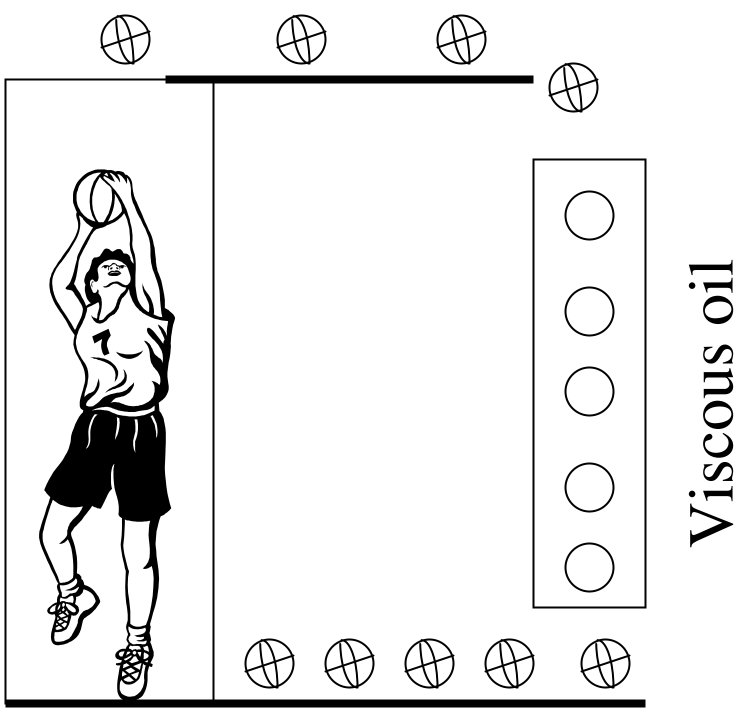
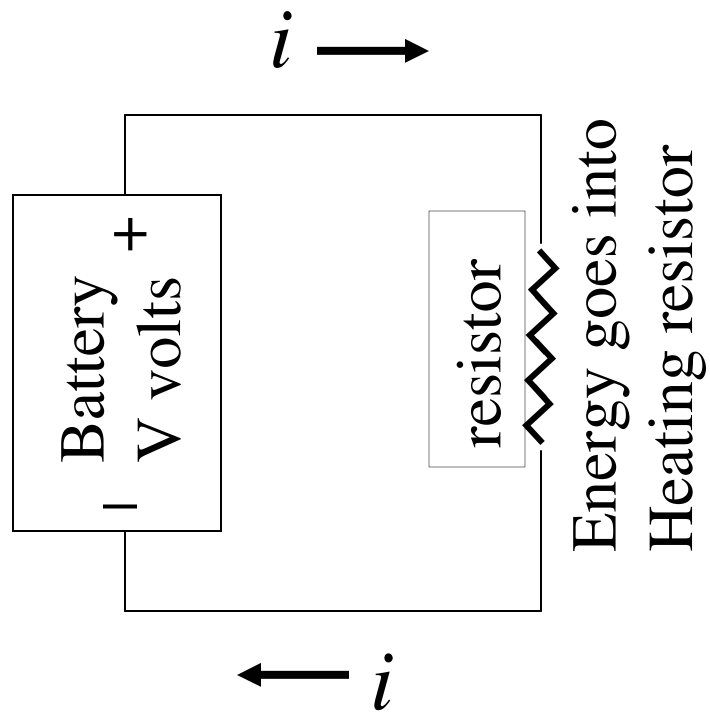
Lecture 9 – Phys 272
Currents, EMF (voltage) Sources & Power

Electromotive Force and Circuits

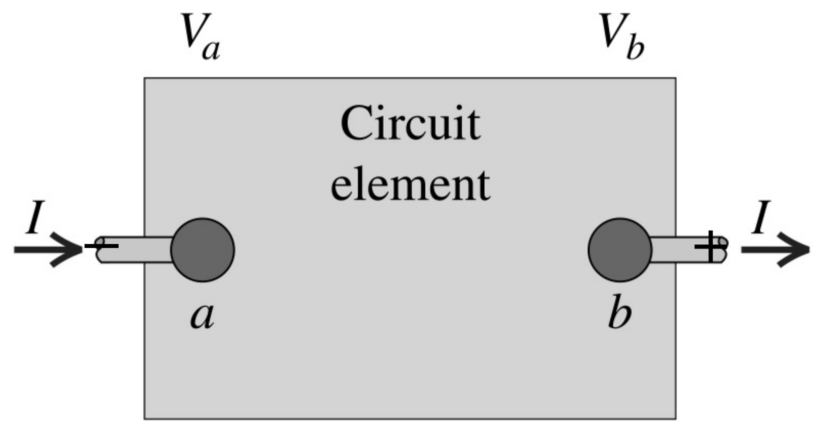
Here we discuss “sources of electromotive force”, such as batteries, electric generators and solar cells, and we consider how they behave in a closed circuit. Below is an analogy between basketball and current in a closed circuit. The player does work to move the ball up and the ball loses energy in the viscous oil giving off heat. The battery does work to move q from – to + terminals, gaining energy qV. The charge q moves through wire to resistor and loses energy in the resistor and goes to the – terminal.



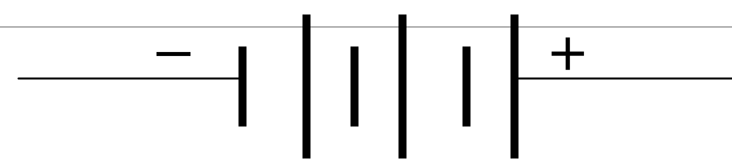


Electromotive Force (EMF)

A battery is a device that keeps a & b terminals at a fixed potential difference and will move a positive charge or current from the a to the b terminals by some process such as electrolysis (storage battery) or the photoelectric effect (solar cells). This "force" is called the *electromotive force* or EMF or script $\mathcal{E}$.

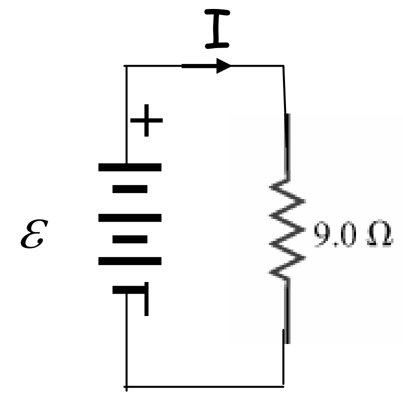


The battery circuit diagram is given by perpendicular lines, with + terminal with the bigger line.



Idealized Battery

The ideal battery with potential ε has <u>no internal resistance</u> and is represented by



$$V_B = V_R$$

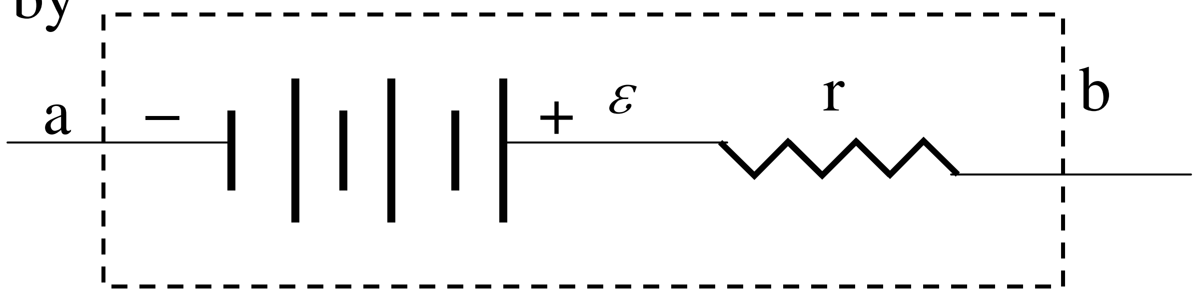
$$\varepsilon = IR$$

$$I = \frac{\varepsilon}{R}$$

V across battery is ε no matter what current is drawn! Not very physical.

"Real Battery"

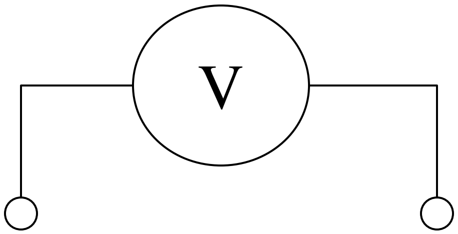
The real battery with potential ε has a ***small internal resistance r*** and is represented by



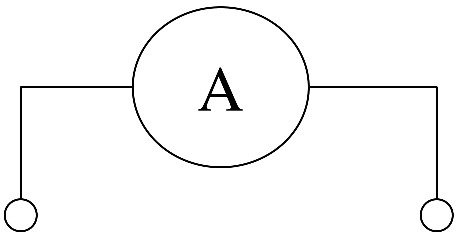
Voltage, between a & b, is slightly less than ε

Electrical Meters

Voltmeter, measures voltage and has large internal resistance. An ideal voltmeter has infinite resistance and does not conduct any current.



Ammeter, measures current and has very small internal resistance. An ideal ammeter has zero resistance and behaves like a conducting wire.



How should we connect these meters in circuits ?

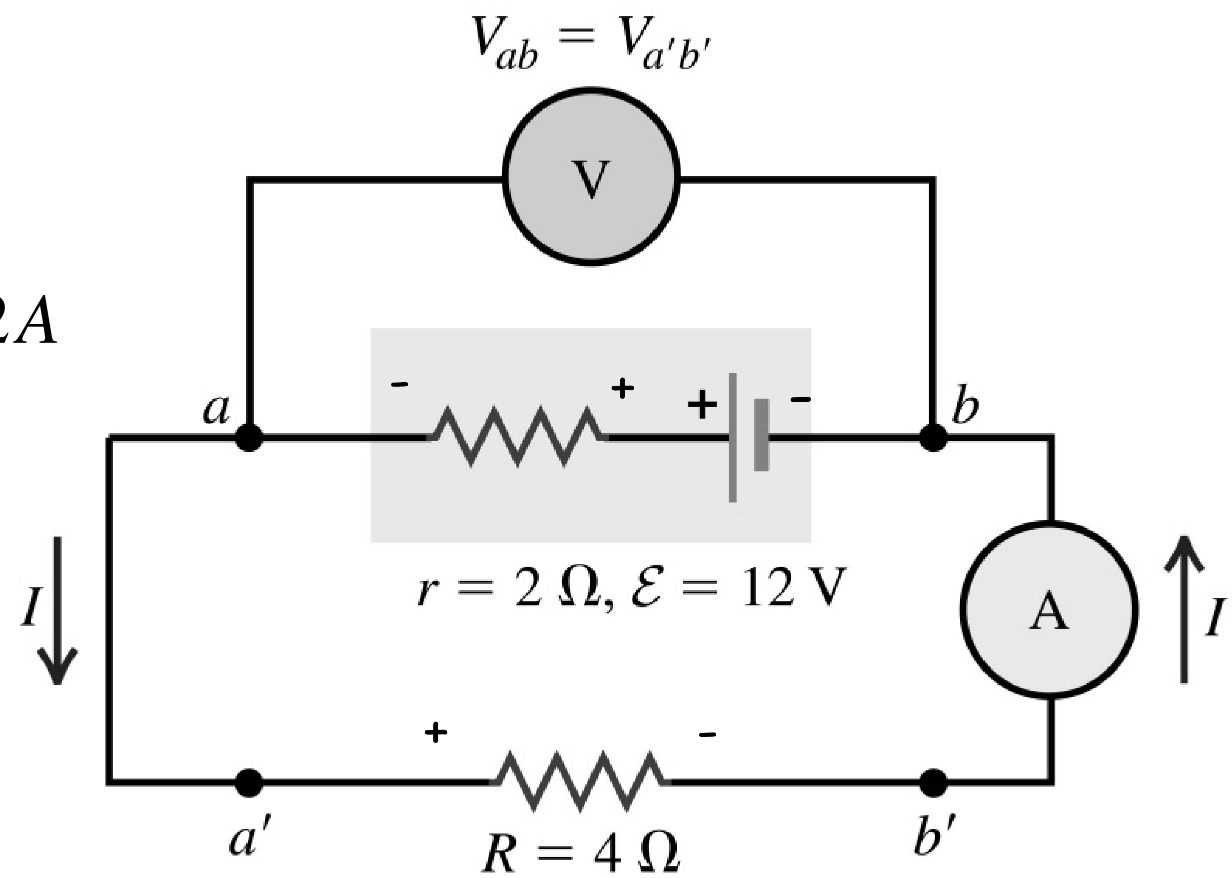
Real Battery with 12volts and an internal resistance of 2 ohms in a circuit with a resistor of 4 ohms

$$V_{AB} = V_{A'B'}$$

$$\varepsilon - Ir = IR$$

$$I(R+r) = \varepsilon$$

$$I = \frac{\varepsilon}{R+r} = \frac{12V}{6\Omega} = 2A$$



Voltage drop across 2 Ohms is 4 volts

Voltage drop across 4 Ohms is 8 volts

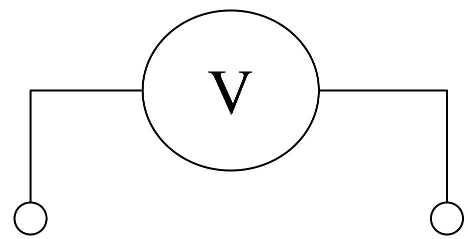
$V_{ab} = V_{a'b'} = 8$ volts

Terminal potential difference $V_{AB} = 12 - 4 = 8$ V

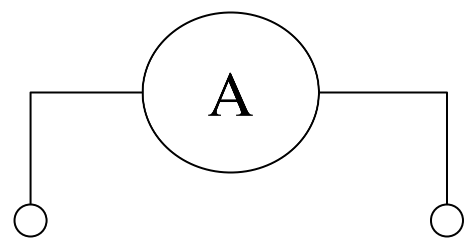
Electrical Meters

<u>How should we connect these meters in circuits ?</u>

In parallel

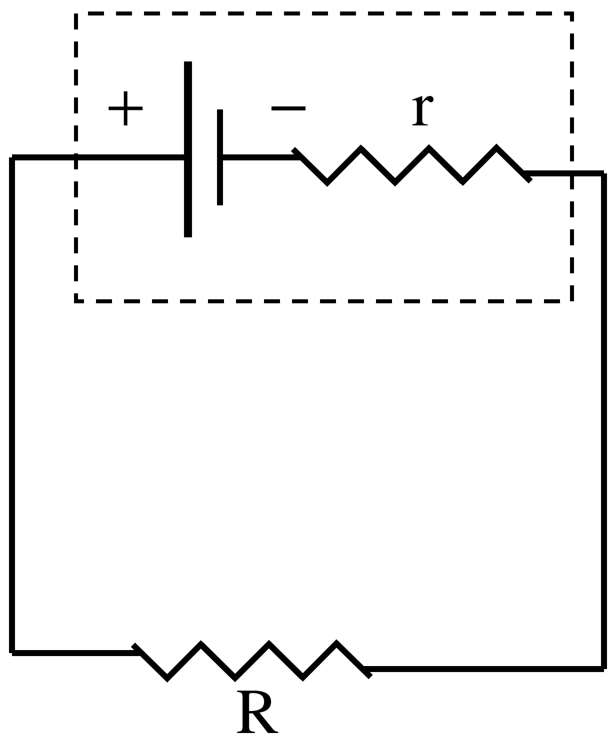


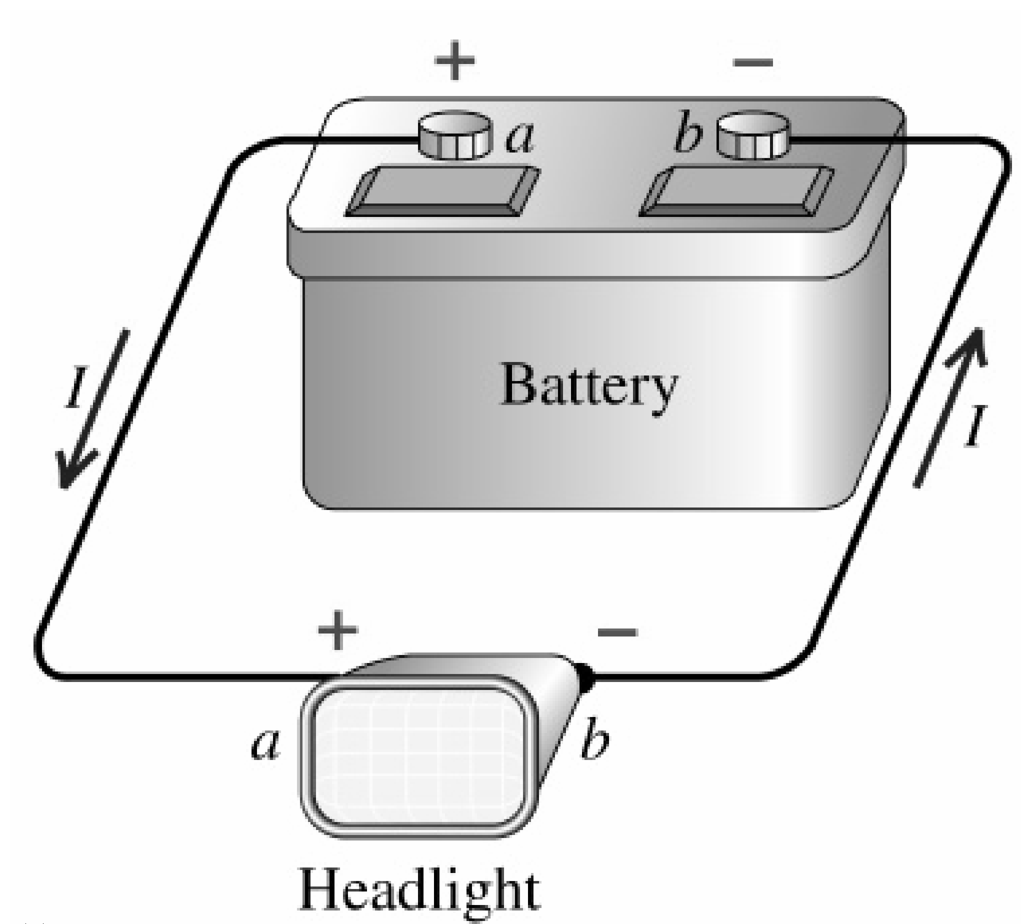
In series



Look back at the last example

Real life example of previous circuit is a car battery and a headlamp





R = resistance in headlight
r = internal resistance in battery

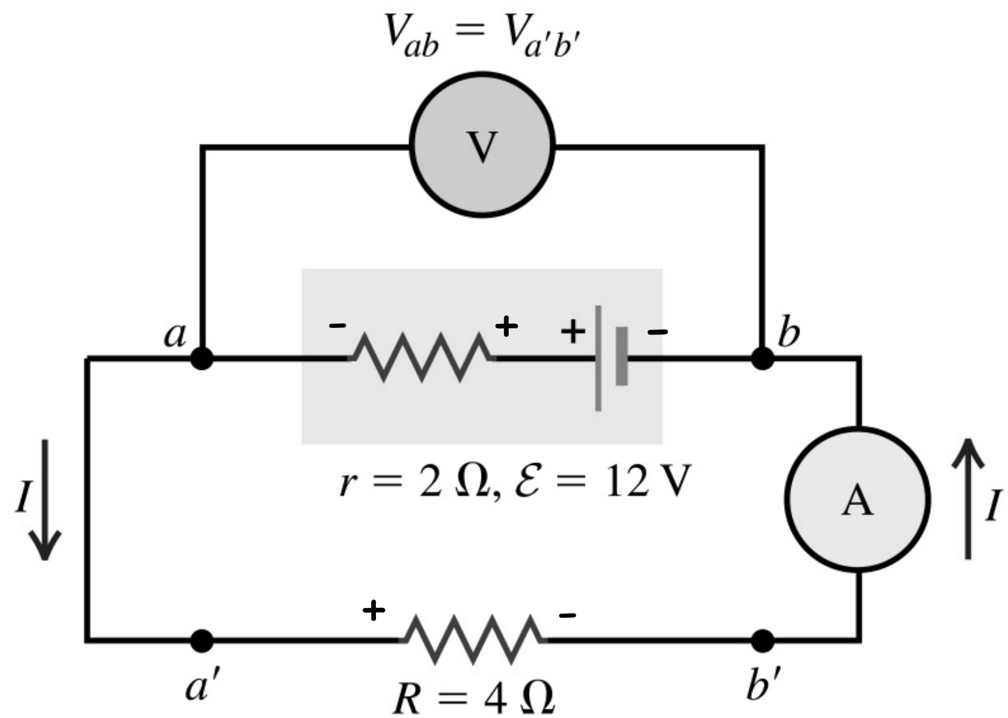
Real Battery with 12 Volts and an internal resistance of 2 ohms in a circuit with a resistor of 4 ohms

$$\varepsilon - Ir = IR$$

Rearranging:

$$\varepsilon - Ir - IR = 0$$

Can interpret this as the sum of all potential differences around a closed loop must add to zero.



Kirchoff's voltage law or loop rule.

Can define a voltage rise as positive OR a voltage fall as positive.

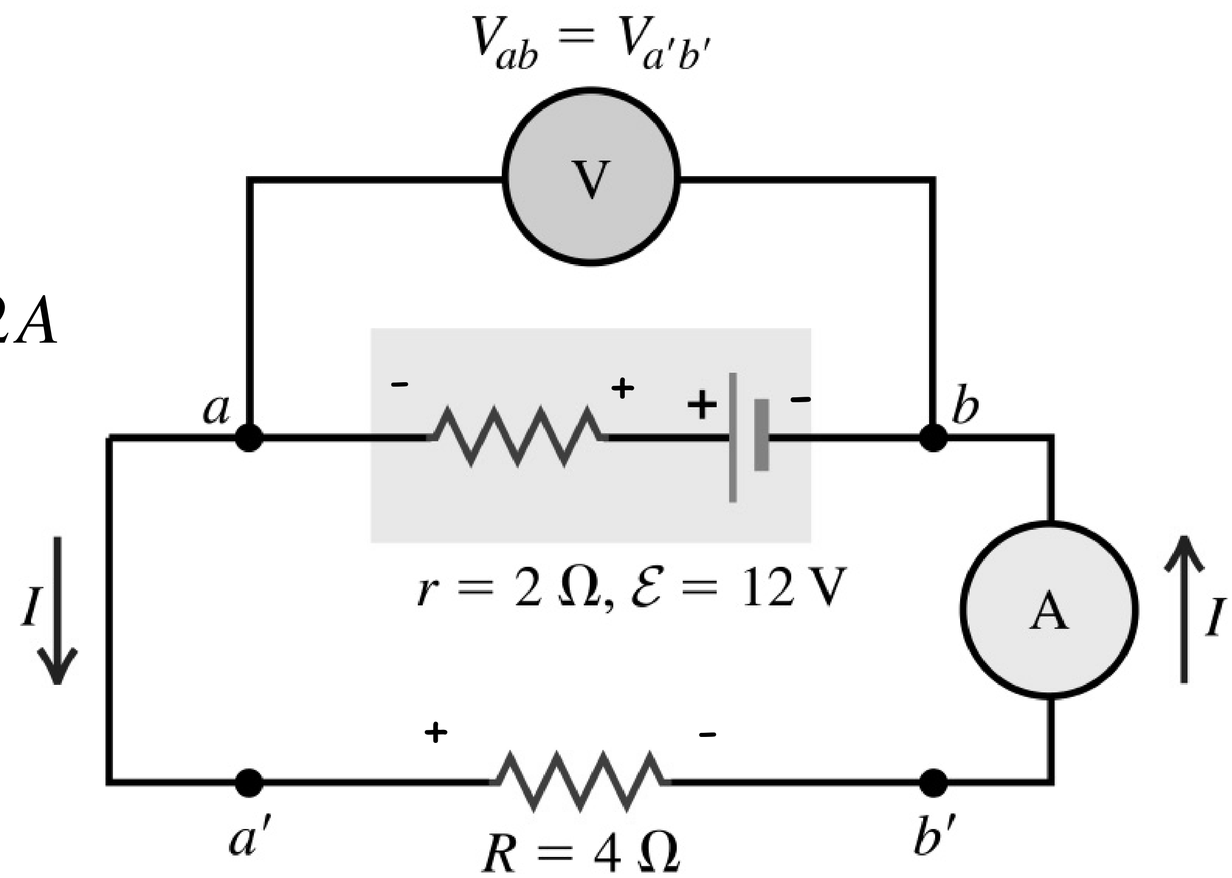
Real Battery with 12 volts and an internal resistance of 2Ω in a circuit with a resistor of 4Ω

$$V_{AB} = V_{A'B'}$$

$$\varepsilon - Ir = IR$$

$$I(R + r) = \varepsilon$$

$$I = \frac{\varepsilon}{R + r} = \frac{12V}{6\Omega} = 2A$$



Voltage drop across 2 Ω is 4 volts

Voltage drop across 4 Ω is 8 volts

V_{ab}= $V_{a'b'}$ = 8 volts

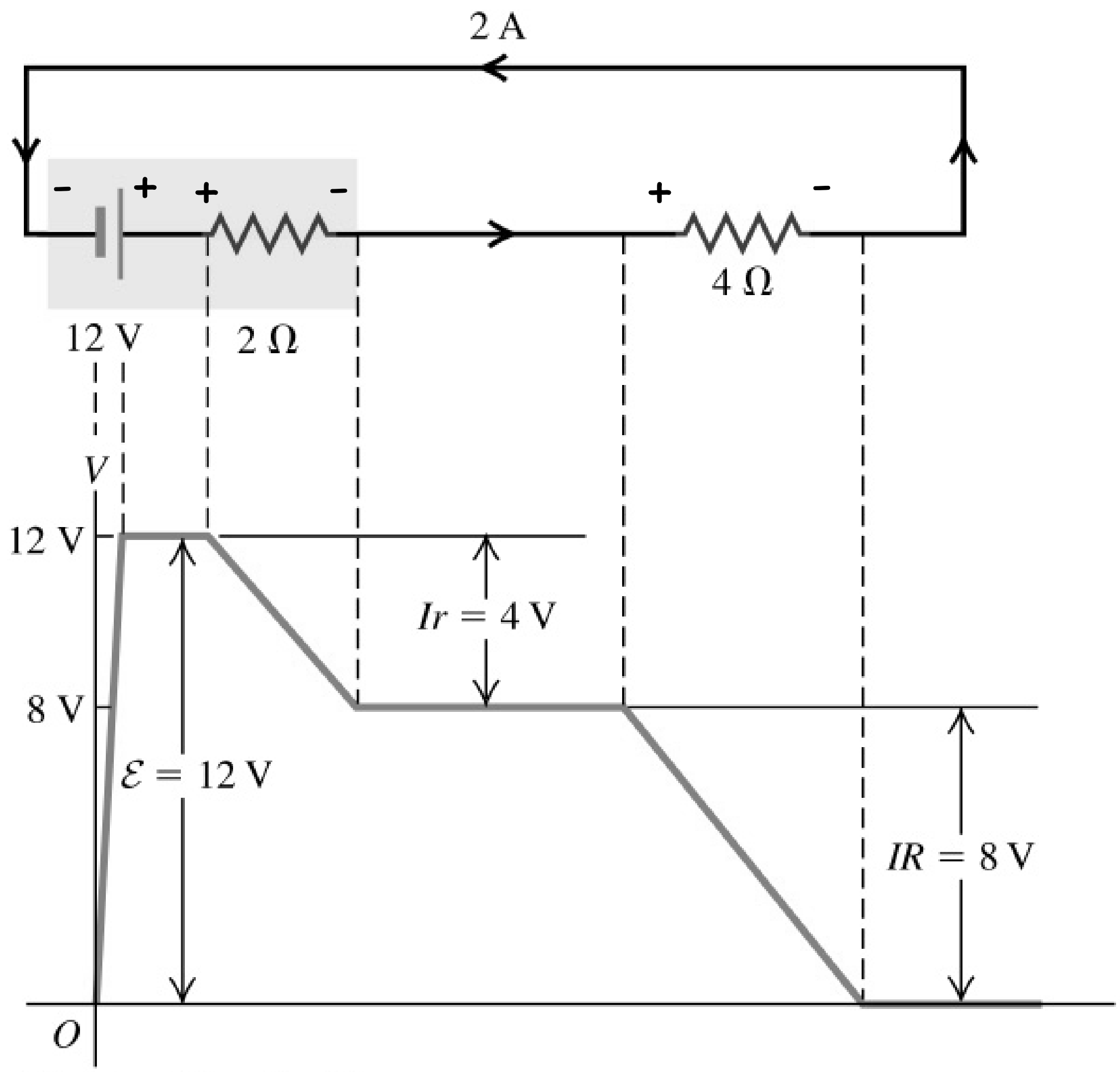
Terminal potential difference V_{AB} = 12 – 4 = 8 V

Diagram of Electric Potential/Voltage in the circuit

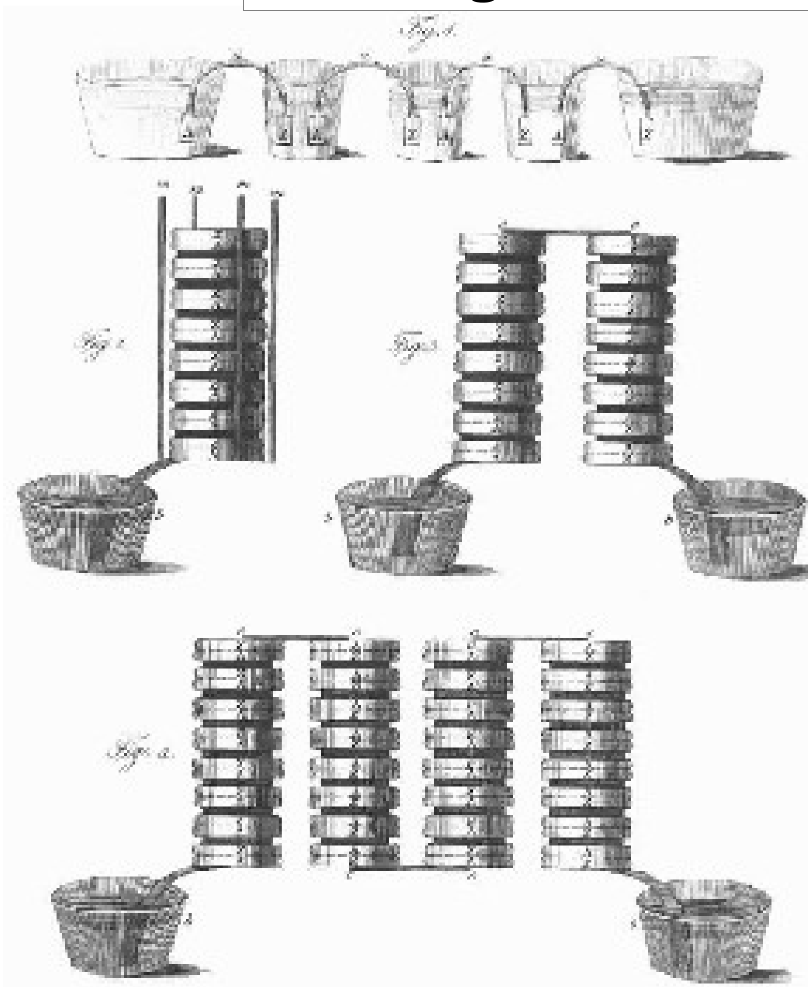
Voltage drop across 2 Ohms is 4 volts

Voltage drop across 4 Ohms is 8 volts

NOTE 4Ω resistor has only 8 of the 12 volts.



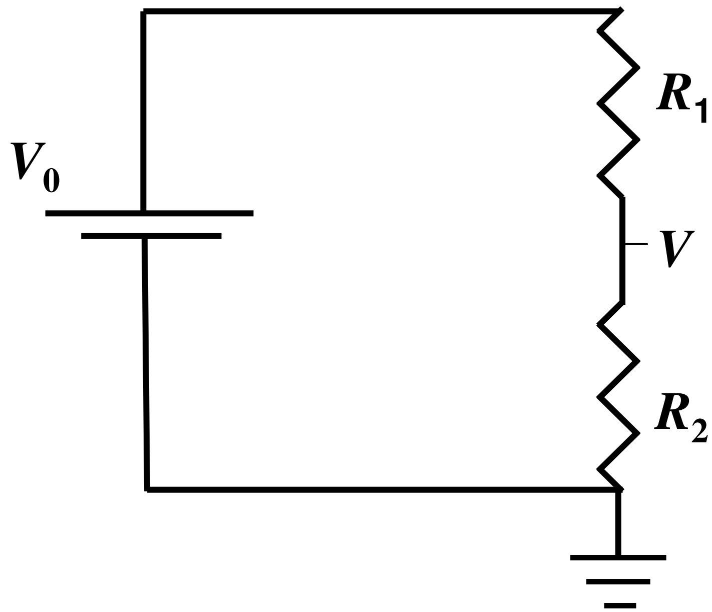
Drawing of Volta's Pile or Battery



Demonstrating before Napoleon

Manuscript on the invention of the battery sent to the Royal Society of London. Cardboard soaked in salt water was placed in between the zinc and silver disks.

The World's Simplest (and most useful) circuit: Voltage Divider



$$V = ?$$

$$V = IR_2 = \left(\frac{V_0}{R_1 + R_2}\right) R_2$$

$R_2 << R_1$ V=0

$R_2 = R_1$ $V = \frac{V_0}{2}$

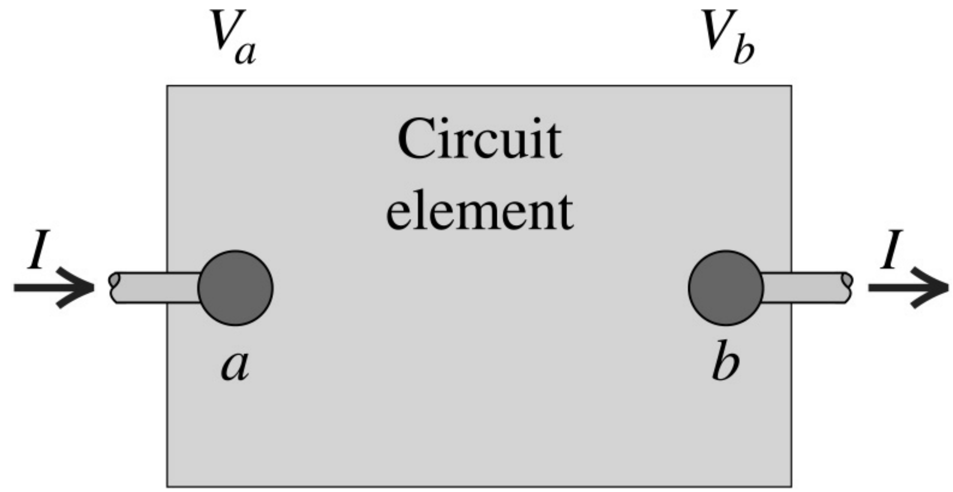
$R_2 >> R_1$ $V = V_0$

By varying R_2 we can controllably adjust the output voltage!

Power

Very important

Suppose we have a circuit element that has a voltage drop of $V_{ab} = V_a - V_b$ and a current flow of I.



What is the change in potential energy in this circuit element?

$$dU = (V_{ab})\, dq$$

What is the time rate change in potential energy in this circuit element?

$$P = \frac{dU}{dt} = (V_{ab})\frac{dq}{dt} = (V_{ab})\ I$$

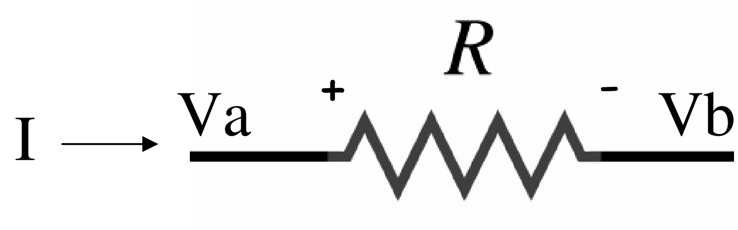
Power, P, is the time rate change in energy and equals voltage $\times$ current

$$P = (V_{ab})\ I$$

Units = voltage-amps = Watts

Power

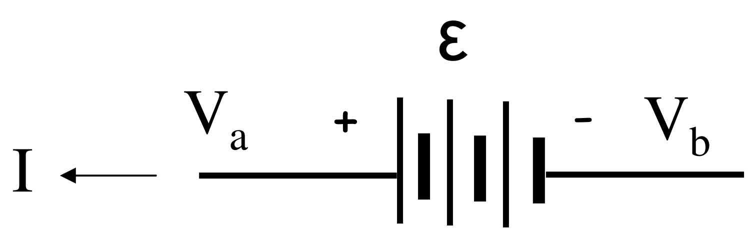
Resistor



Power $P = I\,(Va - Vb) = IV = I\,(IR) = I^2R = V^2/R$

Electrical power converted to Joule heat.

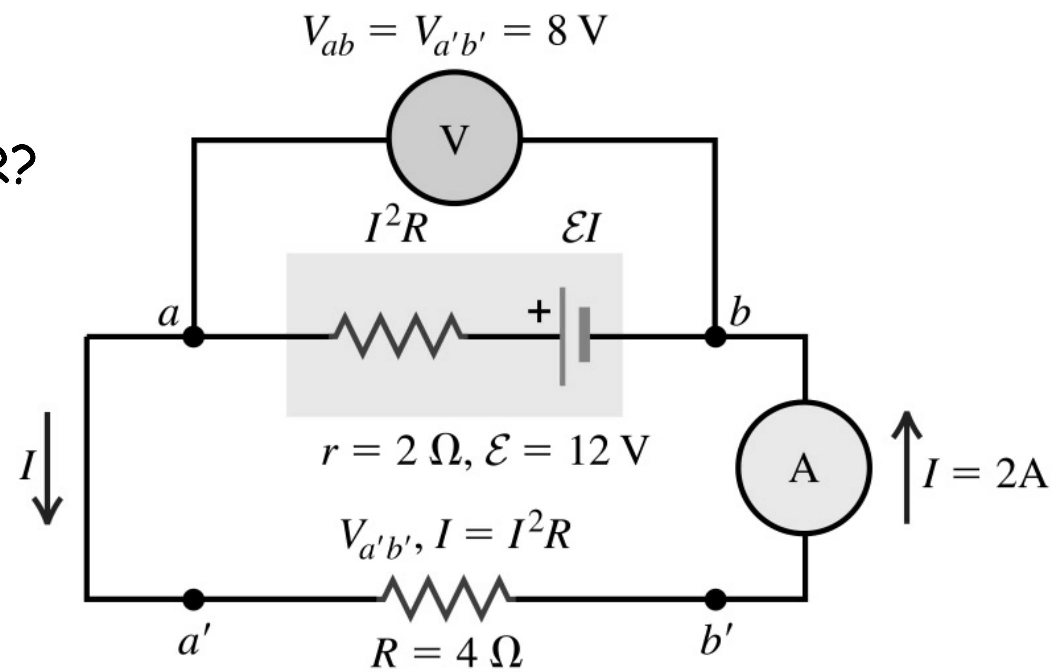
EMF



Power $P = I\,(Va - Vb) = I\,\varepsilon$

Electrical power can be + or – depending on direction of I.

Power Example of Battery and resistor



What is the power in resistor R?

$$I^2R = 2*2 * 4 = 16W$$

What is the power in internal resistance r?

$$I^2 r = 2*2 * 2 = 8W$$

What is the rate of energy conversion of the battery?

$$\mathcal{E} I = 12 * 2 = 24 \text{ W}$$

=> Energy conversion rate equals sum of power in both R and r

Y&F Problem 25.49

The capacity of a storage battery in your car is rated in amp-hours. A 12 volt battery rated at 50·A · h, can supply 50 amps for 1 hour at 12 volts or 25 amps for 2 hours etc.

A.) What is the total energy supplied by this battery?

$$P = \frac{dU}{dt} = IV = (50A)(12V) = 600W$$

$$U = Pt = (600W)(1hr)(3600s/hr) = 2.16MJ$$

B.) if a electric battery charger supplies 0.45 kW, how long does it take to fully charge a dead battery?

$$U = Pt$$

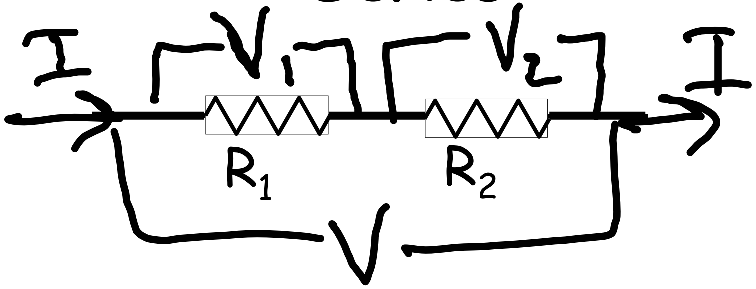
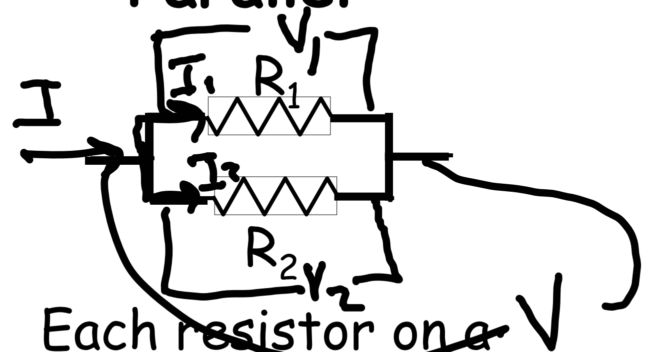
$$t = U/P = (2.16MJ)/0.45kW)$$

$$= 4680s = 78m$$

Georg Simon Ohm (1789-1854)

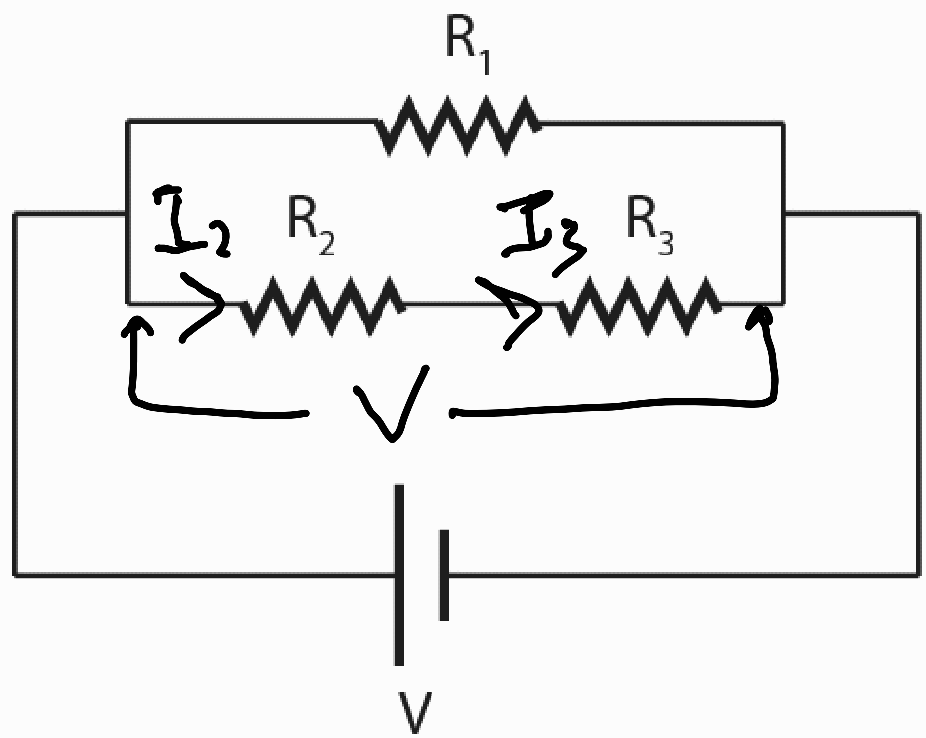
Born in Bavaria. At the university in 1805, he spent too much time dancing, ice skating and playing billiards and left after 3 semesters. Eventually he returned and graduated in 1811. He taught in various high schools and studied privately. He published *Die galvanische Kette, mathematisch bearbeitet* (1827) where his famous law was described. He had difficulty obtaining a university position, but eventually he was recognized by the Royal Society and other academies. In the last 2 years of his life, he was professor at the University of Munich.

How to combine resistors

	Series	Parallel
		
Wiring	Each resistor on the <u>same</u> wire.	Each resistor on a <u>different</u> wire.
Voltage	<u>Different</u> for each resistor. $V_{total} = V_1 + V_2$	<u>Same</u> for each resistor. $V_{total} = V_1 = V_2$
Current	<u>Same</u> for each resistor $I_{total} = I_1 = I_2$	<u>Different</u> for each resistor $I_{total} = I_1 + I_2$
Resistance	<u>Increases</u> $R_{eq} = R_1 + R_2$	<u>Decreases</u> $1/R_{eq} = 1/R_1 + 1/R_2$

Clicker problem

6) Three resistors are connected to a battery with emf V as shown. The resistances of the resistors are all the same, i.e. $R_1 = R_2 = R_3 = R$.

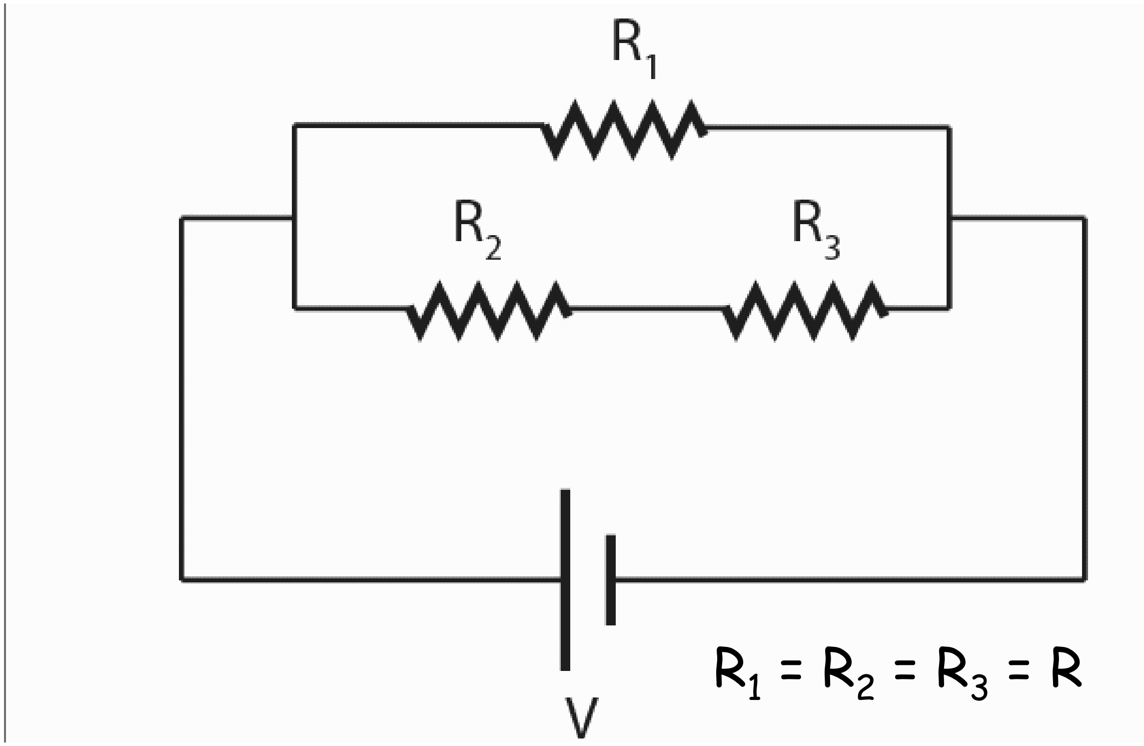


Compare the current through R_2 with the ~~current through~~ R_3

a) $I_2 > I_3$ b) $I_2 = I_3$ c) $I_2 < I_3$

R_2 in series with R_3 ⇒ Current through R_2 and R_3 is the same

$$I = V/(R_1 + R_2)$$



Analyze this

$R_1 = R_2 = R_3 = R$

Compare the current through R_1 with the current through R_2

$I_1/I_2 = 1/2$

$I_1/I_2 = 1/3$

$I_1/I_2 = 1$

$I_1/I_2 = 2$

$I_1/I_2 = 3$

Compare the voltage across R_2 with the voltage across R_3

$V_2 > V_3$

$V_2 = V_3 = V$

$V_2 = V_3 < V$

$V_2 < V_3$

Compare the voltage across R_1 with the voltage across R_2

$V_1 = V_2 = V$

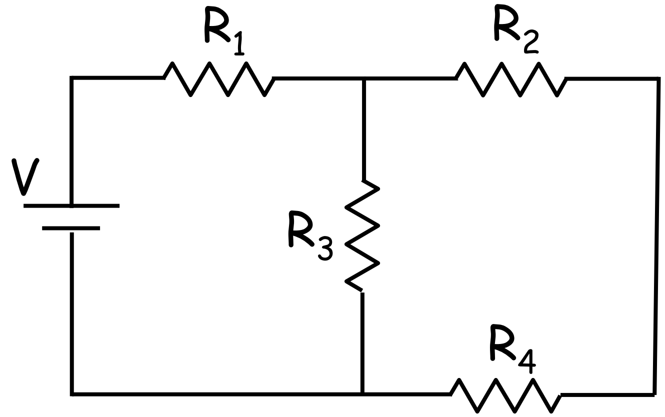
$V_1 = \frac{1}{2} V_2 = V$

$V_1 = 2V_2 = V$

$V_1 = \frac{1}{2} V_2 = 1/5\ V$

$V_1 = \frac{1}{2} V_2 = \frac{1}{2} V$

How do we handle complex problems ?



In the circuit shown: V = 18V, $R_1 = 1\Omega$, $R_2 = 2\Omega$, $R_3 = 3\Omega$, and $R_4 = 4\Omega$.

What is V_2, the voltage across R_2?

- Conceptual Analysis:
  - Ohm's Law: when current *I* flows through resistance *R*, the potential drop *V* is given by: $V = IR$.
  - Resistances are combined in series and parallel combinations
    - $R_{series} = R_a + R_b$
    - $(1/R_{parallel}) = (1/R_a) + (1/R_b)$

Divide and Conquer

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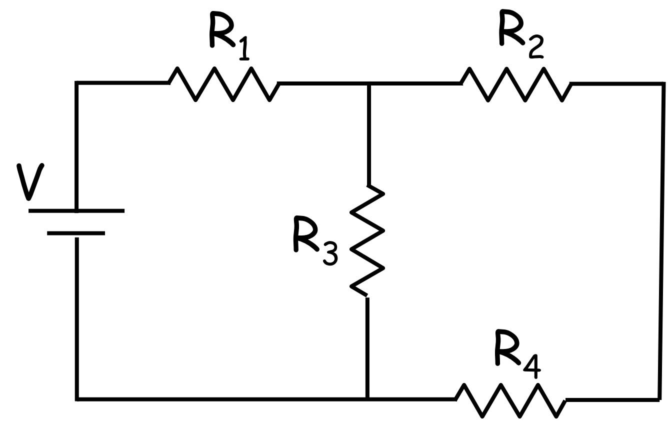
Clicker example



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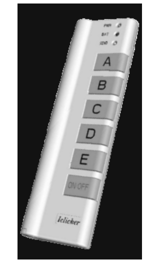


BB

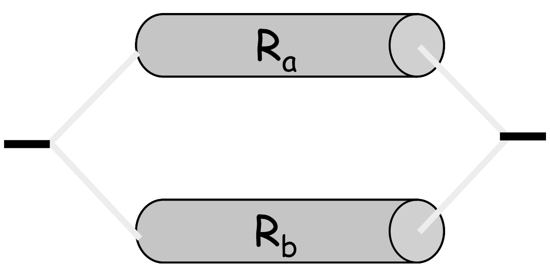
What is V_2, the voltage across R_2?

- Combine Resistances:

R_1 and R_2 are connected:

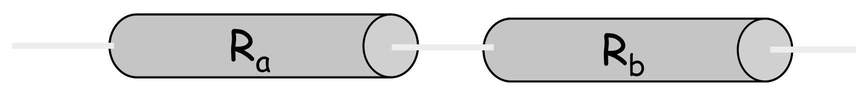
(A) in series (B) in parallel (C) neither in series nor in parallel

Parallel Combination



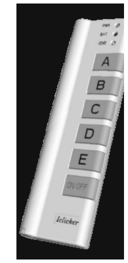
Parallel: Can make a loop that contains only those two resistors

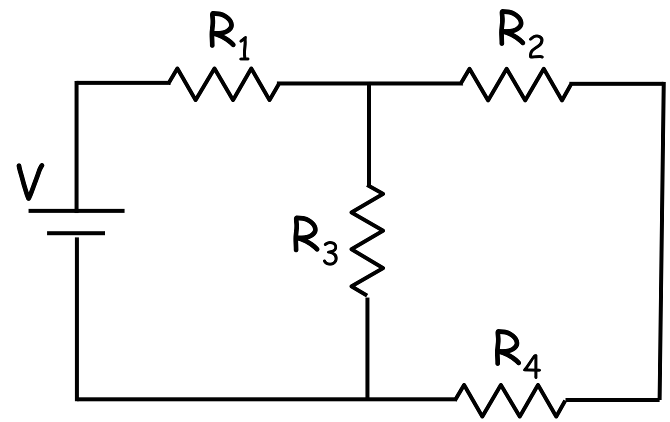
Series Combination



Series : Every loop with resistor 1 also has resistor 2.

Clicker Problem


BB



In the circuit shown: V = 18V, $R_1 = 1\Omega$, $R_2 = 2\Omega$, $R_3 = 3\Omega$, and $R_4 = 4\Omega$.

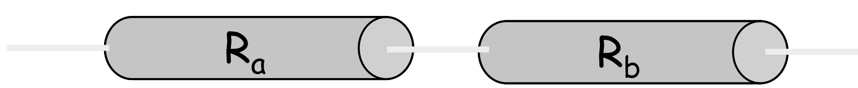
What is V_2, the voltage across R_2?

- Combine Resistances:

R_2 and R_4 are connected:

(A) in series (B) in parallel (C) neither in series nor in parallel

Series Combination



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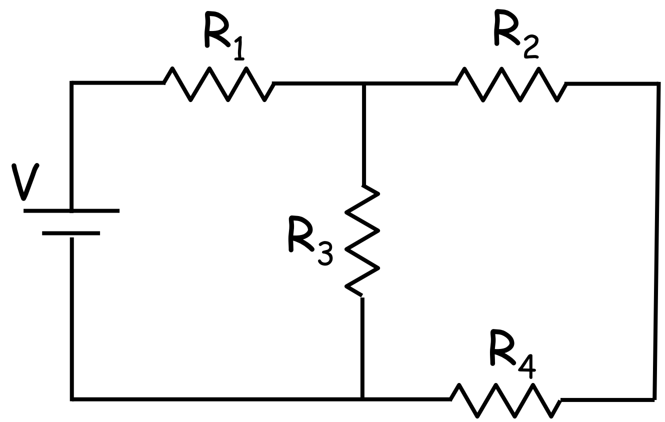
Clicker problem



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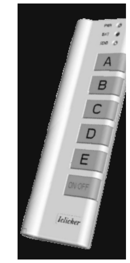
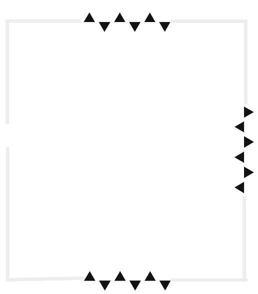


BB

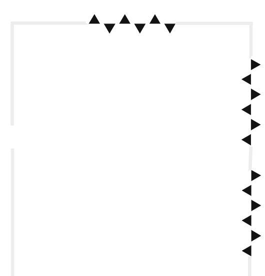
- Combine Resistances:

Redraw the circuit using the equivalent resistor R_{24} = series combination of R_2 and R_4.

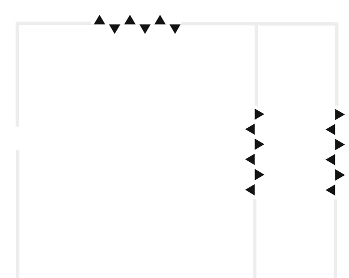
R_2 and R_4 are connected in series = $R_{24} = 2 + 4 = 6\ \Omega$



(A)



(B)



(C)

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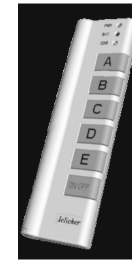
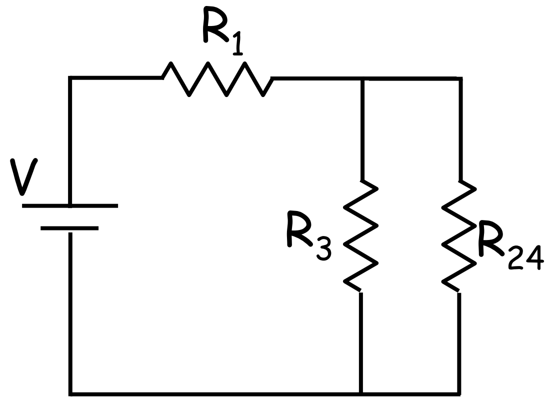
Clicker example





In the circuit shown: $V = 18V$, $R_1 = 1\Omega$, $R_2 = 2\Omega$, $R_3 = 3\Omega$, and $R_4 = 4\Omega$.

$R_{24} = 6\Omega$

What is V_2, the voltage across R_2?

- Combine Resistances:

What is the value of R_{234}?

(A) $R_{234} = 1\ \Omega$ (B) $R_{234} = 2\ \Omega$ (C) $R_{234} = 4\ \Omega$ (D) $R_{234} = 6\ \Omega$

R_2 and R_4 are connected in series = R_{24}
R_3 and R_{24} are connected in parallel = R_{234}

$(1/R_{parallel}) = (1/R_a) + (1/R_b)$ ⇨ $1/R_{234} = (1/3) + (1/6) = (3/6)\ \Omega^{-1}$

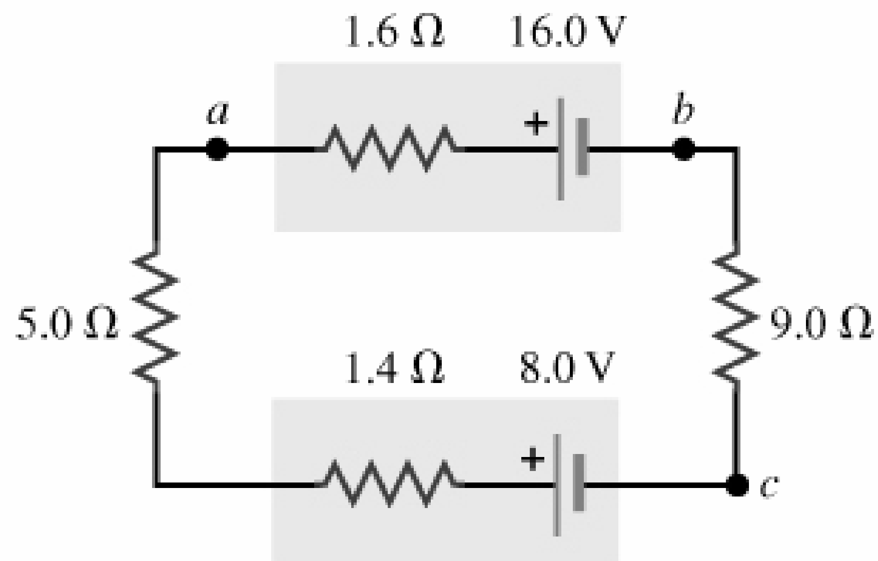
⇨ $R_{234} = 2\ \Omega$

→

Y&F 25.36

The circuit shown in the figure contains two batteries, each with an emf and an internal resistance, and two resistors.

A) Find the direction and magnitude of the current in the circuit
B) Find the terminal voltage Vab of the 16.0-V battery.
C) Find the potential difference Vbc of point b with respect to point c .



Y&F 25.36 (not a clicker problem)

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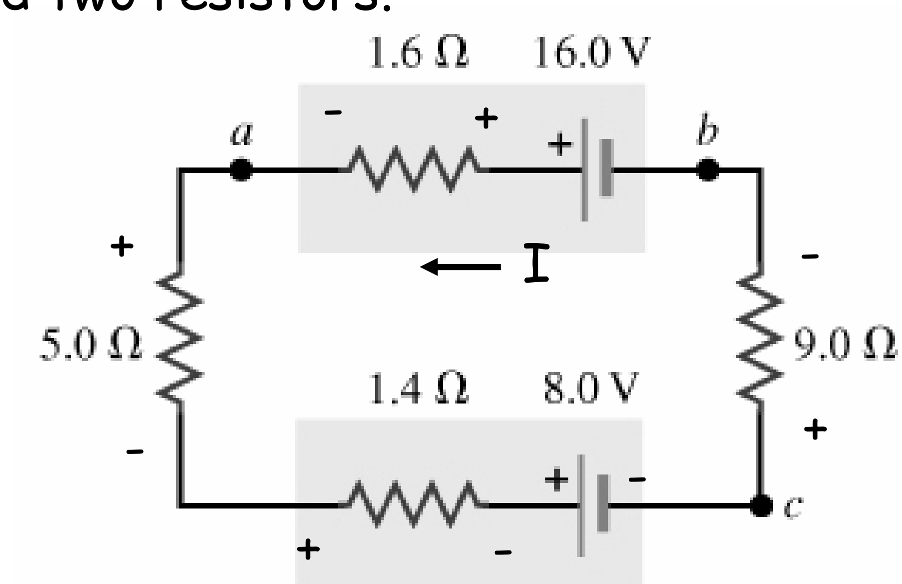


A.) Use Kirchoff's loop law:

$$16V - 1.6\Omega I - 5.0\Omega I - 1.4\Omega I - 8V - 9.0\Omega I = 0$$

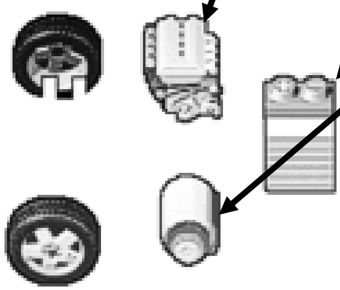
$$8V - 17\Omega I = 0$$

$$I = \frac{8}{17}A = 0.471A$$

B.) V_{ab} = 16V – I(1.6 Ω) = 16V – (0.471 A)(1.6 Ω) = 15.2 V

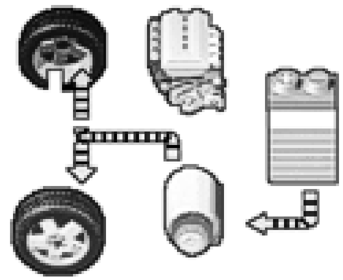
C.) V_{bc} = – I(9.0 Ω) = – (0.471 A)(9.0 Ω) = -4.24 V

Prius – hybrid car and “energy machine”.



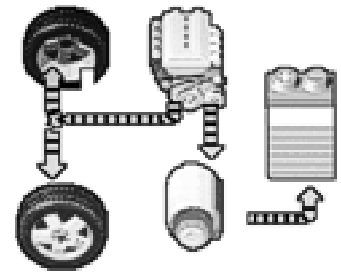
Standby

While waiting at a stoplight, the engine will shut off. The resulting silence and lack of vibration is a pleasure that adds to the driving experience.



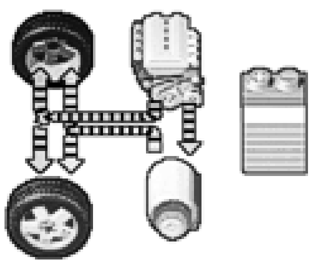
Battery Only

Propulsion is sometimes provided exclusively using the electric motor & battery-pack. The engine can shut off during this time.



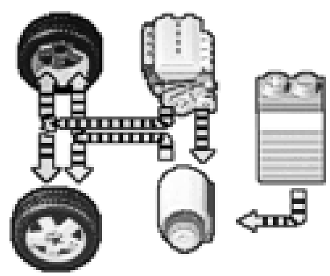
Highway Cruising

This is the most common behavior while traveling at a constant speed on the highway. This electrical activity often surprises those researching how Prius operates.



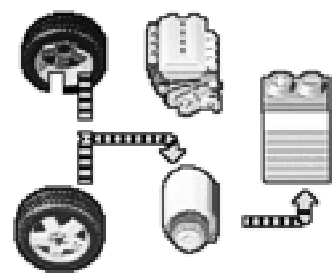
Moderate Acceleration

This configuration is very common when acclerating, including when you need to merge onto a highway. This is also the method Prius uses to climb most hills.



Full Power & Slowing

This mode occurs in 2 very different situations, when maximum thrust is needed and when gradual slowing occurs.



Regenerating

When you step on the brake or remove your foot from the accelerator, the system will automatically convert the kinetic energy to electricity for the battery-pack.

Prius – hybrid car

Battery Pack
- 99 lbs
- NiMH
- 168 cells
- 1.2 V each cell
- <u>6.5 Ah total</u>
- <u>201.6 V total</u>

Electric Motor
- <u>50 kW power</u>
- 67 hp at 1200 – 1540 rpm
- 500 V maximum

Rated MPG
- 60 city
- 51 highway

Gas Engine
- 1.5 L
- 4 cylinder – 16 valve
- 76 HP at 5000 RPM

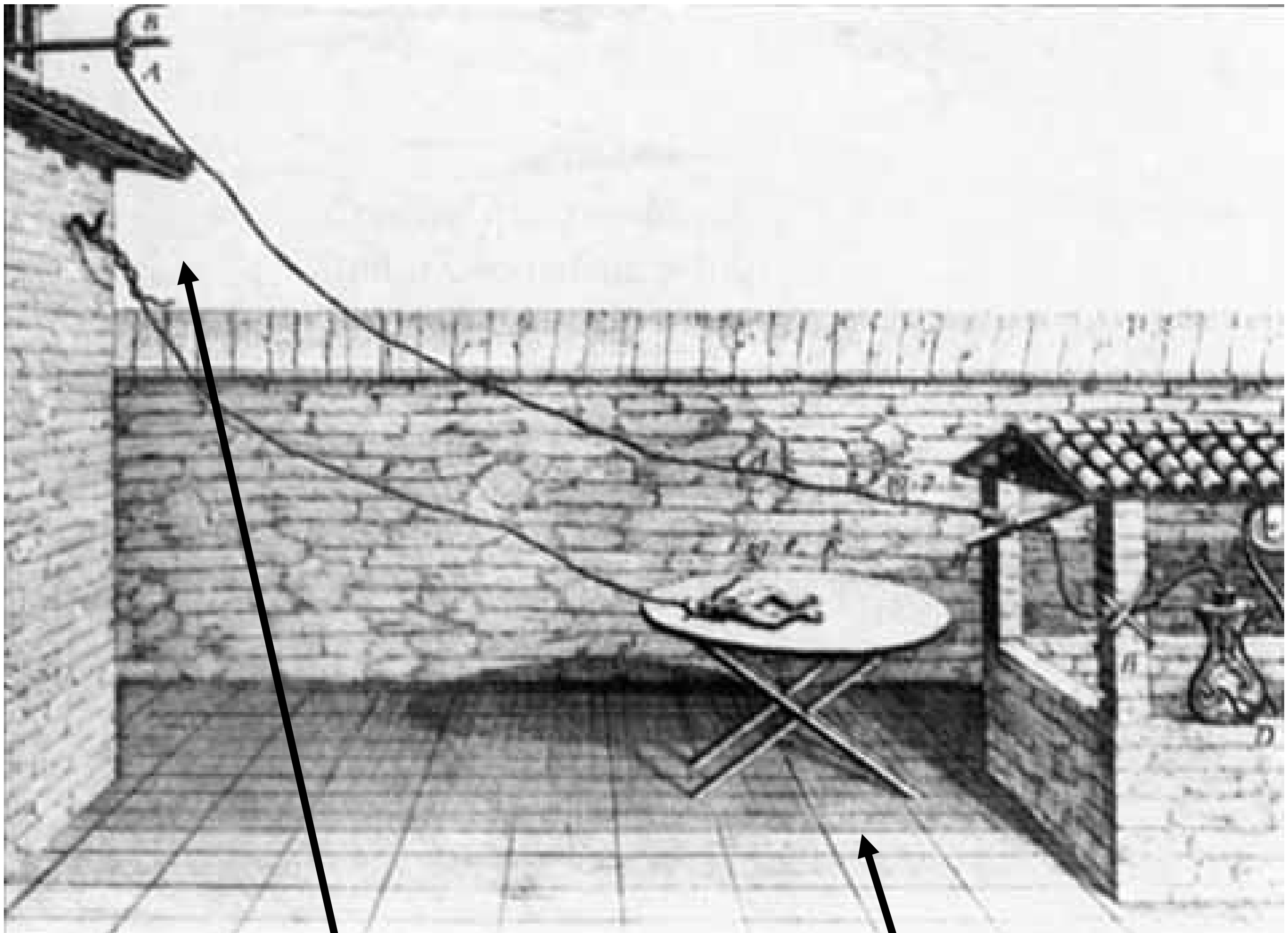
Brakes
- regenerative (primary)
- hydraulic (secondary)
- ABS (anti lock)

Early History of Current and Batteries

The development of the battery has a curious history. Henry Cavendish studied sting rays (called Torpedoes) to investigate how they created electricity around 1776. Around ~1790, Luigi Galvani applied current to frog's legs and observed them twitching. He believed there was an "animal electricity" stored in the frog's brain. About 1800, Allesandro Volta, invented the "pile", a series of silver and zinc disks in salt water. Volta tested his electricity by attaching electrodes to his tongue and eventually demonstrated his pile before Napoleon.

In 1803, George Forster, a convicted murdered was hanged at Newgate prison, and Galvani's nephew, Giovanni Aldini, applied current from a Volta pile to the corpse causing the jaws, eyes, hands and legs to move. This process of resuscitation was eventually applied to drowning victims. This created philosophical and religious controversy about life, death and electricity. This gave Mary Shelley the idea for the 1818 novel, Frankenstein, about a corpse brought to life by electricity.

Drawing of one of Luigi Galvani's experiments



Leyden Jar

lightning rod attached to froggy!!