

For the circuit shown where  $r$  is an internal resistance and  $R$  is an external resistor, which potential difference corresponds to the terminal voltage of the battery?

Terminal voltage is the potential difference measured across the terminals of the battery. In between the battery terminals there are the emf ( $\mathcal{E}$ ) and the internal resistance ( $r$ ). On this diagram, the terminals would be located at points K and M, since the  $\mathcal{E}$  and  $r$  are between these two points.

$$\Delta V_{KM} = \Delta V_T = \text{Terminal voltage}$$

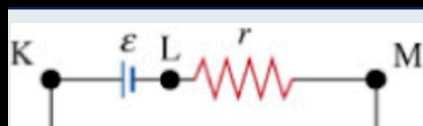
The external resistor  $R$  connects directly to points K and M, so the voltage across  $R$  is exactly the terminal voltage. When current flows through the circuit, some of the emf is "used up" driving current through the internal resistance, and only the remainder of the emf appears across the terminals:

$$\Delta V_T = \mathcal{E} - Ir$$

↑ voltage drop across internal resistor when current flows through it.

This formula assumes the battery is discharging, so the internal resistor produces a voltage drop - meaning the terminal voltage is less than the emf. If instead the battery is being charged by an external source,

current flows in the opposite direction and the internal resistor produces a voltage gain, making the terminal voltage greater than  $\mathcal{E}$ . This is what happens when jump-starting a car: the good battery drives current backward through the dead battery, pushing its terminal voltage above its own  $\mathcal{E}$ .



A battery has emf = 12.0 V and internal resistance = 3.00  $\Omega$ . A voltmeter is connected to the terminals of the battery; the battery is not connected to any other external circuit elements.

What is the reading of the voltmeter?

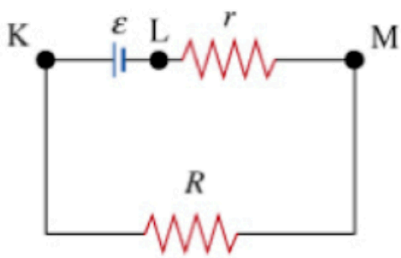
The voltmeter reads 12 V.

When the battery is not connected to any external circuit elements, the circuit is open and no current flows ( $I = 0$ ).

$$\Delta V_T = \mathcal{E} - Ir$$

$$\Delta V_T = 12\text{ V} - (0)(3\Omega) = 12\text{ V}$$

Since there is no current, there is no voltage drop across the internal resistor, and the full emf is measured at the terminals. The voltmeter reads exactly the emf of the battery.



A battery has emf = 12.0 V and internal resistance  $r = 3.00 \Omega$ . A  $21.0\text{-}\Omega$  resistor is connected to the terminals of the battery.

What is the current through the battery?

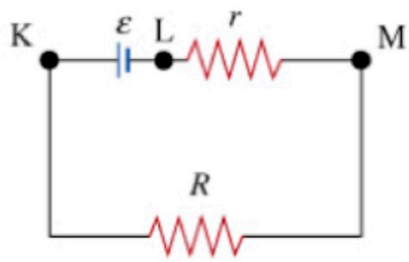
The current through the battery (and through every element in the circuit) is  $0.5 \text{ A}$ .

When the  $21\text{-}\Omega$  external resistor is connected across the terminals K and M, the internal resistance and the external resistance are in series, so the total resistance in the circuit is:

$$R_{\text{total}} = R + r = 21 \Omega + 3 \Omega = 24 \Omega$$

The emf is the voltage source driving current through the total resistance in the circuit. So we can apply Ohm's law using the full emf and total resistance:

$$I = \frac{\mathcal{E}}{R_{\text{total}}} = \frac{12 \text{ V}}{24 \Omega} = 0.5 \text{ A}$$

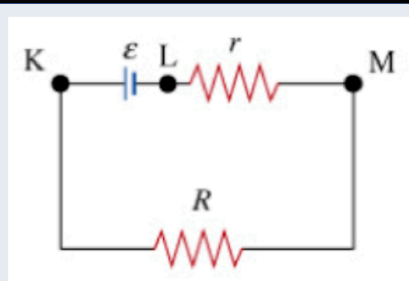


A battery has emf = 12.0 V and internal resistance  $r = 3.00 \Omega$ . A 21.0- $\Omega$  resistor is connected to the terminals of the battery.

What is the current through the 21.0- $\Omega$  resistor?

The current through the 21  $\Omega$  resistor is 0.5 A.

Since there is only one loop in this circuit, there is only one path for current to flow. This means the same current flows through every element in the circuit - the battery, the internal resistor, and the external resistor all carry the same current calculated in the previous part.



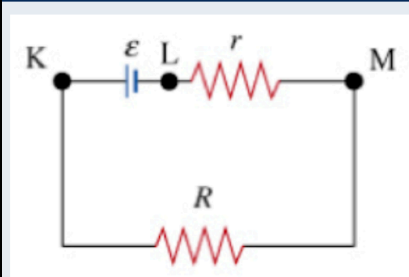
A battery has emf = 12.0 V and internal resistance  $r = 3.00 \Omega$ . A 21.0- $\Omega$  resistor is connected to the terminals of the battery.

What is the potential difference across the 21.0- $\Omega$  resistor?

The potential difference across the 21  $\Omega$  resistor is 10.5 V.

The external resistor  $R$  has a current of 0.5 A flowing through it. We can find the potential difference across it by applying Ohm's law - the voltage across a resistor is simply the current through it multiplied by its resistance :

$$\Delta V_R = IR = (0.5 \text{ A})(21 \Omega) = 10.5 \text{ V}$$



A battery has emf = 12.0 V and internal resistance  $r = 3.00 \Omega$ . A 21.0- $\Omega$  resistor is connected to the terminals of the battery.

What is the terminal voltage of the battery connected to the 21.0- $\Omega$  resistor?

The terminal voltage of the battery is 10.5 V.

The terminal voltage is the potential difference

across the terminals of the battery:  $\Delta V_{KM}$ .  
Since the external resistor  $R$  is connected directly between  $K$  and  $M$ , the potential difference across  $R$  is the same as the potential difference across the terminals:

$$\Delta V_{KM} = \Delta V_R = 10.5 \text{ V}$$

We can confirm this using the terminal voltage formula, which adds the potential difference across the emf and the voltage drop across the internal resistor:

$$\Delta V_{KM} = \mathcal{E} - Ir = 12 \text{ V} - (0.5 \text{ A})(3 \Omega) = 12 \text{ V} - 1.5 \text{ V} = 10.5 \text{ V}$$

Both approaches give the same result, as expected. The terminal voltage is less than the emf because the internal resistor produces a voltage drop of  $1.5 \text{ V}$  when current flows through it.