Unit 14

Answers: Electricity and Magnetism

Quick checks

1 b Both have tiny atomic magnets (or, in aluminium, electrons that act like them). In aluminium, heat keeps them pointing at random, and a field lines up only a tiny share of them. In iron they are already lined up in domains, and a field turns whole domains, so iron is magnetized tens of thousands of times more strongly, or more.

2 c Discharging turns both plates into lead sulphate, which takes sulphate from the sulphuric acid and makes water. The acid becomes more dilute, so its density falls. Charging reverses it.

3 d A voltmeter must take very little current. A high resistance in series with the coil (a multiplier) keeps the current through it at I_g or less even for a large voltage, and makes the whole voltmeter's resistance high.

4 b An LDR's resistance is low in light and high in the dark. With the LDR between the base and 0 V, a higher LDR resistance takes a bigger share of the 6 V, so the base voltage rises above the 0.7 V that switches the transistor on. Its collector current then lights the lamp.

1 a. **c** Nickel, like iron and cobalt, has its atomic magnets lined up in domains and is strongly attracted by a magnet. Aluminium and platinum are paramagnetic (weakly attracted); copper is diamagnetic (weakly repelled).

1 b. **c** In a paramagnetic material, heat scatters the atomic magnets again as soon as the field is gone, so no magnetism is left.

1 c. **b** A lead-acid cell uses dilute sulphuric acid, about 1.28 g/cm^3 when fully charged. Potassium hydroxide is the electrolyte of NiCd and NiMH cells; ammonium chloride paste is in a dry (primary) cell.

1 d. **c** Discharging turns both the lead dioxide of the positive plate and the spongy lead of the negative plate into lead sulphate, $PbSO_4$.

1 e. **a** A low resistance in parallel (a shunt) carries most of the current round the coil, so a large current can be measured, and the whole meter has a low resistance, as an ammeter must.

1 f. **c** The soft-iron cylinder inside the coil concentrates the field in the narrow gaps and points it along the radius, so the turning effect is the same at every angle and the scale is even. The current goes in and out through the hairsprings.

1 g. **c** Boron has three outer electrons, one fewer than silicon, so each boron atom leaves a hole: a p-type semiconductor. Phosphorus and arsenic, with five, make n-type silicon; germanium is itself a semiconductor with four.

1 h. **c** A diode lets current through in one direction only, so it passes only the halves of an a.c. wave that drive it forward: rectification. A transformer changes the size of an a.c. voltage but leaves it a.c.

2 a. In a ferromagnetic material the atomic magnets are already lined up in domains, and a field turns whole domains to point along it, so the material becomes a strong magnet. In a paramagnetic material the atomic magnets point at random and are kept random by heat; a field can line up only a tiny share of them, so it becomes only a very weak magnet.

2 b. When it is charged, the electrical energy from the charger is stored as chemical energy (lead dioxide, lead and sulphuric acid are made again). When it is used, the stored chemical energy is given back as electrical energy. It stores energy and gives it back many times over.

2 c. Near the end of charging, the current splits water in the acid into hydrogen and oxygen, which bubble out of the vents. Together they form an explosive mixture; in a closed room it can collect, and a flame or a spark can make it explode.

2 d. An ammeter is put in series, so all the current passes through it. If its resistance were large, it would reduce the current it is measuring. A voltmeter is put in parallel; if its resistance were low, it would take a large share of the current away from the part it is across and change the voltage it is measuring. A very high resistance means it takes almost no current.

2 e. The turning effect on the coil depends on the direction of the current: reversing the current reverses the forces on the coil's sides, so the coil turns the other way. A galvanometer is used to detect small currents and to show which way they flow, so its zero is in the middle and it can swing either way.

3 i.

Primary cell	Secondary cell
Can't be recharged.	Can be recharged many times.
Its chemical reaction is irreversible.	Its chemical reaction is reversed by charging.
Gives a small current; fairly high internal resistance.	Can give a large current; very low internal resistance.
Cheaper to buy, costlier over time.	Costlier to buy, cheaper over its life.
Example: dry cell (zinc–carbon).	Example: lead-acid cell, lithium-ion cell.

3 ii.

Ammeter	Voltmeter
Measures electric current, in amperes.	Measures potential difference, in volts.
Connected in series.	Connected in parallel.
Has a very low resistance.	Has a very high resistance.
Made from a galvanometer with a low resistance (shunt) in parallel.	Made from a galvanometer with a high resistance (multiplier) in series.

3 iii.

p-type semiconductor	n-type semiconductor
Made by adding an element with three outer electrons (boron, gallium) to silicon.	Made by adding an element with five outer electrons (phosphorus, arsenic) to silicon.
The charges that move are mostly holes, which act as positive charges.	The charges that move are mostly free electrons, which are negative.

4 a. In some substances, each atom or molecule has unpaired electrons whose magnetic fields don't cancel, so each atom or molecule is a tiny magnet: this is molecular magnetism. Drawings (as in the activity of 14.1):

- paramagnetic, no field: small arrows pointing every which way;
- paramagnetic, strong field: still nearly random, leaning only slightly towards the field (draw them tilted partly towards it and write "only a tiny share line up");
- ferromagnetic, no field: regions (domains), each with all its arrows one way, different regions different ways;
- ferromagnetic, strong field: all the domains' arrows along the field.

4 b. A lead-acid cell has a plastic case holding dilute sulphuric acid (about 1.28 g/cm^3 when charged). In it stand a positive plate of lead dioxide (PbO_2, brown) and a negative plate of spongy lead (Pb, gray), each on a grid of lead alloy, kept apart by porous separators; real cells have several plates of each kind joined in parallel. A vent cap lets out the gases made while charging. The cell gives about 2 V. The diagram shows the case, the acid, the two plates with their + and − terminals and the separator, as in the widget in 14.2.

4 c. At the negative plate: $Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$.
At the positive plate: $PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$.
Overall: $Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$.
During charging, a current passed the other way reverses every reaction: $2PbSO_4 + 2H_2O \rightarrow Pb + PbO_2 + 2H_2SO_4$. Lead dioxide and lead are formed again on the plates, and the sulphuric acid becomes stronger again.

4 d. It has a coil of many turns of fine insulated copper wire on a light frame, free to turn on an axle between the curved pole pieces of a strong permanent magnet, with a fixed soft-iron cylinder inside the coil that makes the field strong and radial. Two hairsprings hold the coil at zero and lead the current in and out; a pointer fixed to the coil moves over a scale.
When a current flows, the two sides of the coil carry it in opposite directions in the field, so by the motor effect one side is pushed one way and the other the other way, and the coil turns. It twists the hairsprings until their push balances the turning effect. The deflection is proportional to the current, and reverses when the current reverses.

4 e. A diode is a p–n junction of semiconductor that lets current through in one direction only. Forward bias: the p side is joined to the positive terminal; holes and electrons are pushed to the junction and cross it, and current flows (once the voltage is above about 0.7 V for silicon). Reverse bias: the p side is joined to the negative terminal; the charges are pulled away from the junction, the depletion layer widens, and practically no current flows. Uses: as a rectifier, changing a.c. to d.c. in chargers and adapters; as an LED for lighting; also in solar cells and to protect circuits from batteries put in the wrong way.

4 f. A transistor is a three-layer semiconductor device, npn or pnp, with three terminals: emitter, base and collector. A small current into the base controls a much larger current between the collector and the emitter, typically about 100 times bigger. As a switch: with no base current it is off; a small base current turns on a large collector current, as in an automatic night light, where an LDR sets the base voltage, or in a computer chip. As an amplifier: a small, changing base current (from a microphone, say) makes a large collector current that changes in the same way, a stronger copy of the signal that can drive a loudspeaker.

4 g. The base voltage would now be the share of the 6 V across the fixed resistor, which is the lower part. In daylight the LDR's resistance is low (1 kΩ), so the base gets $6 \times 10/11 \approx 5.5$ V and the transistor is on; in the dark (100 kΩ) the base gets $6 \times 10/110 \approx 0.55$ V and it is off. **The lamp would come on in the light and go off in the dark**: a circuit that works as a light alarm, for example to warn when a fridge or a darkroom door is opened.

5 a. i. $V = I_g G = 0.001 \times 100 = 0.1$.

ii. $$S = \frac{I_g G}{I - I_g} = \frac{0.001 \times 100}{1 - 0.001} = \frac{0.1}{0.999} = 0.100\ \Omega$$

iii. $$R = \frac{V}{I_g} - G = \frac{5}{0.001} - 100 = 4{,}900\ \Omega$$

So: 0.1 V for full scale, a 0.100 Ω shunt in parallel for the ammeter, and 4,900 Ω in series for the voltmeter.

5 b. $$S = \frac{0.01 \times 50}{2 - 0.01} = \frac{0.5}{1.99} = 0.251\ \Omega$$

Whole ammeter: $\frac{GS}{G+S} = \frac{50 \times 0.251}{50.251} = 0.25\ \Omega$. (Also: at full scale, 0.5 V drives 2 A through it, and $0.5 \div 2 = 0.25\ \Omega$.)

A shunt of 0.251 Ω; the ammeter's resistance is 0.25 Ω.

5 c. $$R = \frac{20}{0.01} - 50 = 2{,}000 - 50 = 1{,}950\ \Omega$$

1,950 Ω in series; the voltmeter's resistance is 1,950 + 50 = 2,000 Ω.

5 d. At full scale the p.d. across the coil is $I_g G = 0.002 \times 40 = 0.08$. The same p.d. is across the shunt, so the shunt carries $\frac{0.08}{0.04} = 2$.

$$I = I_g + I_S = 0.002 + 2 = 2.002$$

About 2 A.

5 e. $$V = I_g(G + R) = 0.005 \times (20 + 980) = 0.005 \times 1{,}000 = 5$$

0 to 5 V.

5 f. From $I_g G = (I - I_g)S$:

$$G = \frac{(I - I_g)S}{I_g} = \frac{(5 - 0.025) \times 0.25}{0.025} = \frac{4.975 \times 0.25}{0.025} = 49.75\ \Omega$$

About 49.75 Ω (about 50 Ω).

5 g. i. $6 \times 2.1 =$ **12.6 V**.

ii. $t = \frac{60}{9} = 6.7$: **about 6⅔ hours** in the ideal case. (A battery drained flat that way would be badly damaged, and might not start the car.)

5 h. i. Power: $4 \times 10 + 60 = 100$ W. Energy: 100 W × 3 h = **300 Wh**.

ii. Charge: $\frac{300}{12} =$ **25 Ah** (the current is $100 \div 12 \approx 8.3$ A for 3 hours).

iii. If only half may be used, the battery must hold twice that: **50 Ah** at least. (Shops would choose a larger one, since the inverter loses some energy and old batteries hold less.)

5 i. Forward: $I = \frac{9-0.7}{1{,}000} = 0.0083\ =$ **8.3 mA**.

Reversed: **practically no current**, so there is no p.d. across the resistor, and **the whole 9 V is across the diode**.

5 j. The resistor must take the rest of the voltage: $5 - 2 = 3$ V, at 20 mA $= 0.02$ A.

$$R = \frac{3}{0.02} = 150\ \Omega$$

150 Ω in series. Without it, the LED would take far too much current and burn out.

5 k. i. $I_C = 100 \times 0.04$ $=$ **4 mA**.

ii. $I_B = \frac{150}{100}$ $=$ **1.5 mA**.