Chapter 28

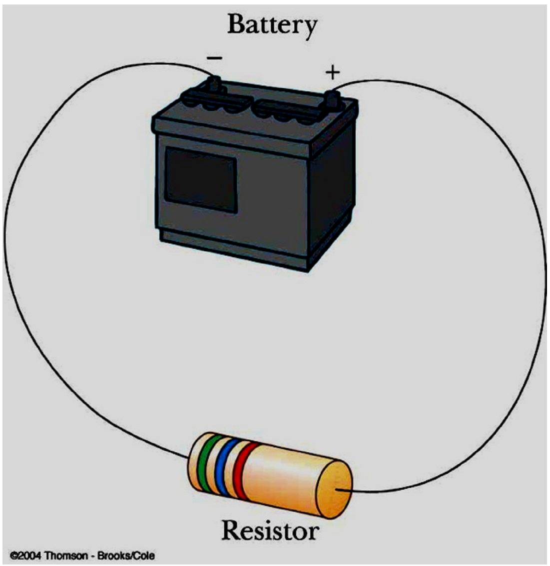
Direct Current Circuit

28.1 Electromotive Force

A constant current can be maintained in a closed circuit through the use of a source of *emf, (such as a battery or generator)* that produces an electric field and thus may cause charges to move around a circuit.

The emf describes the work done per unit charge, and hence the SI unit of emf is the volt.

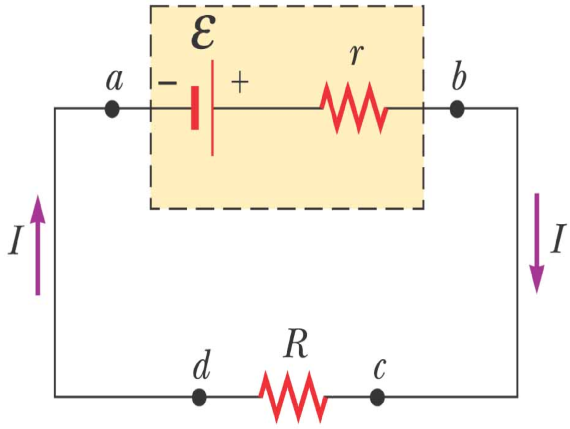
The electromotive force is defined as the maximum voltage that produced by the energy source.



In the figure above, assume that the connecting wires have no resistance.

- The positive terminal of the battery is at a higher potential than the negative terminal. If we neglect the internal resistance of the battery, the potential difference across it (called the terminal voltage) equals its emf.
- However, because a real battery always has some internal resistance *r, the terminal voltage is not equal to the emf for a battery in a* circuit in which there is a current.

In the figure in front, As we pass from the negative terminal to the positive terminal, the potential *increases by an amount* ε.

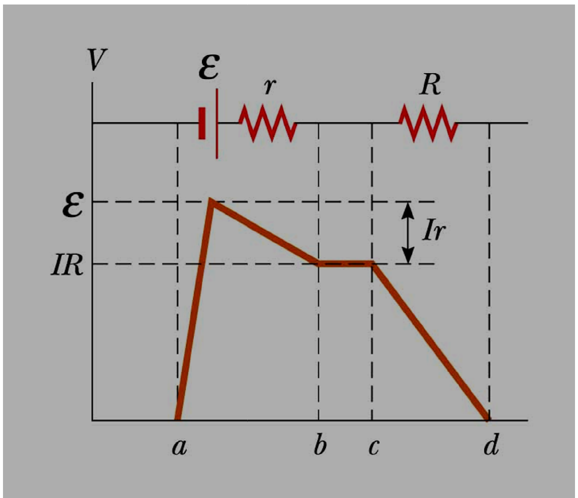


(a)

As we move through the resistance *r, the potential decreases by an amount Ir, where I is the current* in the circuit.

ΔV=ε-Ir (28-1)

ε*:* is equivalent to the open-circuit voltage—that is, the *terminal voltage when the current is zero. The emf is the voltage labeled on a* battery,… .



(b)

The terminal voltage *V must equal the potential difference across the external* resistance *R, often called the load resistance.*

The resistor represents a *load on the battery because the battery must supply energy to* operate the device. The potential difference across the load resistance is

ΔV = IR (28-2)

$$\varepsilon = IR + Ir = I(R + r) \qquad (28\text{-}3)$$

$$I = \frac{\varepsilon}{(R + r)}$$

The total power output $I\varepsilon$ *of the battery is delivered to the external load resistance in the* amount I^2R *and to the internal resistance in the amount* I^2r.

$$I\varepsilon = I^2R + I^2r$$

Example 28-1

A battery has an emf of 12.0 V and an internal resistance of 0.05 Ω. Its terminals are connected to a load resistance of 3.00 Ω.

(A) Find the current in the circuit and the terminal voltage of the battery.

Solution Equation 28.3 gives us the current:

$$I = \frac{\mathcal{E}}{R + r} = \frac{12.0\text{ V}}{3.05\ \Omega} = \boxed{3.93\text{ A}}$$

and from Equation 28.1, we find the terminal voltage:

$$\Delta V = \mathcal{E} - Ir = 12.0\text{ V} - (3.93\text{ A})(0.05\ \Omega) = \boxed{11.8\text{ V}}$$

To check this result, we can calculate the voltage across the load resistance R:

$$\Delta V = IR = (3.93\text{ A})(3.00\ \Omega) = 11.8\text{ V}$$

(B) Calculate the power delivered to the load resistor, the power delivered to the internal resistance of the battery, and the power delivered by the battery.

Solution The power delivered to the load resistor is

$$\mathcal{P}_R = I^2R = (3.93\text{ A})^2\,(3.00\ \Omega) = \boxed{46.3\text{ W}}$$

The power delivered to the internal resistance is

$$\mathcal{P}_r = I^2r = (3.93\text{ A})^2\,(0.05\ \Omega) = \boxed{0.772\text{ W}}$$

Hence, the power delivered by the battery is the sum of these quantities, or 47.1 W. You should check this result, using the expression $\mathcal{P} = I\mathcal{E}$.

What If? As a battery ages, its internal resistance increases. Suppose the internal resistance of this battery rises to 2.00 Ω toward the end of its useful life. How does this alter the ability of the battery to deliver energy?

Answer Let us connect the same 3.00-Ω load resistor to the battery. The current in the battery now is

$$I = \frac{\mathcal{E}}{R + r} = \frac{12.0\text{ V}}{(3.00\ \Omega + 2.00\ \Omega)} = 2.40\text{ A}$$

and the terminal voltage is

$$\Delta V = \mathcal{E} - Ir = 12.0\text{ V} - (2.40\text{ A})\,(2.00\ \Omega) = 7.2\text{ V}$$

Notice that the terminal voltage is only 60% of the emf. The powers delivered to the load resistor and internal resistance are

$$\mathcal{P}_R = I^2R = (2.40\text{ A})^2\,(3.00\ \Omega) = \boxed{17.3\text{ W}}$$

$$\mathcal{P}_r = I^2r = (2.40\text{ A})^2\,(2.00\ \Omega) = 11.5\text{ W}$$

Notice that 40% of the power from the battery is delivered to the internal resistance. In part (B), this percentage is 1.6%. Consequently, even though the emf remains fixed, the increasing internal resistance significantly reduces the ability of the battery to deliver energy.