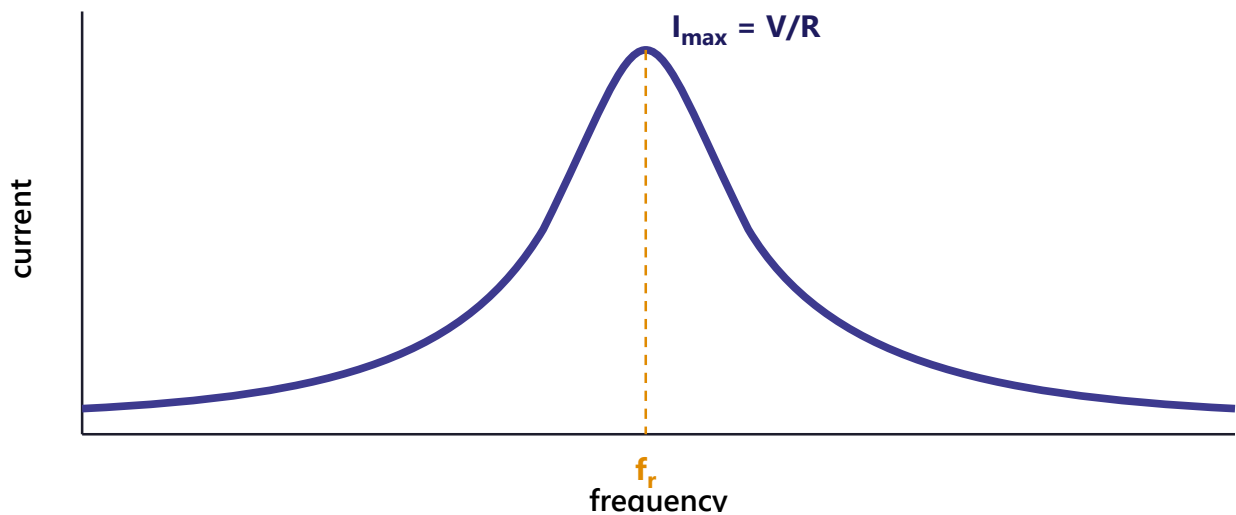


Figure 6.4 — Resonance curve of a series RLC circuit: current peaks at f_r . Higher Q gives a sharper peak.

6.6 Power in AC circuits

In AC circuits containing inductance or capacitance, not all the current does useful work. Energy flows back and forth between the source and the reactive elements every cycle. So we define three kinds of power:

Power	Symbol	Unit	Formula	Meaning
Real (active) power	P	watt (W, kW)	$V I \cos \phi = I^2 R$	Power actually converted into heat, light, motion — what does useful work
Reactive power	Q	volt-ampere reactive (VAR, kVAR)	$V I \sin \phi = I^2 X$	Power that oscillates between source and L/C; builds magnetic/electric fields; does no net work
Apparent power	S	volt-ampere (VA, kVA)	$V I = \sqrt{P^2 + Q^2}$	Total the supply must deliver — sets cable, transformer and generator size

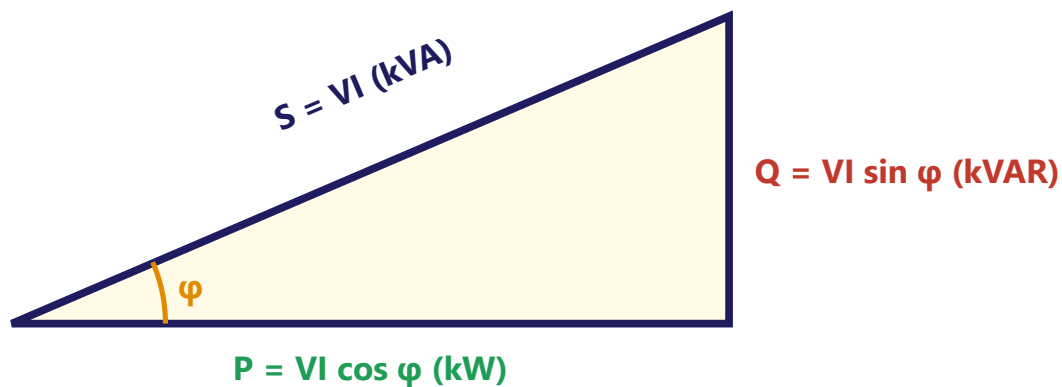


Figure 6.5 — The power triangle.

6.7 Power factor

Formula — power factor

$$\text{Power factor (pf)} = \cos \varphi = P \div S = R \div Z$$

pf is between 0 and 1. It is **lagging** for inductive loads (motors) and **leading** for capacitive loads. Resistive loads (heaters, incandescent lamps) have $\text{pf} = 1$.

Worked example 6.5

For the coil in Example 6.2 (230 V, 4.6 A, $\varphi = 53.1^\circ$):

$$S = 230 \times 4.6 = \mathbf{1,058 \text{ VA}}. \text{ pf} = \cos 53.1^\circ = \mathbf{0.6 \text{ lagging}}.$$

$$P = 1,058 \times 0.6 = \mathbf{635 \text{ W}} \text{ (check: } I^2 R = 4.6^2 \times 30 = 635 \text{ W } \checkmark).$$

$$Q = 1,058 \times \sin 53.1^\circ = 1,058 \times 0.8 = \mathbf{846 \text{ VAR}}.$$

Why low power factor is a problem

For the same real power, a lower power factor means a **larger current** ($I = P \div (V \cos \varphi)$). That causes:

- Higher $I^2 R$ losses in cables, transformers and lines.
- Larger voltage drops.
- Bigger (more expensive) cables, switchgear, transformers and generators for the same useful output.
- Penalties on industrial electricity bills — DISCOMs charge extra when the power factor falls below a set limit (often around 0.9), or bill on kVAh.

Worked example 6.6 — the cost of a poor power factor

A 415 V three-phase factory load needs 100 kW. Line current $I = P/(\sqrt{3} V \cos \phi)$.

At pf 0.7: $I = 100,000/(1.732 \times 415 \times 0.7) = \mathbf{198.8 \text{ A}}$.

At pf 0.95: $I = 100,000/(1.732 \times 415 \times 0.95) = \mathbf{146.5 \text{ A}}$.

Improving pf cuts the current by 26% and the I^2R losses by about 46%.

6.8 Power factor correction

Because inductive loads draw lagging reactive power and capacitors draw leading reactive power, adding **capacitors in parallel** with the load cancels part of the reactive power. The real power is unchanged, but the supply current and apparent power fall.

Formula — capacitor kVAR needed

$$Q_C = P (\tan \phi_1 - \tan \phi_2)$$

$$C = Q_C \div (2\pi f V^2) \quad (\text{single-phase})$$

ϕ_1 = original angle; ϕ_2 = target angle.

Worked example 6.7

A single-phase 230 V, 50 Hz motor takes 2 kW at pf 0.7 lagging. Find the capacitor needed to raise pf to 0.95.

$$\phi_1 = \cos^{-1} 0.7 = 45.57^\circ, \tan \phi_1 = 1.020. \phi_2 = \cos^{-1} 0.95 = 18.19^\circ, \tan \phi_2 = 0.329.$$

$$Q_C = 2,000 \times (1.020 - 0.329) = \mathbf{1,382 \text{ VAR}}.$$

$$C = 1,382/(2\pi \times 50 \times 230^2) = 1,382/16,619,000 = 83 \times 10^{-6} \text{ F} = \mathbf{83 \mu\text{F}}.$$

$$\text{Current before: } 2,000/(230 \times 0.7) = 12.4 \text{ A; after: } 2,000/(230 \times 0.95) = 9.15 \text{ A}.$$

6.9 Parallel AC circuits (brief)

In parallel AC circuits, the **voltage** is common and the branch **currents** add as phasors. Resistive branch currents are in phase with V; inductive currents lag by 90° ; capacitive currents lead by 90° . A parallel LC circuit also resonates at $f_r = 1/(2\pi\sqrt{LC})$, but there the **current drawn from the supply is minimum** and the impedance is maximum — used in oscillators and filters ("tank circuits").

Worked example 6.8

A 230 V supply feeds a heater drawing 8 A (resistive) and a motor drawing 6 A lagging by 90° (idealised). Total current = $\sqrt{8^2 + 6^2} = \mathbf{10\text{ A}}$, not 14 A.

6.10 Three-phase power

Formulas — balanced three-phase

$$P = \sqrt{3} \times V_L \times I_L \times \cos \varphi$$

$$S = \sqrt{3} V_L I_L \quad Q = \sqrt{3} V_L I_L \sin \varphi$$

Star (Y): $V_L = \sqrt{3} V_{ph}$, $I_L = I_{ph}$. Delta (Δ): $V_L = V_{ph}$, $I_L = \sqrt{3} I_{ph}$.

Worked example 6.9

A 415 V, three-phase motor draws 20 A per line at pf 0.85. $P = 1.732 \times 415 \times 20 \times 0.85 = \mathbf{12.2\text{ kW}}$ input.

Module 6 — Summary

- $X_L = 2\pi fL$ (I lags 90°); $X_C = 1/(2\pi fC)$ (I leads 90°). "CIVIL".
- $Z = \sqrt{R^2 + X^2}$; $I = V/Z$; $\varphi = \tan^{-1}(X/R)$.
- Series resonance: $X_L = X_C$, $f_r = 1/(2\pi\sqrt{LC})$, $Z = R$, current maximum.
- $P = VI \cos \varphi$ (W); $Q = VI \sin \varphi$ (VAR); $S = VI$ (VA); $S^2 = P^2 + Q^2$.
- $\text{pf} = \cos \varphi = P/S$; low pf $\rightarrow$ more current, losses, penalties.
- Capacitors correct lagging pf: $Q_C = P(\tan \varphi_1 - \tan \varphi_2)$.
- Three-phase: $P = \sqrt{3} V_L I_L \cos \varphi$.

Practice questions — Module 6

1. Find X_L of a 50 mH coil at 50 Hz and at 5 kHz. (Ans: 15.7 Ω ; 1,571 Ω)
2. Find X_C of a 4.7 μ F capacitor at 50 Hz. (Ans: 677 Ω)
3. $R = 6 \Omega$, $X_L = 8 \Omega$ in series across 100 V. Find Z, I, pf, P, Q and S. (Ans: 10 Ω ; 10 A; 0.6; 600 W; 800 VAR; 1,000 VA)
4. Find the resonant frequency for $L = 25$ mH, $C = 1 \mu$ F. (Ans: $\approx 1,007$ Hz)
5. Explain three disadvantages of a low power factor.
6. A load takes 5 kW at pf 0.8 lagging. Find kVA and kVAR. (Ans: 6.25 kVA; 3.75 kVAR)
7. Find the capacitor kVAR to improve the load in Q6 to pf 1.0. (Ans: 3.75 kVAR)
8. A 415 V three-phase heater draws 10 A per line (pf 1). Find its power. (Ans: 7.19 kW)

Semiconductor Devices: Diodes

What a semiconductor is, how a p-n junction works, diode characteristics, rectifiers and smoothing, Zener regulators, LEDs, and protection circuits.

7.1 Semiconductors

Semiconductors such as **silicon (Si)** and **germanium (Ge)** have a resistivity between that of conductors and insulators. Silicon atoms have four valence electrons and form a regular crystal in which each atom shares electrons with four neighbours through covalent bonds.

At absolute zero, all electrons are held in bonds and silicon is an insulator. At room temperature, heat energy breaks a few bonds, releasing **free electrons** and leaving behind **holes** (missing electrons that behave like positive charges). Both can carry current. Pure silicon is called an **intrinsic** semiconductor — it conducts only weakly. Unlike metals, a semiconductor's resistance **falls** as temperature rises, because more bonds break.

7.2 Doping: n-type and p-type

Adding a tiny, controlled amount of impurity — **doping**, around one atom in a million — transforms silicon's conductivity:

	n-type	p-type
Dopant	Pentavalent (5 valence electrons): phosphorus, arsenic, antimony	Trivalent (3 valence electrons): boron, gallium, indium
Name of dopant	Donor (donates an electron)	Acceptor (accepts an electron)
Majority carriers	Electrons	Holes
Minority carriers	Holes	Electrons
Overall charge	Electrically neutral	Electrically neutral

7.3 The p-n junction

When p-type and n-type regions are formed in one crystal, electrons near the boundary diffuse from the n-side into the p-side and fill holes. This leaves a thin **depletion region** with no free carriers, containing fixed positive ions on the n-side and fixed negative ions on the p-side. The resulting electric field creates a **barrier potential** of about **0.7 V for silicon** (0.3 V for germanium) that stops further diffusion.

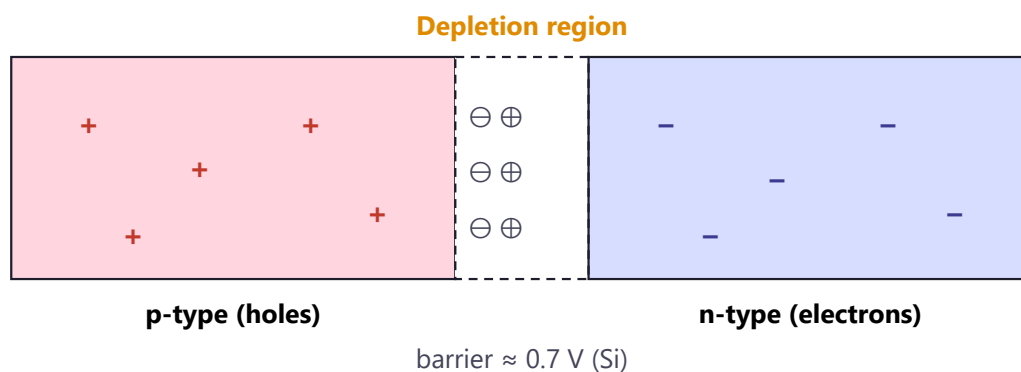


Figure 7.1 — The p-n junction and its depletion region.

7.4 The diode — a one-way valve for current

A p-n junction with two terminals is a **diode**. The p-side terminal is the **anode (A)**; the n-side is the **cathode (K)**, marked by a band on the body. The symbol's arrow points in the direction conventional current can flow.

- **Forward bias** (anode more positive than cathode): the external voltage opposes the barrier. Once it exceeds about 0.7 V (the **knee or cut-in voltage**), the depletion region collapses and current flows easily. The diode's voltage stays close to 0.7 V even as current rises.
- **Reverse bias** (cathode more positive): the depletion region widens and only a tiny **leakage current** (nA to μ A) flows. If the reverse voltage exceeds the **breakdown voltage**, current rises sharply and an ordinary diode is usually destroyed.

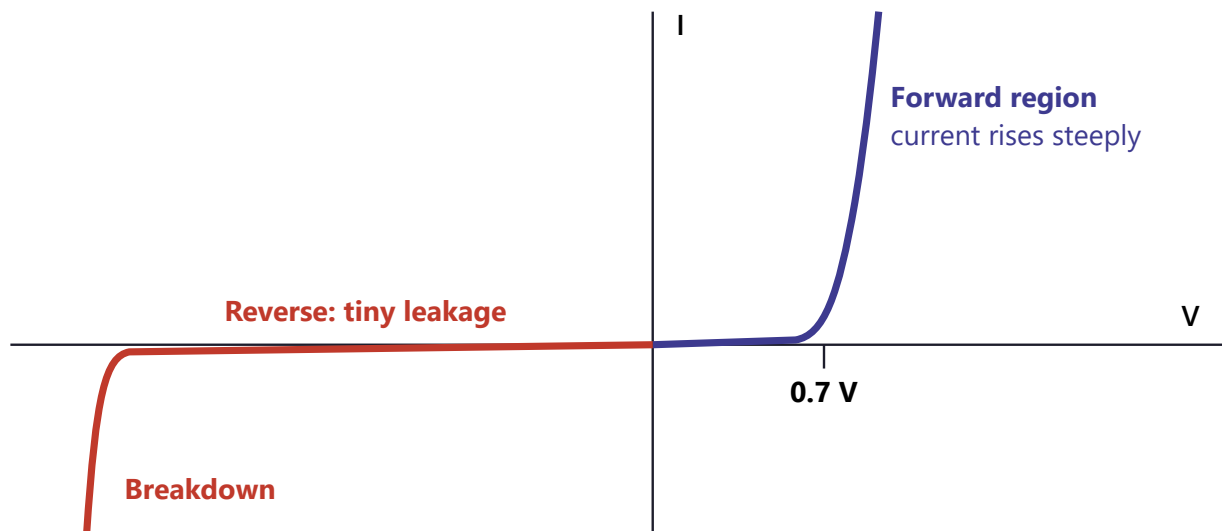


Figure 7.2 — Silicon diode V-I characteristic.

Simple diode models

- **Ideal:** a perfect switch — short circuit when forward biased, open when reverse biased.
- **Practical (constant-drop):** 0.7 V drop when conducting (silicon); open when reversed. Use this for most calculations.

Worked example 7.1

A silicon diode and a 1 k Ω resistor are in series across 10 V (forward biased). $I = (10 - 0.7)/1,000 = \mathbf{9.3 \text{ mA}}$. If the diode is reversed, $I \approx 0$.

Key diode ratings

Rating	Meaning	Example: 1N4007
$I_{F(AV)}$	Maximum average forward current	1 A
V_{RRM} / PIV	Peak inverse (reverse) voltage it can withstand	1,000 V
V_F	Forward voltage drop at rated current	$\approx 1.0 \text{ V}$ at 1 A
I_{FSM}	Surge current (one-off)	30 A
t_{rr}	Reverse recovery time (speed)	Slow (general purpose)

7.5 Rectifiers — turning AC into DC

Almost every electronic device runs on DC but is powered from the AC mains. A **power supply** converts it in four stages: a **transformer** steps 230 V down, a **rectifier** converts AC to pulsating DC, a **filter** (capacitor) smooths it, and a **regulator** holds the output steady.



Figure 7.3 — Block diagram of a linear DC power supply.

Half-wave rectifier

One diode in series with the load conducts only during positive half-cycles. The negative halves are blocked. Simple, but wasteful and very rippled.

Full-wave bridge rectifier

Four diodes in a bridge steer both half-cycles through the load in the same direction. In each half-cycle, two diodes conduct in series (so the drop is $2 \times 0.7 = 1.4$ V). This is the standard rectifier in chargers and power supplies; it is also sold as a single four-terminal package.

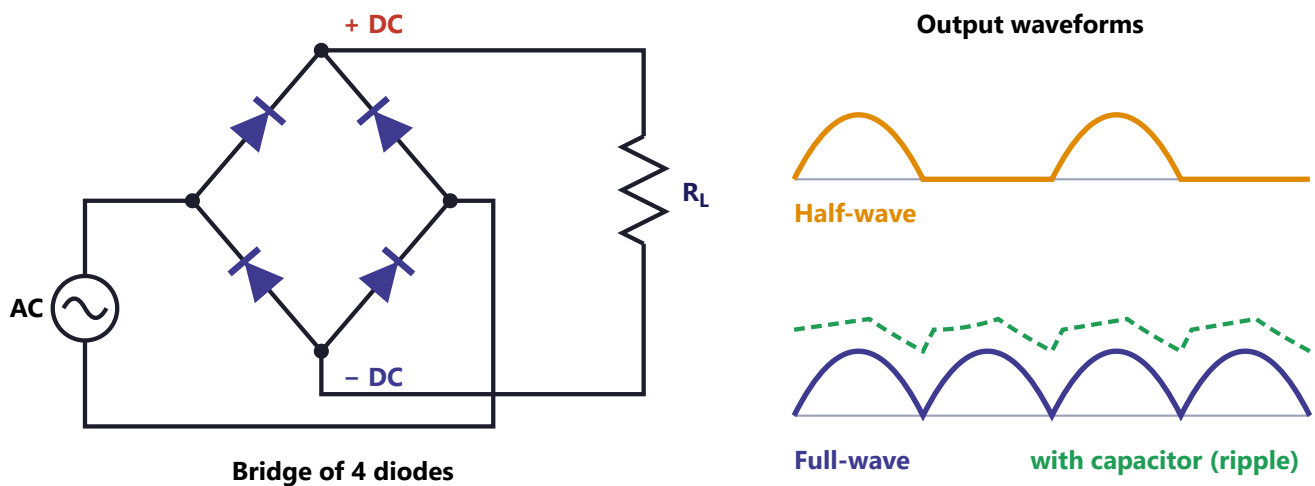


Figure 7.4 — Bridge rectifier, and rectified output with and without a smoothing capacitor.

Formulas — rectifier outputs (sine input, peak V_m)

Half-wave: $V_{DC} = V_m \div \pi = 0.318 V_m$; ripple frequency = f

Full-wave: $V_{DC} = 2V_m \div \pi = 0.637 V_m$; ripple frequency = $2f$

With capacitor filter: $V_{DC} \approx V_m$; ripple $V_{r(p-p)} \approx I_{load} \div (f_r C)$

f_r = ripple frequency (100 Hz for full-wave on 50 Hz mains). Subtract diode drops from V_m (0.7 V half-wave, 1.4 V bridge).

Worked example 7.2 — designing a simple 12 V supply

A transformer gives 12 V RMS. A bridge rectifier and a capacitor supply a 0.5 A load.

Peak = $12 \times 1.414 = 16.97$ V. After the bridge: $16.97 - 1.4 = \mathbf{15.6\text{ V}}$ peak.

For ripple ≤ 2 V p-p: $C = I/(f_r \times V_r) = 0.5/(100 \times 2) = 2.5 \times 10^{-3} \text{ F} = \mathbf{2,500\text{ }\mu\text{F}}$ → use **2,200–3,300 μF , 25 V**.

The output swings between about 13.6 V and 15.6 V; a 7812 regulator then gives a steady 12 V (it needs about 2 V headroom).

Diode PIV in a bridge $\approx V_m = 17$ V → 1N4007 (1,000 V, 1 A) is more than enough; choose diodes rated above the load current.

7.6 Zener diodes and voltage regulation

A **Zener diode** is designed to operate safely in reverse breakdown. Its reverse voltage stays almost constant at the **Zener voltage V_Z** (e.g. 3.3 V, 5.1 V, 12 V) over a wide range of current. With a series resistor, it makes a simple voltage regulator or reference.

Formula — Zener regulator

$$R_S = (V_{in} - V_Z) \div (I_Z + I_L)$$

Choose I_Z of a few mA minimum so the Zener stays in regulation at the lowest input voltage and highest load current. Check Zener power $P = V_Z \times I_{Z(max)}$.

Worked example 7.3

Make 5.1 V from a 12 V supply for a load of 20 mA, keeping $I_Z \geq 5$ mA.

$$R_S = (12 - 5.1)/(0.005 + 0.020) = 6.9/0.025 = \mathbf{276\ \Omega} \rightarrow \text{use } 270\ \Omega.$$

If the load is disconnected, all 25.6 mA flows in the Zener: $P = 5.1 \times 0.0256 = 0.13\text{ W} \rightarrow$ a 0.5-W Zener is fine.

7.7 Light-emitting diodes (LEDs)

In an LED, electrons and holes recombining at the junction release energy as **light**. The colour depends on the semiconductor material (e.g. gallium arsenide phosphide for red, indium gallium nitride for blue; white LEDs use a blue chip with a yellow phosphor). LEDs have higher forward voltages than silicon diodes and must always have their **current limited**.

Colour	Typical V_F	Typical current (indicator)
Red	1.8–2.2 V	10–20 mA
Yellow / Green (old)	2.0–2.4 V	10–20 mA
Blue / White / true green	2.8–3.4 V	10–20 mA
Infrared (remote controls)	1.2–1.5 V	20–100 mA

Other light devices: **photodiodes** produce current when light falls on them (used in light sensors, optical fibre receivers); **optocouplers** combine an LED and a phototransistor to pass signals while keeping two circuits electrically isolated; **solar cells** are large-area photodiodes.

7.8 Other diode types and applications

Device / circuit	What it does
Schottky diode	Metal–semiconductor junction; low forward drop (0.2–0.4 V) and very fast — used in switch-mode supplies and solar bypass diodes
Flyback / freewheeling diode	Across relay coils and motors to absorb the inductive kick (Module 4)
Reverse-polarity protection	Series diode prevents damage if a battery is connected backwards
TVS diode / varistor	Clamps voltage spikes and surges (e.g. lightning-induced)

Clipper	Removes part of a waveform above/below a level
Clamper	Shifts a waveform's DC level using a diode and capacitor
Voltage multiplier	Diode–capacitor ladders produce high DC voltages (e.g. in mosquito bats, CRTs)
Varactor	Capacitance varies with reverse voltage — used for electronic tuning

Practical tip — testing a diode

Set a digital multimeter to the diode-test mode. Red probe on the anode, black on the cathode: a good silicon diode reads about 0.5–0.7 (V). Reverse the probes: it should read "OL" (open). A reading near 0 both ways means shorted; "OL" both ways means open.

Module 7 — Summary

- Doping: phosphorus → n-type (electrons); boron → p-type (holes).
- p-n junction: depletion region, barrier ≈ 0.7 V (Si).
- Diode conducts when forward biased above ~ 0.7 V; blocks in reverse (until breakdown).
- Half-wave $V_{DC} = 0.318V_m$; full-wave $0.637V_m$; capacitor filter → $\approx V_m$, ripple $\approx I/(f_r C)$.
- Zener regulator: $R_S = (V_{in} - V_Z)/(I_Z + I_L)$.
- LEDs need a current-limiting resistor; photodiodes, optocouplers, Schottky and TVS diodes have special roles.

Practice questions — Module 7

1. Explain how n-type and p-type materials are made, naming the majority carriers.
2. Draw and explain the V–I characteristic of a silicon diode.
3. Find the current: 5 V supply, silicon diode, 430 Ω resistor. (Ans: 10 mA)
4. A half-wave rectifier has an input of 20 V peak. Find V_{DC} (ideal diode). (Ans: 6.37 V)
5. Draw a bridge rectifier and explain its operation in both half-cycles.
6. A full-wave supply feeds 1 A. Find C for 1.5 V ripple on 50 Hz mains. (Ans: $\approx 6,667 \mu F$)
7. Design a Zener regulator: 9 V in, 5.1 V out, load 10 mA, $I_{Z(min)} = 5$ mA. (Ans: 260 Ω → 270 Ω)
8. How would you test a diode with a multimeter?

Semiconductor Devices: Transistors

The bipolar junction transistor as a switch and as an amplifier — intuition first, then the equations — plus biasing, a look at MOSFETs, and practical transistor circuits.

8.1 Why the transistor changed the world

The transistor, invented at Bell Laboratories in 1947 by John Bardeen, Walter Brattain and William Shockley, is a device in which a **small current or voltage controls a much larger current**. That simple ability does two jobs that run all of modern electronics:

- **Switching:** turning loads fully ON or fully OFF — the basis of every digital circuit. A modern processor contains billions of transistors switching billions of times a second.
- **Amplification:** making a small signal (from a microphone, sensor or antenna) larger without changing its shape.

8.2 Construction of the bipolar junction transistor (BJT)

A BJT is a sandwich of three doped regions forming two p-n junctions:

- **NPN:** n-type emitter, very thin lightly-doped p-type base, n-type collector.
- **PNP:** p-type emitter, n-type base, p-type collector.

The three terminals are the **emitter (E)**, which emits charge carriers (heavily doped); the **base (B)**, the thin control region; and the **collector (C)**, which collects the carriers (largest region, dissipates most heat). In the symbol, the arrow is on the emitter and points in the direction of conventional current: **out** of the emitter for NPN ("Not Pointing iN"), **into** the emitter for PNP.

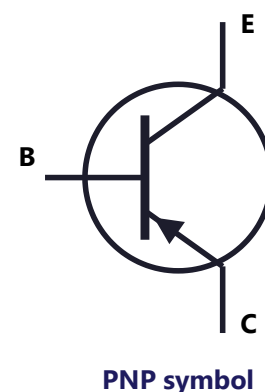
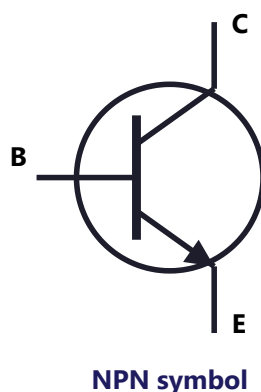
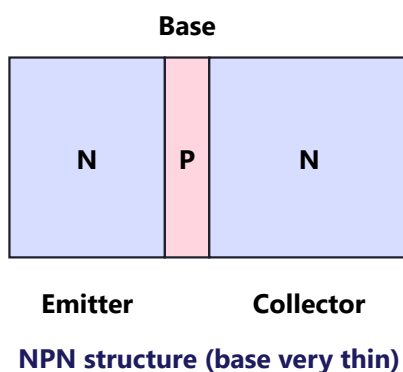


Figure 8.1 — NPN structure and NPN/PNP circuit symbols. The emitter arrow shows conventional current direction.

8.3 How a BJT works — intuition first

Think of a transistor as a **water valve controlled by a small side stream**. A small trickle into the base "opens the gate", allowing a much bigger flow from collector to emitter. Stop the trickle and the gate closes.

In an NPN transistor, the **base–emitter junction is forward biased** (about 0.7 V) and the **collector–base junction is reverse biased**. Electrons flood from the emitter into the base. Because the base is extremely thin and lightly doped, only about 1% of these electrons recombine there (forming the small base current). The other ~99% are swept across the base into the collector by the strong field of the reverse-biased collector junction. So a small base current I_B controls a large collector current I_C .

Formulas — BJT currents

$$I_E = I_B + I_C$$

$$I_C = \beta \times I_B \quad (\beta = h_{FE} = \text{DC current gain, typically 50–400})$$

$$\alpha = I_C \div I_E = \beta \div (\beta + 1) \quad (\text{just below 1})$$

$$V_{BE} \approx 0.7 \text{ V when conducting (silicon)}$$

Worked example 8.1

A transistor with $\beta = 150$ has $I_B = 40 \mu\text{A}$. Find I_C , I_E and α .

$$I_C = 150 \times 40 \mu\text{A} = \mathbf{6 \text{ mA}}. \quad I_E = 6 + 0.04 = \mathbf{6.04 \text{ mA}}. \quad \alpha = 6/6.04 = \mathbf{0.993}.$$

8.4 Transistor characteristics and regions of operation

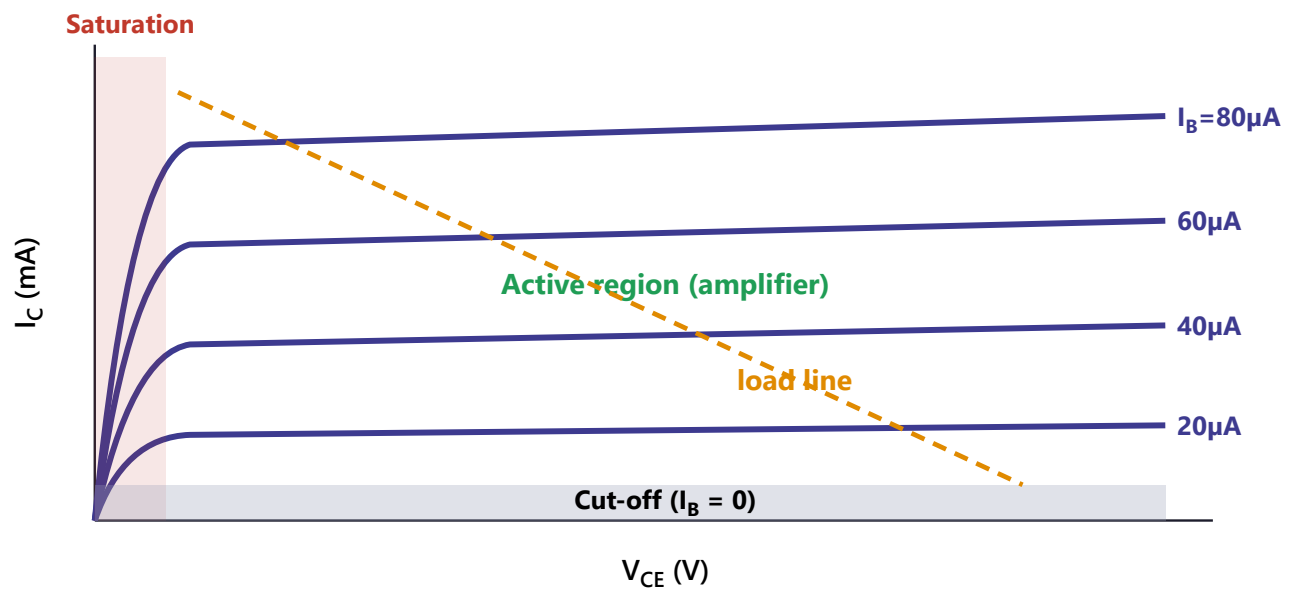


Figure 8.2 — Output characteristics (common emitter): each curve is for one value of base current.

Region	B–E junction	C–B junction	Behaviour	Used as
Cut-off	Not forward biased ($V_{BE} < \sim 0.6 \text{ V}$)	Reverse	$I_C \approx 0$ — switch OFF	Switch (off)
Active	Forward	Reverse	$I_C = \beta I_B$, controlled by base	Amplifier
Saturation	Forward	Forward	I_C limited by the external circuit; $V_{CE(\text{sat})} \approx 0.1\text{--}0.3 \text{ V}$ — switch ON	Switch (on)

8.5 The transistor as a switch

This is the most common use in practical circuits: a microcontroller or sensor output (a few mA) switching a relay, motor, buzzer, LED strip or lamp that needs much more current.

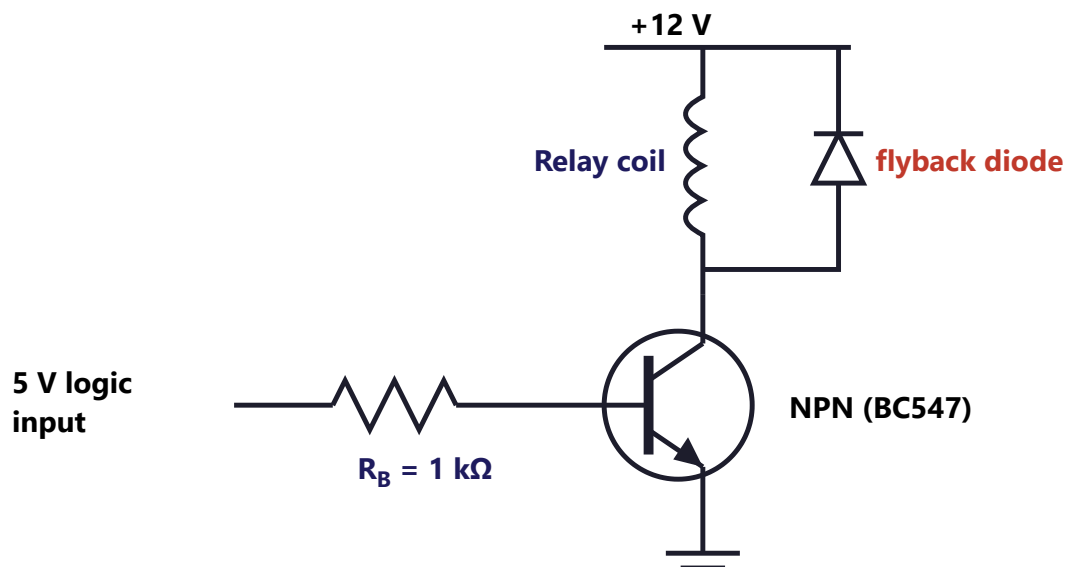


Figure 8.3 — NPN transistor switching a relay from a 5 V logic signal, with a flyback diode.

Designing a transistor switch

$$I_C = \text{load current} \quad I_{B(\min)} = I_C \div \beta_{\min}$$

Use $I_B \approx 2\text{--}5 \times I_{B(\min)}$ (overdrive for hard saturation)

$$R_B = (V_{\text{in}} - 0.7) \div I_B$$

Worked example 8.2

A 12 V relay coil of 400 Ω is switched by a BC547 ($\beta_{\min} = 110$) from a 5 V microcontroller pin.

$I_C = 12/400 = \mathbf{30 \text{ mA}}$ (well within the BC547's 100 mA rating).

$I_{B(\min)} = 30/110 = 0.27 \text{ mA}$. With overdrive $\times 3$: $I_B \approx 0.8 \text{ mA}$.

$R_B = (5 - 0.7)/0.0008 = 5,375 \Omega \rightarrow$ use **4.7 k Ω** (gives 0.91 mA). The 1 k Ω in the figure (4.3 mA) also works and saturates harder; either is acceptable.

Power in the transistor when ON: $V_{CE(\text{sat})} \times I_C \approx 0.2 \times 0.03 = 6 \text{ mW}$ — tiny, because a saturated switch has almost no voltage across it.

Key idea — why switches run cool

A transistor switch is either OFF (current ≈ 0) or fully ON (voltage ≈ 0). In both states, $P = V \times I$ is very small. The transistor gets hot only when it lingers in the middle (active region) — which is exactly what an amplifier does.

8.6 The transistor as an amplifier

To amplify, the transistor must sit in the **active region**, biased at a steady DC operating point called the **quiescent point (Q-point)**, roughly in the middle of the load line. A small AC input signal at the base then makes the base current swing up and down around its DC value; the collector current swings β times as much; and this larger current through the collector resistor R_C produces a larger voltage swing.

The common-emitter (CE) amplifier with voltage-divider bias

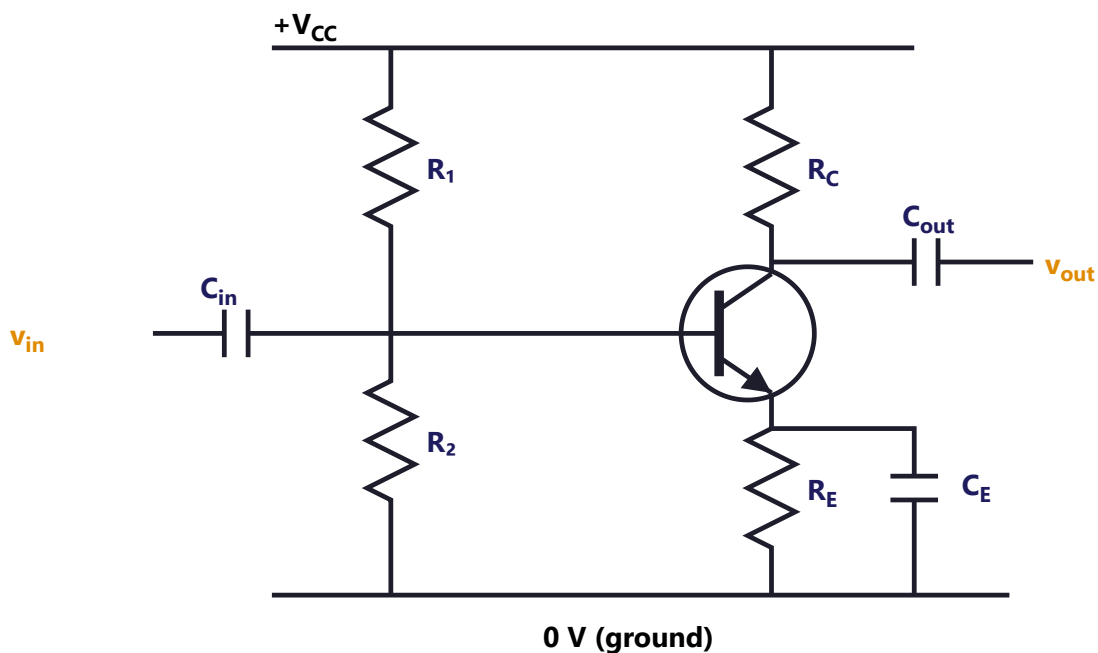


Figure 8.4 — Common-emitter amplifier with voltage-divider bias.

- R_1 and R_2 form a voltage divider that sets a stable base voltage.
- R_E (emitter resistor) stabilises the Q-point against changes in β and temperature.
- R_C converts collector current changes into output voltage changes.
- C_{in} , C_{out} (coupling capacitors) pass the AC signal and block DC.
- C_E (bypass capacitor) removes R_E 's effect for AC signals, restoring high gain.

DC bias analysis (approximate)

$$V_B = V_{CC} \times R_2 \div (R_1 + R_2)$$

$$V_E = V_B - 0.7 \quad I_E = V_E \div R_E \approx I_C$$

$$V_C = V_{CC} - I_C R_C \quad V_{CE} = V_C - V_E$$

$$\text{Voltage gain (with } C_E): A_v \approx -R_C \div r_e, \quad r_e \approx 25 \text{ mV} \div I_E$$

The minus sign means the output is **inverted** (180° phase shift) relative to the input.

Worked example 8.3 — biasing a CE amplifier

$V_{CC} = 12 \text{ V}$, $R_1 = 47 \text{ k}\Omega$, $R_2 = 10 \text{ k}\Omega$, $R_C = 3.3 \text{ k}\Omega$, $R_E = 1 \text{ k}\Omega$, $\beta = 200$.

$$V_B = 12 \times 10/57 = \mathbf{2.11 \text{ V}}. \quad V_E = 2.11 - 0.7 = 1.41 \text{ V}. \quad I_E = 1.41/1,000 = \mathbf{1.41 \text{ mA}} \approx I_C.$$

$V_C = 12 - 1.41 \times 3.3 = 7.35 \text{ V}$. $V_{CE} = 7.35 - 1.41 = \mathbf{5.94 \text{ V}}$ — close to mid-supply, a good Q-point.

$r_e = 25/1.41 = 17.7 \text{ }\Omega$. $A_v \approx -3,300/17.7 \approx \mathbf{-186}$. A 10 mV input gives about 1.86 V output (inverted).

8.7 Transistor configurations

Configuration	Input / output	Voltage gain	Current gain	Phase	Typical use
Common emitter (CE)	Base / collector	High	High (β)	180° (inverted)	General amplifier, switch
Common collector (CC) — emitter follower	Base / emitter	≈ 1	High ($\beta + 1$)	0°	Buffer; drives low-impedance loads
Common base (CB)	Emitter / collector	High	≈ 1 (α)	0°	High-frequency (RF) amplifiers

8.8 Darlington pair

Two transistors connected so that the emitter current of the first drives the base of the second give a combined gain $\beta_{\text{total}} \approx \beta_1 \times \beta_2$ (e.g. $100 \times 100 = 10,000$). Used to switch heavy loads from very weak signals (e.g. the ULN2003 driver IC for relays and stepper motors). The drawback is a larger base–emitter voltage ($\approx 1.4 \text{ V}$) and higher saturation voltage.

8.9 Field-effect transistors (MOSFETs)

A **MOSFET** (metal-oxide-semiconductor FET) has three terminals — **gate (G)**, **drain (D)** and **source (S)**. Unlike a BJT, it is controlled by **voltage**, not current: the gate is insulated by a thin oxide layer, so almost no gate current flows (except briefly to charge the gate capacitance).

- An **n-channel enhancement MOSFET** turns ON when V_{GS} exceeds the threshold $V_{GS(th)}$ (typically 1–4 V). A "logic-level" MOSFET is fully ON at 4.5–5 V.
- When fully ON, it behaves like a very small resistance $R_{DS(on)}$ (milliohms), so power loss is $I^2 \times R_{DS(on)}$.
- MOSFETs are the switches in inverters, SMPS chargers, motor drivers, e-bike controllers and every CMOS digital IC.

Feature	BJT	MOSFET
Controlled by	Base current	Gate voltage
Input impedance	Low–medium	Very high
ON-state loss	$V_{CE(sat)} \times I_C$	$I^2 \times R_{DS(on)}$
Switching speed	Good	Very fast
Typical use	Small-signal amplifiers, simple switches	Power switching, digital ICs

Worked example 8.4

A MOSFET with $R_{DS(on)} = 0.02 \, \Omega$ switches a 10 A motor. $P = 10^2 \times 0.02 = \mathbf{2 \, W} \rightarrow$ needs a small heat sink. A BJT with $V_{CE(sat)} = 0.5 \, V$ would waste 5 W.

8.10 Reading transistor datasheets and testing

Parameter	BC547 (small NPN)	2N2222 (NPN)	TIP122 (Darlington)	IRLZ44N (logic MOSFET)
Max current	100 mA	600–800 mA	5 A	47 A
Max voltage	45 V	40 V	100 V	55 V
Gain / $R_{DS(on)}$	β 110–800	β 100–300	$\beta \geq 1,000$	$\approx 0.022\text{--}0.025 \, \Omega$

Package	TO-92	TO-92 / TO-18	TO-220	TO-220
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Practical tip — testing a BJT with a multimeter

A BJT behaves like two diodes back to back at the base. For NPN, with the meter in diode mode: red on base, black on emitter → ~0.6–0.7; red on base, black on collector → ~0.6–0.7; all reverse readings → OL; collector–emitter both ways → OL. Any 0 reading means a short. Always check the pin-out on the datasheet — it varies between types.

Module 8 — Summary

- BJT: small base current controls large collector current; $I_C = \beta I_B$, $I_E = I_B + I_C$.
- Regions: cut-off (OFF), active (amplifier), saturation (ON).
- Switch design: $R_B = (V_{in} - 0.7)/I_B$ with 2–5× overdrive; add a flyback diode for inductive loads.
- CE amplifier: voltage-divider bias; $A_v \approx -R_C/r_e$, $r_e = 25 \text{ mV}/I_E$; inverted output.
- Emitter follower: gain ≈ 1 , buffer. Darlington: $\beta_1\beta_2$.
- MOSFET: voltage-controlled, very high input impedance, loss = $I^2 R_{DS(on)}$.

Practice questions — Module 8

1. Draw NPN and PNP symbols and label the terminals.
2. $\beta = 100$, $I_C = 5 \text{ mA}$. Find I_B and I_E . (Ans: $50 \mu\text{A}$; 5.05 mA)
3. Name the three regions of operation and state the use of each.
4. Design R_B to switch a 100 mA lamp ($\beta_{min} = 50$) from a 3.3 V signal with ×2 overdrive. (Ans: $I_B = 4 \text{ mA}$; $R_B = 650 \Omega \rightarrow 620 \Omega$)
5. For Example 8.3, if R_C is changed to 4.7 kΩ, find V_{CE} . (Ans: $\approx 3.96 \text{ V}$)
6. Why does a CE amplifier invert the signal?
7. Two transistors with $\beta = 80$ and 120 form a Darlington. Find the total gain. (Ans: $\approx 9,600$)
8. A MOSFET has $R_{DS(on)} = 0.05 \Omega$ and carries 6 A. Find its power loss. (Ans: 1.8 W)

Digital Logic Basics

Number systems, logic gates and truth tables, Boolean algebra, simplifying expressions by hand and with Karnaugh maps, and the building blocks of digital systems.

9.1 Analog versus digital

An **analog** signal can take any value within a range — like the voltage from a microphone or a temperature sensor. A **digital** signal has only two allowed levels: **HIGH (1)** and **LOW (0)**. In 5 V logic, roughly 0–0.8 V is read as 0 and 2–5 V as 1; in 3.3 V logic, the thresholds are lower.

Digital systems are used almost everywhere because two-level signals are very resistant to noise, easy to store and copy perfectly, and can be processed by billions of simple, cheap transistor switches.

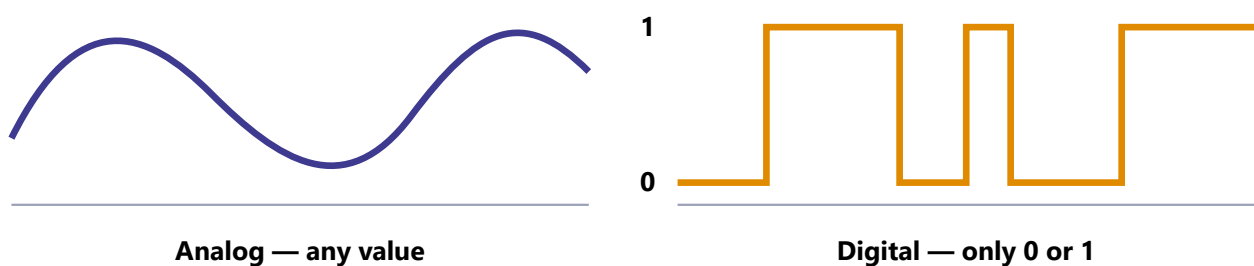


Figure 9.1 — Analog and digital signals.

9.2 Number systems

We count in **decimal** (base 10) because we have ten fingers. Digital circuits count in **binary** (base 2) because a transistor switch has two states. Engineers also use **hexadecimal** (base 16) as a compact way to write long binary numbers.

Decimal	Binary	Hex	Decimal	Binary	Hex
0	0000	0	8	1000	8
1	0001	1	9	1001	9
2	0010	2	10	1010	A
3	0011	3	11	1011	B
4	0100	4	12	1100	C

5	0101	5	13	1101	D
6	0110	6	14	1110	E
7	0111	7	15	1111	F

Binary to decimal

Each binary digit (bit) has a place value that doubles from right to left: 1, 2, 4, 8, 16, 32, 64, 128...

Worked example 9.1

Convert $1011\ 0110_2$ to decimal: $128 + 0 + 32 + 16 + 0 + 4 + 2 + 0 = \mathbf{182}$.

Decimal to binary — repeated division by 2

Worked example 9.2

Convert 45 to binary: $45 \div 2 = 22\ \text{r}\ \mathbf{1}$; $22 \div 2 = 11\ \text{r}\ \mathbf{0}$; $11 \div 2 = 5\ \text{r}\ \mathbf{1}$; $5 \div 2 = 2\ \text{r}\ \mathbf{1}$; $2 \div 2 = 1\ \text{r}\ \mathbf{0}$; $1 \div 2 = 0\ \text{r}\ \mathbf{1}$. Read remainders bottom to top: $\mathbf{101101}_2$. Check: $32 + 8 + 4 + 1 = 45\ \checkmark$.

Binary $\leftrightarrow$ hexadecimal

Group bits in fours from the right; each group is one hex digit. $1011\ 0110_2 = \mathbf{B6}_{16}$. Colour codes on web pages (#1E1B5E), memory addresses and MAC addresses use hex.

Binary addition

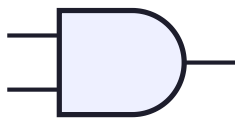
$0 + 0 = 0$; $0 + 1 = 1$; $1 + 1 = 10$ (0 carry 1); $1 + 1 + 1 = 11$ (1 carry 1).

Worked example 9.3

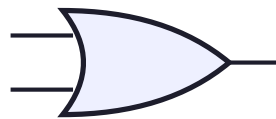
$0101\ 1011\ (91) + 0011\ 0110\ (54) = \mathbf{1001\ 0001}\ (145)\ \checkmark$.

9.3 Logic gates

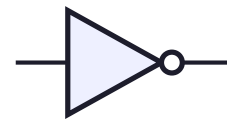
A **logic gate** is a circuit (made of transistors) that produces a digital output from one or more digital inputs according to a fixed rule. A **truth table** lists the output for every possible input combination; with n inputs there are 2^n rows.



AND
 $Y = A \cdot B$



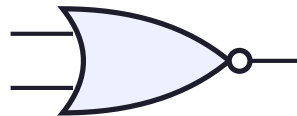
OR
 $Y = A + B$



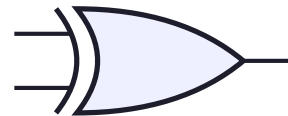
NOT
 $Y = \bar{A}$



NAND
 $Y = (A \cdot B)^{\bar{}}$



NOR
 $Y = (A + B)^{\bar{}}$



XOR
 $Y = A \oplus B$

A bubble (O) on the output means "inverted" (NOT).

Figure 9.2 — Standard (ANSI) symbols of the basic logic gates.

A	B	AND	OR	NAND	NOR	XOR	XNOR
0	0	0	0	1	1	0	1
0	1	0	1	1	0	1	0
1	0	0	1	1	0	1	0
1	1	1	1	0	0	0	1

- **AND:** output is 1 only if **all** inputs are 1. (Two switches in series.)
- **OR:** output is 1 if **any** input is 1. (Two switches in parallel.)
- **NOT (inverter):** output is the opposite of the input.
- **NAND:** AND followed by NOT. **NOR:** OR followed by NOT.
- **XOR (exclusive OR):** output is 1 when the inputs are **different**. Used in adders, parity checking and comparators.
- **XNOR:** output is 1 when the inputs are the **same** (an equality detector).

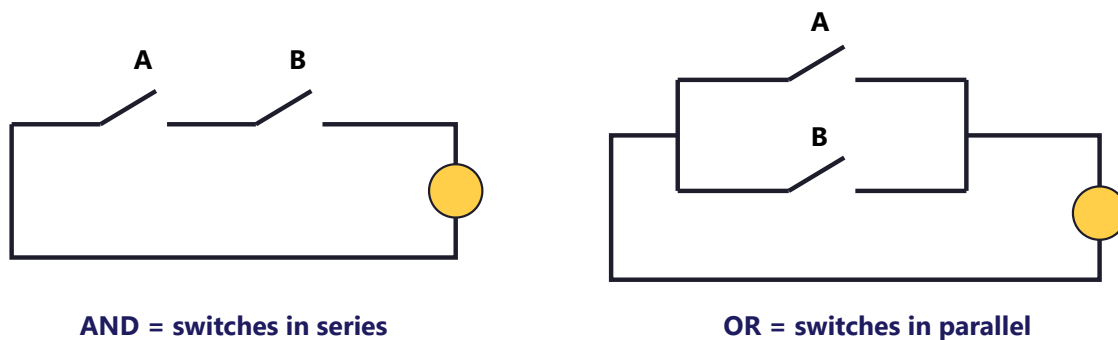


Figure 9.3 — Switch models of AND and OR: the lamp lights only if A AND B are closed, or if A OR B is closed.

Key idea — universal gates

NAND and NOR are called **universal gates**: any logic function can be built using only NAND gates (or only NOR gates). For example, a NAND with both inputs tied together is a NOT gate. Manufacturers often build complete chips from NAND gates alone.

9.4 Boolean algebra

Boolean algebra, developed by George Boole in 1854, is the mathematics of logic. Variables are 0 or 1. The operators are AND ($\cdot$), OR ($+$) and NOT (overbar or $'$).

Law	AND form	OR form
Identity	$A \cdot 1 = A$	$A + 0 = A$
Null / dominance	$A \cdot 0 = 0$	$A + 1 = 1$
Idempotent	$A \cdot A = A$	$A + A = A$
Complement	$A \cdot A' = 0$	$A + A' = 1$
Double negation	$(A')' = A$	
Commutative	$A \cdot B = B \cdot A$	$A + B = B + A$
Associative	$(AB)C = A(BC)$	$(A + B) + C = A + (B + C)$
Distributive	$A(B + C) = AB + AC$	$A + BC = (A + B)(A + C)$
Absorption	$A(A + B) = A$	$A + AB = A$
Useful identity	$A + A'B = A + B$	

De Morgan's theorems

De Morgan's theorems

$$(A \cdot B)' = A' + B'$$

$$(A + B)' = A' \cdot B'$$

"Break the bar and change the sign." These show that a NAND equals an OR with inverted inputs, and a NOR equals an AND with inverted inputs.

9.5 Simplifying Boolean expressions by hand

Simpler expressions need fewer gates — cheaper, faster, lower power.

Worked example 9.4

Simplify $Y = AB + AB'$.

$Y = A(B + B')$ (distributive) $= A \cdot 1$ (complement) $= \mathbf{A}$. A two-gate circuit reduces to a single wire!

Worked example 9.5

Simplify $Y = A'B'C + A'BC + AB'C$.

$Y = A'C(B' + B) + AB'C = A'C + AB'C = C(A' + AB') = C(A' + B')$ (using $A' + AB' = A' + B'$)
 $= \mathbf{A'C + B'C}$, or equivalently $C(AB)'$.

Worked example 9.6 — De Morgan

Simplify $Y = ((A + B)' + C)'$.

By De Morgan: $Y = (A + B)'' \cdot C' = \mathbf{(A + B) C'}$.

9.6 From a truth table to a circuit

To design a circuit for any truth table: write a product (AND) term for every row where the output is 1, using each variable plain if it is 1 and inverted if it is 0; then OR all the terms together. This is the **sum-of-products (SOP)** form. Simplify, then draw the gates.

Worked example 9.7 — a majority voter

A circuit has three inputs A, B, C (three judges) and outputs 1 when at least two inputs are 1.

A	B	C	Y	A	B	C	Y
0	0	0	0	1	0	0	0
0	0	1	0	1	0	1	1
0	1	0	0	1	1	0	1
0	1	1	1	1	1	1	1

SOP: $Y = A'BC + AB'C + ABC' + ABC$. Simplified (next section): $Y = AB + BC + AC$ — three 2-input AND gates and one 3-input OR gate.

9.7 Karnaugh maps (K-maps)

A **K-map** is a grid version of the truth table arranged so that neighbouring cells differ in only one variable (Gray-code order: 00, 01, 11, 10). Grouping adjacent 1s in rectangles of 1, 2, 4 or 8 cells eliminates the variables that change within the group.

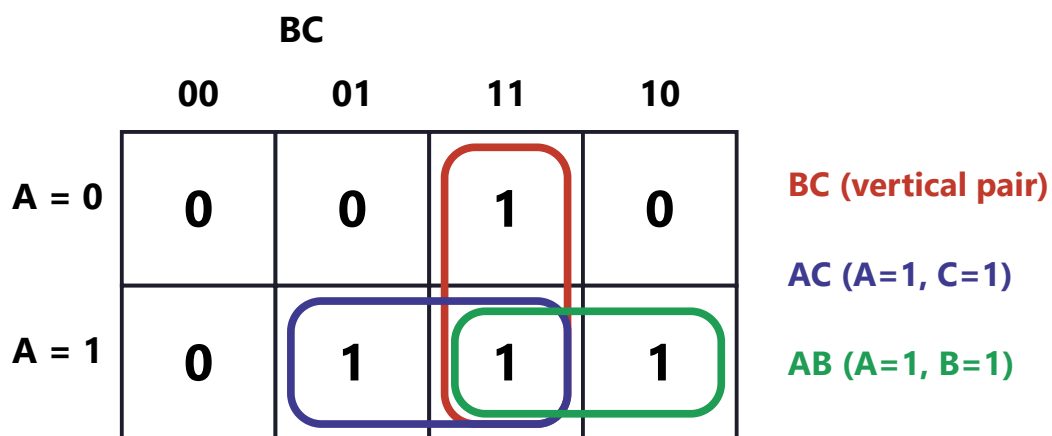


Figure 9.4 — K-map of the majority function: three groups of two give $Y = AB + BC + AC$.

K-map rules

- Group only 1s, in rectangles of 1, 2, 4 or 8 cells.
- Make groups as large as possible, and use as few groups as possible.
- Groups may overlap and may wrap around the edges.
- Every 1 must be in at least one group.

9.8 Combinational building blocks

Block	Function	Example use
Half adder	Adds two bits: $\text{Sum} = A \oplus B$, $\text{Carry} = A \cdot B$	Arithmetic
Full adder	Adds two bits plus a carry-in; chained for multi-bit adders	Processors (ALU)
Multiplexer (MUX)	Selects one of many inputs using select lines	Data routing
Demultiplexer / decoder	Routes one input to one of many outputs; decoder activates one output for each code	Memory addressing, 7-segment displays
Encoder	Converts an active input line into a binary code	Keyboards
Comparator	Tells whether $A = B$, $A > B$ or $A < B$	Control logic

Worked example 9.8 — half adder

$1 + 1$: $\text{Sum} = 1 \oplus 1 = 0$, $\text{Carry} = 1 \cdot 1 = 1 \rightarrow$ "10" in binary = 2 ✓. $1 + 0$: $\text{Sum} = 1$, $\text{Carry} = 0$ ✓.

9.9 Sequential logic — circuits with memory

Combinational circuits' outputs depend only on the present inputs. **Sequential** circuits also depend on past inputs — they have memory. The basic memory element is the **flip-flop**, which stores one bit.

- **SR latch**: Set and Reset inputs; built from two cross-coupled NOR (or NAND) gates.
- **D flip-flop**: copies input D to output Q on each clock edge — the building block of registers.
- **JK and T flip-flops**: T (toggle) flip-flops change state on each clock pulse — used in counters and frequency dividers.

- **Registers** (groups of flip-flops) store bytes; **shift registers** move bits along; **counters** count clock pulses (digital clocks, timers).

9.10 Logic families and practical ICs

IC	Contents
7400	Quad 2-input NAND
7402	Quad 2-input NOR
7404	Hex inverter (NOT)
7408	Quad 2-input AND
7432	Quad 2-input OR
7486	Quad 2-input XOR
7474	Dual D flip-flop

TTL (74xx, 74LSxx) chips use bipolar transistors and run on 5 V. **CMOS** chips (4000 series, 74HCxx) use MOSFETs, consume very little power when idle and work over wider supply ranges. Microcontrollers (Arduino, ESP32) and processors are huge CMOS logic circuits. Unused CMOS inputs must never be left floating — tie them to 0 V or V_{CC} .

Module 9 — Summary

- Digital = two levels (0/1); robust against noise.
- Binary place values 1, 2, 4, 8...; hex groups four bits.
- Gates: AND, OR, NOT, NAND, NOR, XOR, XNOR; NAND/NOR are universal.
- Boolean laws and De Morgan: $(AB)' = A' + B'$; $(A + B)' = A'B'$.
- Design: truth table → SOP → simplify (algebra or K-map) → gates.
- Combinational blocks (adders, MUX, decoders) vs sequential (flip-flops, registers, counters).

Practice questions — Module 9

1. Convert $1110\ 1001_2$ to decimal and hex. (Ans: 233; E9)
2. Convert 100 to binary. (Ans: 1100100)
3. Draw the truth table for a 3-input AND gate.
4. Prove that a NAND gate with both inputs joined acts as a NOT gate.
5. Simplify $Y = A + AB + A'B$. (Ans: $A + B$)
6. Apply De Morgan to $(A' + B)'$. (Ans: AB')
7. Design a circuit whose output is 1 only when exactly one of two inputs is 1. (Ans: XOR)
8. Write Sum and Carry expressions for a half adder and draw its circuit.

Instrumentation, Practical Project and Revision

Using a multimeter safely and correctly, other essential instruments, a complete hands-on project with full design calculations, and a one-page formula sheet for the whole course.

10.1 The digital multimeter (DMM)

The multimeter is the most important tool for anyone working with circuits. A typical digital multimeter measures:

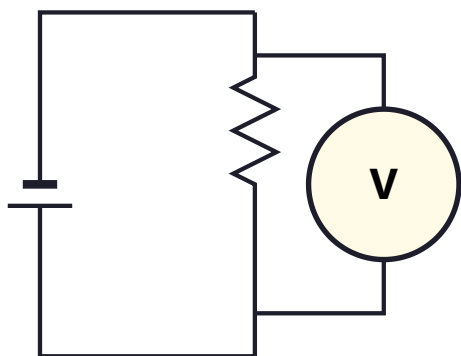
- **DC voltage ($V=$)** and **AC voltage ($V\sim$)**
- **DC current ($A=$)** and often **AC current ($A\sim$)**
- **Resistance (Ω)**, **continuity** (beeps below a few ohms) and **diode test**
- Often also capacitance, frequency, temperature and transistor h_{FE}

Measuring voltage — connect in PARALLEL

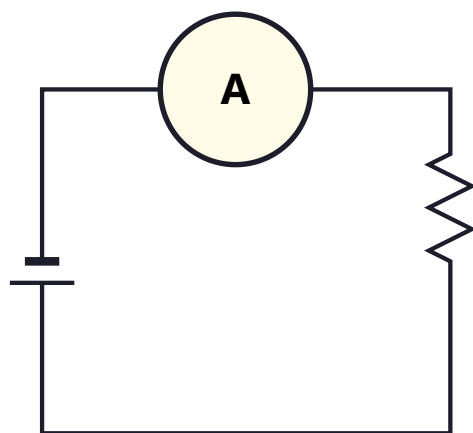
Voltage is measured **across** a component: red probe at the higher-potential end, black at the lower (COM). The meter has a very high internal resistance (typically 10 M Ω), so it draws almost no current and does not disturb the circuit.

Measuring current — connect in SERIES

Current must flow **through** the meter: break the circuit and insert the meter in the gap. The meter's current range has a very **low** resistance (a shunt). Move the red lead to the **A** or **mA** socket.



Voltmeter in PARALLEL (across R)



Ammeter in SERIES (current flows through it)

Figure 10.1 — Correct connection of a voltmeter and an ammeter.

Caution — the most common meter accident

Never connect a meter set to **current** (leads in the A/mA socket) **across** a voltage source. Its near-zero resistance creates a short circuit: the internal fuse blows at best; at worst, on mains or batteries, the meter can explode and cause burns. After measuring current, **always return the red lead to the V/ Ω socket**.

Measuring resistance

Resistance must be measured with the circuit **switched off** and, for accuracy, with the component disconnected at one end (other parallel paths change the reading). The meter supplies its own small test current. Discharge capacitors first.

Meter safety categories

Category	Where	Examples
CAT I	Protected electronic circuits	Low-voltage electronics, battery devices
CAT II	Single-phase plug-in loads	Appliances, sockets
CAT III	Building installation	Distribution boards, fixed wiring, three-phase motors
CAT IV	Origin of supply	Service entrance, meters, overhead lines

Use a meter and leads rated for the category and voltage you work on (e.g. CAT III 600 V for house wiring). Check leads for cracks and use finger guards.

Safe measurement habits

1. Choose the function and range **before** connecting; if unsure, start at the highest range (or use auto-range).
2. Connect the black (COM) lead first and remove it last.
3. Keep fingers behind the probe guards; use one hand where possible on live circuits.
4. Test the meter on a known live source before and after checking a circuit is dead ("live–dead–live").
5. Never measure resistance or continuity on a live circuit.

Worked example 10.1 — meter loading

A divider of two 1 M Ω resistors across 10 V should give 5 V. A 10 M Ω meter across the lower resistor makes it $1 \parallel 10 = 0.909$ M Ω , so the reading is $10 \times 0.909/1.909 = \mathbf{4.76\text{ V}}$ — a 5% error caused by the meter itself. With 1 k Ω resistors the error would be negligible.

10.2 Other essential instruments

Instrument	Measures / does	Tip
Clamp meter	AC (and DC, if Hall-effect type) current without breaking the circuit	Clamp around one conductor only — around a whole cable, the currents cancel
Oscilloscope	Displays voltage versus time — waveforms, frequency, noise, ripple	Probe ground clip must go to circuit ground; never to mains live
Function generator	Produces sine, square and triangle test signals	Use for testing amplifiers and filters
Bench power supply	Adjustable DC voltage with current limit	Set the current limit low when testing a new circuit
Insulation tester (megger)	Insulation resistance at 250–1,000 V	Circuit must be dead and disconnected
Earth tester	Earth-electrode resistance	Aim for low values (typically $\leq 5\ \Omega$ for installations)
Non-contact voltage tester	Indicates presence of AC voltage	Useful first check, but never proof that a circuit is dead
LCR meter	Inductance, capacitance, resistance	Checks components before use

10.3 Soldering and breadboarding basics

- **Breadboard:** for building circuits without soldering. The long rails carry power; the short vertical strips of five holes are connected internally.
- **Soldering:** heat the joint (pad and lead together) with a clean, tinned iron ($\approx 330\text{--}370\text{ }^{\circ}\text{C}$ for leaded solder), then feed solder into the joint, not onto the iron. A good joint is shiny and cone-shaped.
- Work in a ventilated area; do not breathe flux fumes; wash hands after handling leaded solder.

- Check polarity of electrolytic capacitors, diodes, LEDs and ICs before powering up.

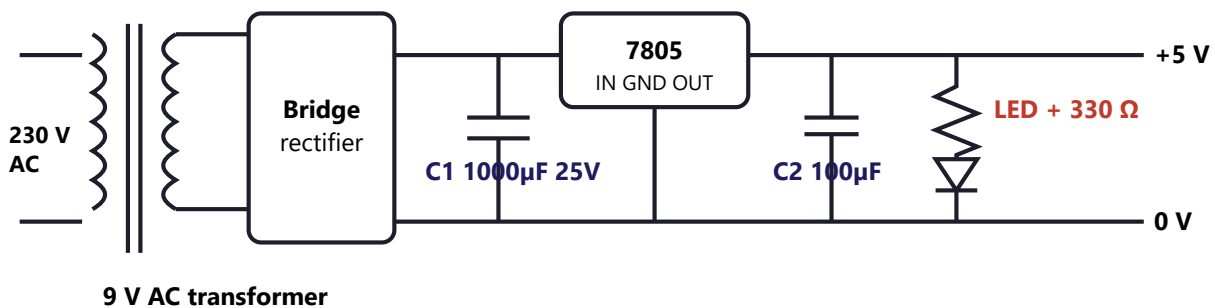
10.4 Practical project — a regulated 5 V USB power supply with an automatic night lamp

This project combines almost every module: transformer and AC (Module 5), bridge rectifier, filter and regulation (Module 7), voltage divider (Module 2), capacitors (Module 4), a transistor switch (Module 8) and measurement (this module).

Safety first

The mains side (230 V AC) is dangerous. Use a **ready-made, enclosed step-down transformer or a certified 9–12 V AC/DC adapter**, keep all mains connections insulated and inside a closed box, fit a fuse, and have a qualified person check the mains wiring before first use. Beginners should start from a 9 V or 12 V DC adapter and build only the low-voltage stages.

Part A — Regulated 5 V supply



Add 0.1 μF ceramic capacitors at the 7805 input and output, close to the pins.

Figure 10.2 — Regulated 5 V power supply.

Design calculations — Part A

Transformer: 9 V RMS → peak 12.7 V. After the bridge: $12.7 - 1.4 = 11.3 \text{ V}$.

Regulator: the 7805 needs at least about 2 V headroom → minimum input $\approx 7 \text{ V}$.

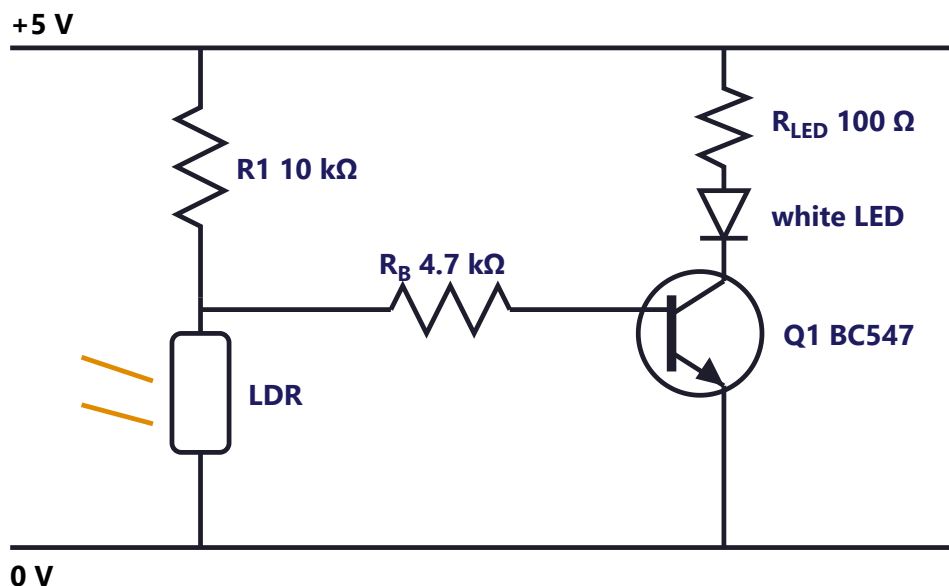
Filter capacitor for a 500 mA load and ripple $\leq 3 \text{ V}$ p-p (so the trough stays above 8 V):
 $C = I / (f_r V_r) = 0.5 / (100 \times 3) = 1,667 \mu\text{F} \rightarrow$ use **2,200 μF , 25 V** (1,000 μF is fine for loads up to $\sim 300 \text{ mA}$).

Regulator heat: $P = (V_{\text{in(avg)}} - 5) \times I \approx (10 - 5) \times 0.5 = 2.5 \text{ W} \rightarrow$ the 7805 needs a small heat sink.

Power LED: $R = (5 - 2) / 0.01 = 300 \Omega \rightarrow 330 \Omega$.

Fuse: on the primary side, a 100–250 mA slow-blow fuse.

Part B — Automatic night lamp (dark-activated LED)



Dark → LDR resistance high → base voltage rises → Q1 ON → LED lights

Figure 10.3 — Dark-activated LED using an LDR voltage divider and a transistor switch.

Design calculations — Part B

LDR: about 1 k Ω in daylight, 100 k Ω or more in darkness.

Daylight: divider voltage = $5 \times 1/(10 + 1) = \mathbf{0.45\text{ V}}$ — below 0.7 V, so Q1 is OFF (cut-off).

Dark: divider = $5 \times 100/(10 + 100) = \mathbf{4.55\text{ V}}$ — Q1 turns ON (saturation).

LED current: white LED $V_F \approx 3.1\text{ V}$; $V_{CE(sat)} \approx 0.2\text{ V} \rightarrow I = (5 - 3.1 - 0.2)/100 = \mathbf{17\text{ mA}}$ ✓.

Base current check (dark): the divider's Thevenin equivalent is $\approx 4.55\text{ V}$ behind (10 k $\parallel$ 100 k $\approx 9.1\text{ k}\Omega$); with $R_B\ 4.7\text{ k}\Omega$: $I_B \approx (4.55 - 0.7)/(9.1\text{ k} + 4.7\text{ k}) \approx 0.28\text{ mA}$. Needed: $17\text{ mA}/110 = 0.15\text{ mA}$ ✓ (about 2 $\times$ overdrive).

Adjust sensitivity by replacing R1 with a 10 k Ω fixed resistor plus a 47 k Ω preset.

Testing checklist

1. Before power: check diode, capacitor, LED and transistor orientations; check for solder bridges with continuity mode.
2. Power up through a current-limited bench supply or with a fuse.
3. Measure: rectified DC across C1 ($\approx 11\text{ V}$), regulator output (4.9–5.1 V), ripple with an oscilloscope if available.
4. Night lamp: measure base voltage in light and dark (cover the LDR); measure LED current by inserting the meter in series.
5. Load test: connect a 10 Ω , 5 W resistor (500 mA) to the 5 V output; check the voltage stays within limits and the regulator temperature is safe.
6. Record all readings in a table and compare them with your calculations.

10.5 Formula sheet — the whole course on one page

Topic	Formulas
Basics	$I = Q/t$; $V = W/Q$; $R = \rho L/A$; $R_T = R_0[1 + \alpha\Delta T]$; $V = IR$
Power & energy	$P = VI = I^2R = V^2/R$; $W = Pt$; 1 kWh = 3.6 MJ; $\eta = P_{out}/P_{in}$
Series / parallel	$R_T = \Sigma R$; $1/R_T = \Sigma 1/R$; two: $R_1R_2/(R_1 + R_2)$
Dividers	$V_2 = V R_2/(R_1 + R_2)$; $I_1 = I R_2/(R_1 + R_2)$
Real source	$V = E - Ir$; P_{max} when $R_L = r$ ($= E^2/4r$)
Kirchhoff	$\Sigma I_{in} = \Sigma I_{out}$; $\Sigma E = \Sigma IR$

Thevenin/Norton	$I_L = V_{TH}/(R_{TH}+R_L)$; $I_N = V_{TH}/R_{TH}$
Capacitor	$Q = CV$; $C = \epsilon_0\epsilon_r A/d$; $W = \frac{1}{2}CV^2$; $\tau = RC$; $v = V(1 - e^{-t/\tau})$
Inductor	$v = L di/dt$; $W = \frac{1}{2}LI^2$; $\tau = L/R$
AC	$f = 1/T$; $\omega = 2\pi f$; $V_{rms} = 0.707V_m$; $V_{avg} = 0.637V_m$; $f = PN/120$
Reactance / impedance	$X_L = 2\pi fL$; $X_C = 1/2\pi fC$; $Z = \sqrt{R^2 + X^2}$; $\phi = \tan^{-1}(X/R)$
Resonance	$f_r = 1/(2\pi\sqrt{LC})$; $Q = X_L/R$
AC power	$P = VI \cos \phi$; $Q = VI \sin \phi$; $S = VI$; $pf = \cos \phi$; $Q_C = P(\tan \phi_1 - \tan \phi_2)$
Three-phase	$V_L = \sqrt{3}V_{ph} \text{ (star)}$; $P = \sqrt{3}V_L I_L \cos \phi$
Diodes	$V_F \approx 0.7 \text{ V}$; half-wave $0.318V_m$; full-wave $0.637V_m$; ripple $\approx I/(f_r C)$; $R_S = (V_{in} - V_Z)/(I_Z + I_L)$
BJT	$I_E = I_B + I_C$; $I_C = \beta I_B$; $R_B = (V_{in} - 0.7)/I_B$; $A_v \approx -R_C/r_e$; $r_e = 25 \text{ mV}/I_E$
Logic	$(AB)' = A' + B'$; $(A + B)' = A'B'$; $A + AB = A$; $A + A'B = A + B$

Module 10 — Summary

- Voltmeter in parallel; ammeter in series; resistance only on dead circuits.
- Use correctly rated (CAT) meters; never put a current-range meter across a source.
- A project brings the modules together: design → calculate → build → measure → compare.

Practice questions — Module 10

1. Explain, with diagrams, how to connect a voltmeter and an ammeter.
2. Why must resistance be measured with the power off?
3. What is a CAT III meter, and where must it be used?
4. Recalculate the filter capacitor in Part A for a 300 mA load and 2 V ripple. (*Ans: 1,500 $\mu F \rightarrow 2,200 \mu F$*)
5. If the LDR measures 20 k Ω at dusk, will the lamp in Part B turn on? (*Ans: divider = 3.33 V $\rightarrow$ yes*)
6. List six checks to make before powering a newly built circuit for the first time.

BONUS

Electrical Safety, Home Wiring and Careers

How electricity harms the body and how to prevent it, how a house is wired and protected, choosing wires and breakers, and where these skills can take you.

B.1 Effects of electric current on the human body

It is **current** through the body that injures, not voltage alone — but voltage drives the current. Dry skin may have a resistance of 100 k Ω or more; wet or broken skin can fall to around 1 k Ω . At 230 V, that allows up to about 230 mA — far above the lethal level.

Current (50 Hz AC, hand to hand/foot)	Typical effect
≈ 1 mA	Threshold of feeling — a slight tingle
5–10 mA	Painful shock; still able to let go
10–20 mA	"Let-go" limit — muscles clamp; may be unable to release the conductor
30–50 mA	Breathing difficulty; risk of ventricular fibrillation begins with longer duration
50–100 mA and above	Ventricular fibrillation (heart stops pumping) likely — often fatal
Several amperes	Severe burns, cardiac arrest, tissue damage

Key idea — why RCCBs trip at 30 mA

A 30 mA residual-current device (RCCB/RCD) disconnects the supply in a few tens of milliseconds when current leaks to earth — for example through a person. It acts before the current can cause fibrillation. It is the single most effective life-saving device in a home.

B.2 Common electrical hazards and prevention

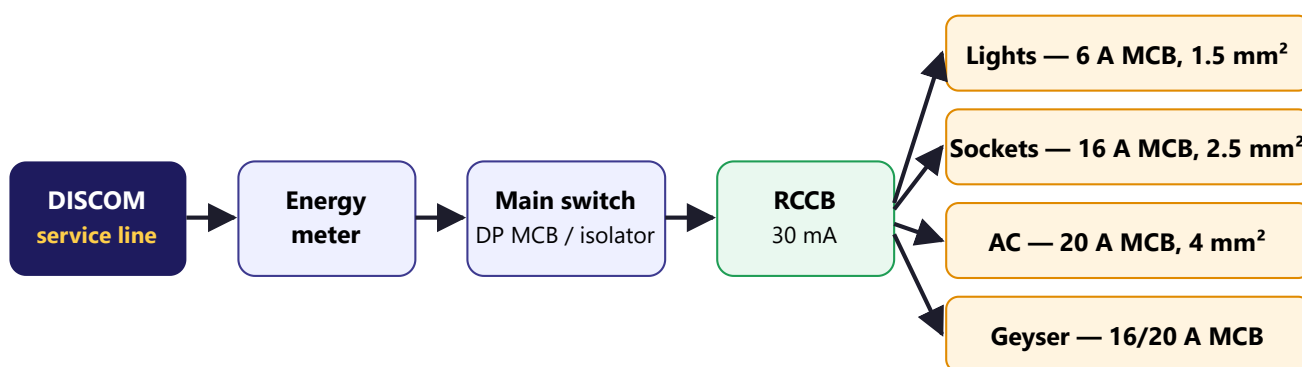
Hazard	Prevention
Touching live parts	Proper insulation, covers on switchboards, isolate before work, "test before touch"

Faulty appliances with live metal body	Earthing of metal bodies, 3-pin plugs, RCCB protection
Wet conditions	Keep water away; RCCB on bathroom, kitchen and outdoor circuits; IP-rated fittings
Overloaded sockets and extension boards	Correct wire size and MCB; avoid chaining extension boards; don't plug heaters into light-duty sockets
Loose connections	Tighten terminals; loose joints heat up and start fires
Damaged cables	Replace — never repair mains cables with tape only
Working on "dead" circuits that are live	Switch off, lock/tag, and verify with a tester before touching

First aid for electric shock

1. **Do not touch** the person while they are in contact with the supply.
2. **Switch off** the supply at the switch, plug or main board. If impossible, push them free with a dry non-conducting object (dry wood, plastic) while standing on dry insulating material.
3. Call for medical help immediately.
4. Check breathing and pulse; if absent and you are trained, start CPR.
5. Treat burns with cool running water; cover loosely. Anyone who has had a significant shock should be medically checked — heart rhythm problems can appear later.

B.3 How a house is wired



istribution board (DB): each circuit has its own MCB; an earth bar connects all protective conductors to the earth electrode.

Figure B.1 — Typical single-phase house supply and distribution board (sizes are common examples; follow local codes).

- **Phase (live), neutral and earth:** in India, the common colours are **red/brown for phase**, **black/blue for neutral**, **green or green-yellow for earth**. Always verify with a tester —

old installations may not follow colours.

- **Switches** must always be connected in the **phase** wire, so the appliance is dead when switched off.
- **Fuses and MCBs** protect wires from overload and short circuit. An MCB (miniature circuit breaker) trips and can be reset; a fuse must be replaced.
- **RCCB / RCD** protects people from earth-leakage shock; an **RCBO** combines MCB and RCCB in one device.
- **Earthing:** all metal bodies of appliances and the earth pins of sockets connect to an earth electrode. Indian practice follows IS 3043 and the National Electrical Code; installations are governed by the CEA safety regulations.

B.4 Choosing wire sizes and breakers

Copper wire (PVC, typical house conditions)	Approximate current capacity	Typical use
1.0 mm ²	≈ 10–11 A	Light fittings (short runs)
1.5 mm ²	≈ 13–15 A	Lighting and fan circuits
2.5 mm ²	≈ 18–20 A	6/16 A socket circuits
4 mm ²	≈ 24–27 A	AC, geyser, kitchen appliances
6 mm ²	≈ 31–35 A	Main feeders, large loads
10 mm ²	≈ 43–50 A	Main incoming supply

Exact ratings depend on insulation type, installation method (in conduit, grouped, buried), ambient temperature and length (voltage drop). Always use the manufacturer's tables and the applicable code.

Rule — co-ordination

$$\text{Load current } I_B \leq \text{Breaker rating } I_n \leq \text{Cable capacity } I_Z$$

The breaker must be larger than the normal load but smaller than what the cable can safely carry.

Worked example B.1

A 1.5-ton AC draws about 7 A running (starting surge higher). Choose: $I_B = 7 \text{ A} \rightarrow$ MCB 16 A or 20 A (C-curve, for motor starting) $\rightarrow$ cable 4 mm^2 ($\approx 25 \text{ A}$) ✓. For a 3 kW geyser: $I = 3,000/230 = 13 \text{ A} \rightarrow 16 \text{ A MCB} \rightarrow 2.5 \text{ mm}^2$ (short run) or 4 mm^2 (long run).

MCB trip curves

Curve	Instantaneous trip at	Use
B	$3-5 \times I_n$	Lighting, resistive loads, long cable runs
C	$5-10 \times I_n$	General: sockets, ACs, small motors (most common)
D	$10-20 \times I_n$	High inrush: transformers, large motors, welding

B.5 Energy saving with electrical knowledge

- Replace old fans (70–75 W) with BLDC fans (28–35 W): saves about 40 W per fan — around 120 units a year for 8 hours a day.
- LED lamps use about one-tenth of the energy of incandescent bulbs for the same light.
- Choose star-rated appliances (BEE star labels): a 5-star AC or fridge uses significantly less energy than a 2-star model.
- Set ACs to 24–26 °C; each degree lower adds roughly 6% to consumption.
- Avoid standby losses — switch off TVs, set-top boxes and chargers at the socket.
- Maintain a good power factor in commercial and industrial installations (Module 6).

B.6 Careers with electrical and electronics skills

Path	Roles	Build these skills
Electrical technician / electrician	House and industrial wiring, panel building, maintenance	Wiring practice, codes, safety, testing instruments; ITI / licence
Electronics technician	Repair of equipment, PCB assembly and testing	Soldering, component testing, fault-finding, oscilloscope use
Power & energy	Substation operation, solar and EV charging installation, energy auditing	AC power, three-phase, protection, power factor; the Solar Energy course

Embedded systems & IoT	Designing smart devices with microcontrollers and sensors	Digital logic, transistors, C/C++ programming, Arduino/ESP32
Design engineer	Circuit and PCB design, power electronics	Circuit theory, simulation tools, PCB software
Instrumentation & automation	Sensors, PLCs, SCADA in factories	Measurement, control, PLC programming
Further study	Diploma / B.Tech in EE, ECE, EEE	Strong maths and circuit fundamentals (this course)

B.7 Quick revision — one line per module

Module	Remember in one line
1 Fundamentals	$V = IR$; $P = VI = I^2R = V^2/R$; energy in kWh; $R = \rho L/A$.
2 Series/parallel	Series: same I , R adds; parallel: same V , $1/R$ adds; dividers.
3 Theorems	KCL/KVL; mesh & nodal; superposition; Thevenin/Norton; $R_L = R_{TH}$ for max power.
4 C and L	C stores $\frac{1}{2}CV^2$, L stores $\frac{1}{2}LI^2$; $\tau = RC$ or L/R ; 63% at 1τ , done at 5τ .
5 AC	50 Hz, $T = 20$ ms; $RMS = 0.707$ peak; 230 V RMS = 325 V peak; three-phase 120° apart.
6 AC circuits	$X_L = 2\pi fL$, $X_C = 1/2\pi fC$; $Z = \sqrt{R^2 + X^2}$; $P = VI \cos \phi$; correct pf with capacitors.
7 Diodes	One-way valve, 0.7 V; bridge + capacitor = DC; Zener regulates; LEDs need resistors.
8 Transistors	$I_C = \beta I_B$; switch (cut-off/saturation) or amplifier (active); MOSFET is voltage-driven.
9 Logic	AND/OR/NOT/NAND/NOR/XOR; De Morgan; K-maps; flip-flops store bits.
10 Practice	Voltmeter parallel, ammeter series; measure, compare with calculation, stay safe.

REVISION

100 Multiple-Choice Questions

Test yourself on all ten modules. The answer key follows the questions.

1. The unit of electric charge is the:
(a) ampere (b) coulomb (c) volt (d) ohm
2. Current is the rate of flow of:
(a) voltage (b) charge (c) resistance (d) power
3. A charge of 120 C passes in 1 minute. The current is:
(a) 2 A (b) 120 A (c) 0.5 A (d) 7,200 A
4. One volt equals one:
(a) joule per second (b) joule per coulomb (c) coulomb per second (d) watt per ampere
5. Resistance of a wire increases when its length:
(a) decreases (b) increases (c) stays the same (d) is painted
6. Resistance of a wire decreases when its cross-sectional area:
(a) increases (b) decreases (c) halves (d) is heated
7. For metals, resistance with rising temperature:
(a) falls (b) rises (c) stays constant (d) becomes zero
8. Ohm's law states:
(a) $V = I/R$ (b) $V = IR$ (c) $V = R/I$ (d) $P = IR$
9. A 12 V source across 6 Ω gives a current of:
(a) 72 A (b) 0.5 A (c) 2 A (d) 18 A
10. Colour code yellow–violet–red means:
(a) 472 Ω (b) 4.7 k Ω (c) 47 k Ω (d) 470 Ω
11. The power in a 10 Ω resistor carrying 3 A is:
(a) 30 W (b) 90 W (c) 3.3 W (d) 300 W
12. 1 kWh equals:
(a) 1,000 J (b) 3,600 J (c) 3.6 MJ (d) 36 MJ
13. A 2 kW heater used for 3 hours consumes:
(a) 6 kWh (b) 0.67 kWh (c) 5 kWh (d) 600 Wh
14. In a series circuit, which quantity is the same everywhere?
(a) voltage (b) current (c) power (d) resistance
15. 10 Ω , 20 Ω and 30 Ω in series give:
(a) 60 Ω (b) 5.45 Ω (c) 20 Ω (d) 6,000 Ω
16. In a parallel circuit, which quantity is the same across all branches?
(a) current (b) voltage (c) power (d) resistance
17. Two 10 Ω resistors in parallel give:
(a) 20 Ω (b) 10 Ω (c) 5 Ω (d) 0.2 Ω
18. Total parallel resistance is always:
(a) larger than the largest (b) smaller than the smallest (c) equal to the average (d) zero
19. Voltage divider: 12 V across 2 k Ω + 4 k Ω . Voltage across 4 k Ω :
(a) 4 V (b) 6 V (c) 8 V (d) 12 V

20. Household loads are connected in:
(a) series (b) parallel (c) series–parallel (d) star only
21. A battery's terminal voltage falls under load because of:
(a) infinite resistance (b) internal resistance (c) frequency (d) capacitance
22. Maximum power is transferred when load resistance equals:
(a) zero (b) infinity (c) the source's internal resistance (d) twice the internal resistance
23. KCL is based on conservation of:
(a) energy (b) charge (c) momentum (d) mass
24. KVL is based on conservation of:
(a) energy (b) charge (c) flux (d) current
25. At a node, 7 A and 3 A enter and 4 A leaves on one wire. The other wire carries:
(a) 6 A leaving (b) 14 A leaving (c) 4 A entering (d) 0 A
26. In the superposition theorem, other ideal voltage sources are:
(a) open-circuited (b) short-circuited (c) doubled (d) removed with their wires
27. Superposition cannot be used directly to find:
(a) current (b) voltage (c) power (d) branch current
28. Thevenin's equivalent consists of:
(a) current source in parallel with R (b) voltage source in series with R (c) two resistors (d) capacitor and resistor
29. Norton's equivalent consists of:
(a) voltage source in series with R (b) current source in parallel with R (c) inductor (d) a battery only
30. $V_{TH} = 12\text{ V}$, $R_{TH} = 4\ \Omega$. Norton current is:
(a) 48 A (b) 3 A (c) 0.33 A (d) 16 A
31. $V_{TH} = 20\text{ V}$, $R_{TH} = 5\ \Omega$. Maximum load power is:
(a) 20 W (b) 80 W (c) 100 W (d) 4 W
32. A Wheatstone bridge is balanced when the galvanometer current is:
(a) maximum (b) zero (c) equal to supply current (d) negative
33. The unit of capacitance is the:
(a) henry (b) farad (c) tesla (d) weber
34. $Q = CV$. A 100 μF capacitor at 10 V holds:
(a) 1 mC (b) 10 mC (c) 0.1 mC (d) 1 C
35. Energy in a capacitor is:
(a) CV (b) $\frac{1}{2}CV^2$ (c) $\frac{1}{2}LI^2$ (d) V^2/C
36. Capacitors in parallel:
(a) reciprocals add (b) values add (c) values multiply (d) cancel out
37. The RC time constant for 10 k Ω and 100 μF is:
(a) 1 s (b) 0.1 s (c) 10 s (d) 1 ms
38. After one time constant, a charging capacitor reaches about:
(a) 37% (b) 50% (c) 63% (d) 100%
39. A capacitor is considered fully charged after about:
(a) 1τ (b) 2τ (c) 5τ (d) 20τ

40. In steady DC, a capacitor behaves like:
(a) a short circuit (b) an open circuit (c) a resistor (d) an inductor
41. The unit of inductance is the:
(a) farad (b) henry (c) hertz (d) siemens
42. Lenz's law says an induced EMF:
(a) aids the change (b) opposes the change
(c) is always zero (d) equals the supply
43. Energy stored in an inductor is:
(a) $\frac{1}{2}CV^2$ (b) $\frac{1}{2}LI^2$ (c) LI (d) L/R
44. The RL time constant is:
(a) RC (b) L/R (c) R/L (d) LR
45. In steady DC, an ideal inductor behaves like:
(a) an open circuit (b) a short circuit (c) a capacitor (d) a diode
46. A diode across a relay coil is called a:
(a) Zener diode (b) flyback diode (c) LED (d) photodiode
47. The Indian mains frequency is:
(a) 60 Hz (b) 50 Hz (c) 100 Hz (d) 230 Hz
48. The period of a 50 Hz wave is:
(a) 50 ms (b) 20 ms (c) 2 ms (d) 0.5 s
49. RMS value of a sine wave equals:
(a) $0.637 \times \text{peak}$ (b) $0.707 \times \text{peak}$ (c) $1.414 \times \text{peak}$ (d) peak
50. The peak of 230 V RMS is about:
(a) 163 V (b) 230 V (c) 325 V (d) 460 V
51. Appliance voltage ratings are given as:
(a) peak values (b) average values (c) RMS values (d) peak-to-peak values
52. The form factor of a sine wave is:
(a) 1.0 (b) 1.11 (c) 1.414 (d) 0.707
53. A 4-pole alternator for 50 Hz runs at:
(a) 3,000 rpm (b) 1,500 rpm (c) 1,000 rpm
(d) 750 rpm
54. Three-phase voltages are displaced by:
(a) 90° (b) 120° (c) 180° (d) 60°
55. In star connection, line voltage equals:
(a) phase voltage (b) $\sqrt{3} \times \text{phase voltage}$
(c) $3 \times \text{phase voltage}$ (d) $\text{phase voltage}/\sqrt{3}$
56. Inductive reactance is:
(a) $1/2\pi fC$ (b) $2\pi fL$ (c) $R + L$ (d) L/f
57. Capacitive reactance when frequency doubles:
(a) doubles (b) halves (c) stays the same (d) becomes zero
58. In a pure inductor, current:
(a) leads V by 90° (b) lags V by 90° (c) is in phase (d) leads by 180°
59. In a pure capacitor, current:
(a) leads V by 90° (b) lags V by 90° (c) is in phase (d) is zero
60. $R = 3 \Omega$ and $X_L = 4 \Omega$ in series give Z of:
(a) 7Ω (b) 1Ω (c) 5Ω (d) 12Ω
61. At series resonance:
(a) $X_L = X_C$ (b) $X_L = 0$ (c) Z is maximum (d) current is minimum
62. The resonant frequency formula is:
(a) $2\pi\sqrt{LC}$ (b) $1/(2\pi\sqrt{LC})$ (c) $\sqrt{L/C}$ (d) $1/(LC)$
63. Real power is measured in:
(a) VA (b) VAR (c) W (d) Ω

54. Apparent power is measured in:
(a) W (b) VA (c) VAR (d) J
55. Power factor equals:
(a) $\sin \phi$ (b) $\tan \phi$ (c) $\cos \phi$ (d) $1/\cos \phi$
56. A load of 10 kVA at pf 0.8 has real power:
(a) 8 kW (b) 6 kW (c) 12.5 kW (d) 10 kW
57. Low power factor causes:
(a) lower current (b) higher current and losses (c) no effect (d) higher frequency
58. Lagging power factor is corrected using:
(a) inductors (b) capacitors (c) resistors (d) diodes
59. Three-phase power is:
(a) $V_L I_L \cos \phi$ (b) $\sqrt{3} V_L I_L \cos \phi$ (c) $3 V_L I_L$ (d) $\sqrt{2} V_L I_L$
70. n-type silicon has majority carriers:
(a) holes (b) electrons (c) protons (d) ions
71. p-type silicon is made by adding:
(a) phosphorus (b) boron (c) arsenic (d) antimony
72. The barrier potential of a silicon diode is about:
(a) 0.3 V (b) 0.7 V (c) 1.5 V (d) 5 V
73. A diode conducts when it is:
(a) reverse biased (b) forward biased (c) open (d) cold
74. A bridge rectifier uses how many diodes?
(a) 1 (b) 2 (c) 4 (d) 6
75. Full-wave rectifier average output is:
(a) $0.318 V_m$ (b) $0.637 V_m$ (c) $0.707 V_m$ (d) V_m
76. Ripple frequency of a full-wave rectifier on 50 Hz mains is:
(a) 25 Hz (b) 50 Hz (c) 100 Hz (d) 200 Hz
77. The capacitor after a rectifier is used for:
(a) amplification (b) smoothing (c) oscillation (d) switching
78. A Zener diode is operated in:
(a) forward bias (b) reverse breakdown (c) cut-off only (d) saturation
79. An LED must be used with a series:
(a) capacitor (b) current-limiting resistor (c) inductor (d) transformer
80. A diode reading ~ 0.6 V one way and OL the other way is:
(a) shorted (b) open (c) good (d) reversed
81. The three terminals of a BJT are:
(a) gate, drain, source (b) base, collector, emitter (c) anode, cathode, gate (d) input, output, ground
82. In an NPN symbol, the emitter arrow points:
(a) inward (b) outward (c) nowhere (d) to the base
83. I_E equals:
(a) $I_B - I_C$ (b) $I_B + I_C$ (c) I_C/I_B (d) βI_E
84. $\beta = 100$ and $I_B = 20 \mu A$ give I_C of:
(a) 2 mA (b) 0.2 mA (c) 20 mA (d) 120 μA
85. For use as an amplifier, a BJT operates in the:
(a) cut-off region (b) active region (c) saturation region (d) breakdown region

36. A transistor switch that is ON is in:
(a) cut-off (b) saturation (c) active (d) breakdown
37. A common-emitter amplifier output is:
(a) in phase (b) inverted (180°) (c) shifted 90° (d) DC only
38. An emitter follower has a voltage gain of about:
(a) 0 (b) 1 (c) 100 (d) β
39. A MOSFET is controlled by:
(a) base current (b) gate voltage (c) drain current (d) light
90. A Darlington pair of $\beta = 50$ and $\beta = 100$ has a total gain of about:
(a) 150 (b) 5,000 (c) 50 (d) 2
91. Binary 1010 equals decimal:
(a) 8 (b) 10 (c) 12 (d) 5
92. Decimal 13 in binary is:
(a) 1011 (b) 1101 (c) 1110 (d) 1001
93. Hex F equals decimal:
(a) 14 (b) 15 (c) 16 (d) 17
94. An AND gate outputs 1 when:
(a) any input is 1 (b) all inputs are 1 (c) all inputs are 0 (d) inputs differ
95. An XOR gate outputs 1 when:
(a) inputs are equal (b) inputs differ (c) both are 1 (d) both are 0
96. Universal gates are:
(a) AND and OR (b) NAND and NOR (c) XOR and XNOR (d) NOT and AND
97. By De Morgan, $(A \cdot B)'$ equals:
(a) $A' \cdot B'$ (b) $A' + B'$ (c) $A + B$ (d) $(A + B)'$
98. $A + AB$ simplifies to:
(a) B (b) A (c) AB (d) $A + B$
99. A voltmeter is connected:
(a) in series (b) in parallel (c) either way (d) only to AC
100. An ammeter is connected:
(a) in parallel (b) in series (c) across the supply (d) only to DC

ANSWERS**MCQ Answer Key**

If you got a question wrong, go back to the module it came from and re-read that section.

Q	Ans	Q	Ans	Q	Ans	Q	Ans	Q	Ans
1	b	21	b	41	b	61	a	81	b
2	b	22	c	42	b	62	b	82	b
3	a	23	b	43	b	63	c	83	b
4	b	24	a	44	b	64	b	84	a
5	b	25	a	45	b	65	c	85	b
6	a	26	b	46	b	66	a	86	b
7	b	27	c	47	b	67	b	87	b
8	b	28	b	48	b	68	b	88	b
9	c	29	b	49	b	69	b	89	b
10	b	30	b	50	c	70	b	90	b
11	b	31	a	51	c	71	b	91	b
12	c	32	b	52	b	72	b	92	b
13	a	33	b	53	b	73	b	93	b
14	b	34	a	54	b	74	c	94	b
15	a	35	b	55	b	75	b	95	b
16	b	36	b	56	b	76	c	96	b
17	c	37	a	57	b	77	b	97	b
18	b	38	c	58	b	78	b	98	b
19	c	39	c	59	a	79	b	99	b
20	b	40	b	60	c	80	c	100	b

Short-answer exam questions (2–3 marks)

1. State Ohm's law and its limitations.
2. Define resistivity and give its unit.
3. State Kirchhoff's current and voltage laws.
4. State Thevenin's theorem.
5. Define the time constant of an RC circuit.
6. State Faraday's laws of electromagnetic induction and Lenz's law.
7. Define RMS value and state its relation to peak value for a sine wave.
8. What is power factor? Why is a low power factor undesirable?
9. Define resonance in a series RLC circuit.
10. What is a depletion region?
11. Why is a Zener diode operated in reverse bias?
12. Name the three regions of operation of a BJT.
13. State De Morgan's theorems.
14. Why are NAND and NOR called universal gates?
15. Why must an ammeter have a very low resistance?

Long-answer exam questions (5–10 marks)

1. Derive the expressions for equivalent resistance of resistors in series and in parallel. Solve a numerical example of a series–parallel network.
2. Using Kirchhoff's laws (or mesh analysis), find the branch currents in a two-source network of your choice. Verify the result using Thevenin's theorem.
3. State and explain the superposition theorem with a worked example.
4. Explain the charging and discharging of a capacitor through a resistor. Sketch the curves and derive the time constant.
5. Explain the generation of an alternating EMF and define cycle, period, frequency, amplitude, RMS and average values.
6. Explain the behaviour of R, L and C in AC circuits with phasor diagrams. Solve a series RLC problem.
7. Explain real, reactive and apparent power with the power triangle. How is power factor improved?
8. Explain the working of a full-wave bridge rectifier with a capacitor filter. Sketch input and output waveforms.

9. Explain how a transistor works as a switch and as an amplifier, with circuit diagrams and characteristics.
10. Design a combinational circuit from a truth table, simplify it using a K-map, and draw the logic diagram.

REFERENCE

Glossary of Terms

Key words used throughout these notes, in alphabetical order.

Alternating current (AC)

Current that periodically reverses direction.

Ammeter

Instrument measuring current; connected in series.

Ampere (A)

Unit of current: one coulomb per second.

Amplifier

Circuit that increases the size of a signal.

Apparent power (S)

$V \times I$ in AC circuits, in VA.

Bandwidth

Range of frequencies a circuit passes effectively.

Barrier potential

Voltage across a p-n junction's depletion region (~0.7 V in Si).

Beta (β , h_{FE})

DC current gain of a BJT, I_C/I_B .

Binary

Base-2 number system using 0 and 1.

BJT

Bipolar junction transistor (NPN or PNP).

Boolean algebra

Algebra of logic variables with AND, OR, NOT.

Capacitance

Charge stored per volt, in farads.

Conductance (G)

Reciprocal of resistance, in siemens.

Coulomb (C)

Unit of electric charge.

Cut-off

Transistor region where it is OFF.

De Morgan's theorems

$(AB)' = A' + B'$ and $(A + B)' = A'B'$.

Depletion region

Carrier-free zone at a p-n junction.

Dielectric

Insulating material between capacitor plates.

Diode

Two-terminal device that conducts in one direction.

Direct current (DC)

Current flowing in one direction only.

Doping

Adding impurities to a semiconductor.

Earthing

Connecting metal parts to earth for safety.

EMF

Electromotive force — the voltage generated by a source.

Farad (F)

Unit of capacitance.

Flip-flop

Circuit that stores one bit.

Frequency (f)

Cycles per second, in hertz.

Henry (H)

Unit of inductance.

Hexadecimal

Base-16 number system (0–9, A–F).

Impedance (Z)

Total opposition to AC, combining R and X.

Inductance

Property of a coil to oppose change in current, in henries.

Internal resistance

Resistance inside a source.

Karnaugh map

Grid method for simplifying logic expressions.

KCL / KVL

Kirchhoff's current and voltage laws.

LED

Light-emitting diode.

Load line

Line on transistor characteristics showing possible operating points.

Logic gate

Circuit implementing a logic function.

MCB

Miniature circuit breaker for overload/short-circuit protection.

Mesh

A loop with no loop inside it.

MOSFET

Voltage-controlled field-effect transistor.

Multimeter

Instrument measuring voltage, current, resistance and more.

Node

Junction of two or more circuit elements.

Norton equivalent

Current source in parallel with a resistance.

Ohm (Ω)

Unit of resistance.

Oscilloscope

Instrument displaying voltage against time.

Period (T)

Time of one cycle.

Phase angle (φ)

Angle between voltage and current waveforms.

Phasor

Rotating arrow representing a sinusoidal quantity.

Power factor

$\cos \varphi = P/S$.

Q-point

DC operating point of an amplifier.

Quality factor (Q)

Sharpness of resonance, X_L/R .

RCCB / RCD

Device that trips on earth-leakage current (e.g. 30 mA).

Reactance (X)

Opposition to AC from L or C.

Reactive power (Q)

$VI \sin \varphi$, in VAR.

Real power (P)

$VI \cos \varphi$, in watts.

Rectifier

Circuit converting AC to DC.

Resistivity (ρ)

Material property setting resistance, in $\Omega \cdot m$.

Resonance

Condition $X_L = X_C$.

Ripple

Residual AC variation on a rectified DC output.

RMS value

Equivalent DC value producing the same heating.

Saturation

Transistor region where it is fully ON.

Semiconductor

Material with conductivity between conductors and insulators.

Superposition

Adding effects of each source acting alone.

Thevenin equivalent

Voltage source in series with a resistance.

Time constant (τ)

RC or L/R; time to reach 63.2% of the final change.

Truth table

Table of outputs for all input combinations.

Volt (V)

Unit of potential difference: one joule per coulomb.

Voltmeter

Instrument measuring voltage; connected in parallel.

Watt (W)

Unit of power: one joule per second.

Wheatstone bridge

Four-arm bridge for precise resistance measurement.

Zener diode

Diode designed to operate in reverse breakdown as a voltage reference.

Keep learning

Use the AI tutor on www.aitutorspark.co.in to ask any question from these notes — it explains step by step. Complete the course quiz to earn your certificate. All the best!