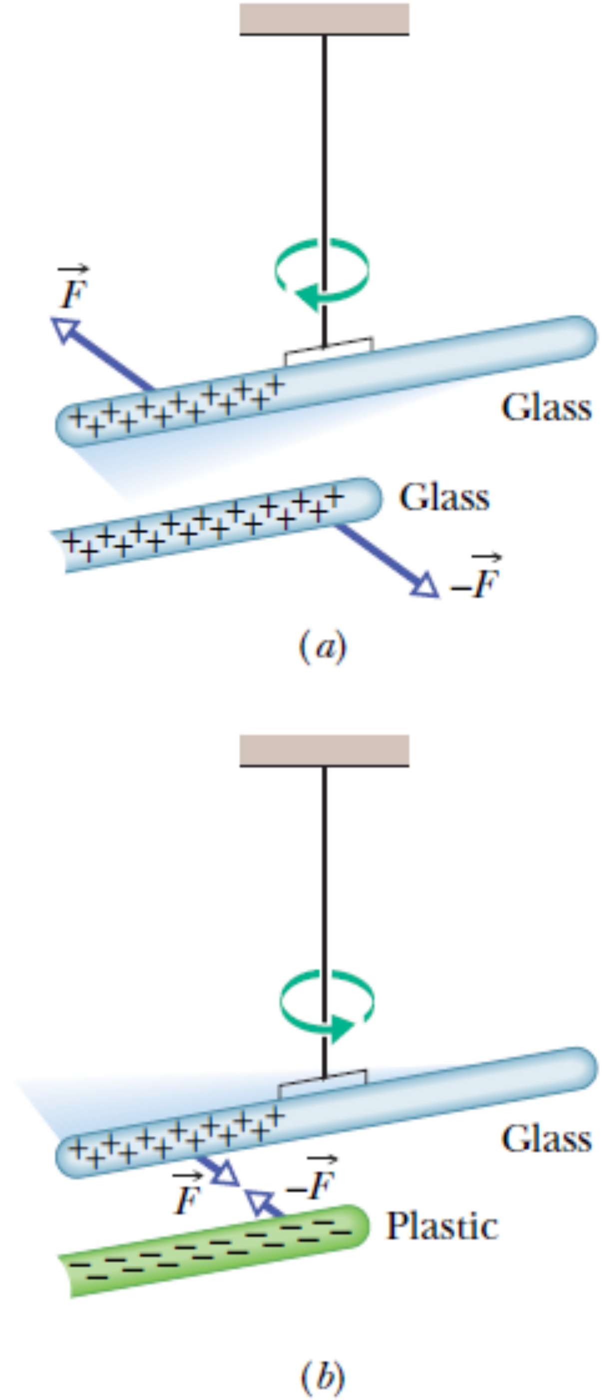
Energy and Electricity and Magnetism

Electric Charge

- Greeks
  - Rubbing amber = attract straw
  - Certain types of stone attract bits of iron
  - Why?
- Electric charge
  - Intrinsic to everything in the world
  - Two kinds of charges, positive (+) and negative (-), designated by Benjamin Franklin
  - Electrically neutral - object with equal positive and negative charge



Conductors and Insulators

1. **Conductors** are materials through which charge can move freely; examples include metals (such as *copper in common lamp wire), the human body, and tap water*.

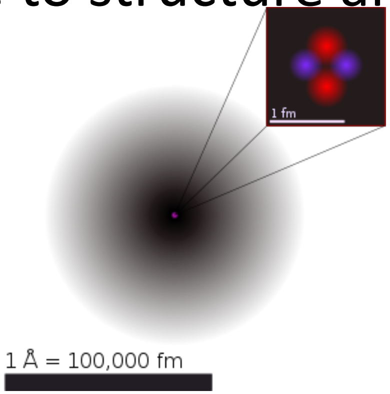
2. **Nonconductors—**also called insulators—are materials through which charge cannot move freely; examples include *rubber, plastic, glass, and chemically pure water.*

3. **Semiconductors** are materials that are intermediate between conductors and insulators; examples include *silicon and germanium in computer chips.*

4. **Superconductors** are materials that are perfect conductors, allowing charge to move without any hindrance.

Conductors and Insulators

- Properties of conductors and insulators are due to structure and electrical nature of atoms
- Atoms
  - positively charged ***protons***
  - negatively charged ***electrons***
  - electrically neutral ***neutrons***
  - The protons and neutrons are packed tightly together in a central nucleus



- Conductor
  - some of outermost (and so most loosely held) electrons become free to wander about within the solid
  - leaving behind positively charged atoms (*positive ions).*
  - We call the mobile electrons ***conduction, or free, electrons.***
- There are few (if any) free electrons in a insulator.

Coulomb's Law

- The equation giving the force for charged particles is called **Coulomb's law**:

$$\vec{F} = k\frac{q_1 q_2}{r^2}$$

  - particle 1 has charge q_1
  - particle 2 has charge q_2
  - F is the force on particle 1 by particle 2
  - r is the distance between them
  - k is the electrostatic constant

$$k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9\,\mathrm{N\cdot m^2/C^2}.$$

  - The quantity ε_0 is called the ***permittivity of free space.***
- The SI unit of charge is the ***coulomb* (C),** named for Chris Coulomb.

Concept Question

Which one of the following statements concerning the electric force is true?

a) Two charged objects with identical charges will exert an attractive force on one another.

b) It is possible for a small negatively-charged particle to float above a negatively charged surface.

c) A positively-charged object is attracted toward another positively-charged object.

d) The electric force cannot alter the motion of an object.

e) Newton's third law of motion does not apply to the electrostatic force

Example Problem

Imagine two conducting spheres separated by two meters. Each sphere carries an excess charge of 0.5 C. What is the magnitude of the electrostatic force that each sphere exerts on the other?

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Let's start with the equation: $\vec{F} = k\frac{q_1 q_2}{r^2}$

And now for the givens:

r = 2 m

q1 = 0.5 C

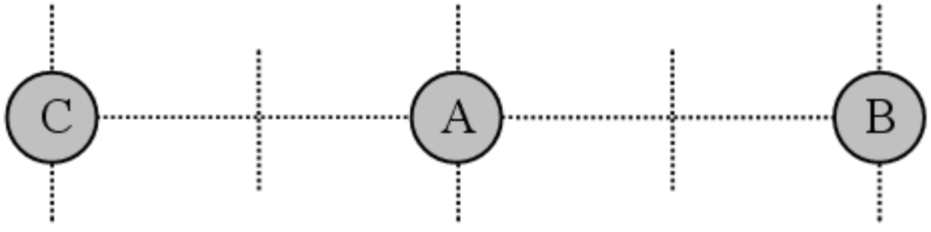
q2 = 0.5 C

$F = 8.99 \times 10^9 * (0.5\ C * 0.5\ C) / (2m)^2$

$F = 5.62 \times 10^8$ N or 562,000,000 N

Concept Question

A charged particle, labeled A, is located at the midpoint between two other charged particles, labeled B and C, as shown. The sign of the charges on all three particles is the same. When particle A is released, it starts drifting toward B. What can be determined from this behavior?



a) The charge on A is larger than the charge on B.
b) The charge on A is larger than the charge on C.
c) The charge on C is larger than the charge on B.
d) The charge on B is larger than the charge on A.
e) The charge on B is larger than the charge on C.

Charge is Quantized

- The total charge for a system is always integer multiples of an elementary charge (e).

$$q = ne, \qquad n = \pm 1, \pm 2, \pm 3, \ldots,$$

- The magnitude of this elementary charges the same for both protons and electrons:

$$e = 1.602 \times 10^{-19}\ \text{C}.$$

- Elementary particles either carry no charge, or carry a single elementary charge.
- When a physical quantity such as charge can have only discrete values, rather than any value, we say the quantity is **quantized.**
- It is possible, For example, to find a particle that has no charge at all, or a charge of +10e, or -6e, but not a particle with a charge of, say, 3.57e.

The Charges of Three Particles

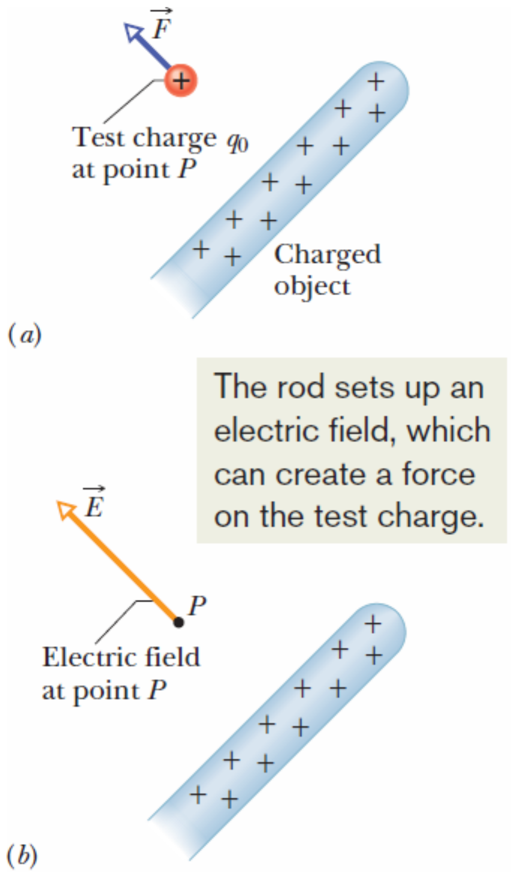
Particle	Symbol	Charge
Electron	e or e^-	$-e$
Proton	p	$+e$
Neutron	n	0

Charge is Conserved

- If one rubs a glass rod with silk, a positive charge appears on the rod. Measurement shows that a negative charge of equal magnitude appears on the silk. This suggests that rubbing does not create charge but only transfers it from one body to another, upsetting the electrical neutrality of each body during the process.
- This hypothesis of conservation of charge has stood up under close examination, both for large-scale charged bodies and for atoms, nuclei, and elementary particles.
- An example is in radioactive decay of nuclei, in which a nucleus transforms into (becomes) a different type of nucleus. A uranium-238 nucleus (^{238}U) transforms into a thorium- 234 nucleus (^{234}Th) by emitting an *alpha particle.* An alpha particle has the same makeup as a helium-4 nucleus, it has the symbol ^{4}He. Here the net charge is 238.

$$^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{Th} + {}^{4}\mathrm{He},$$

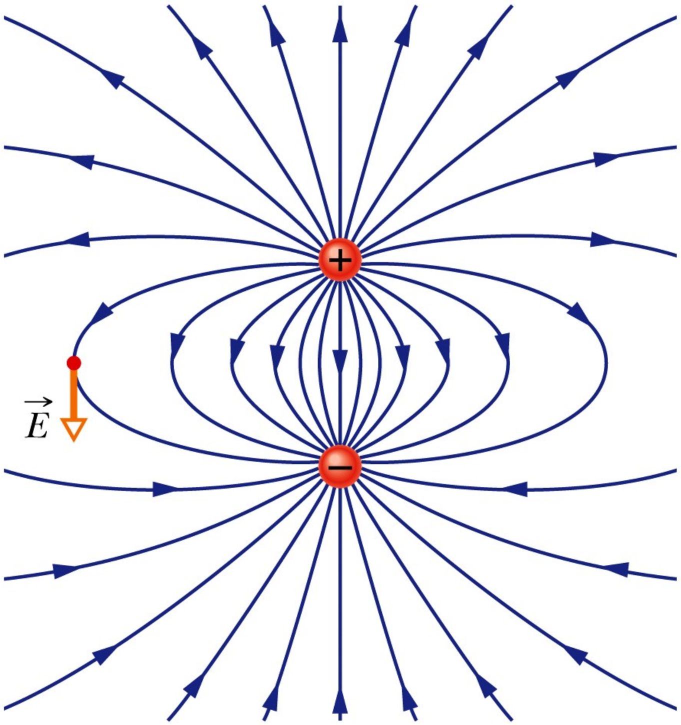
Electric Field due to a Point Charge



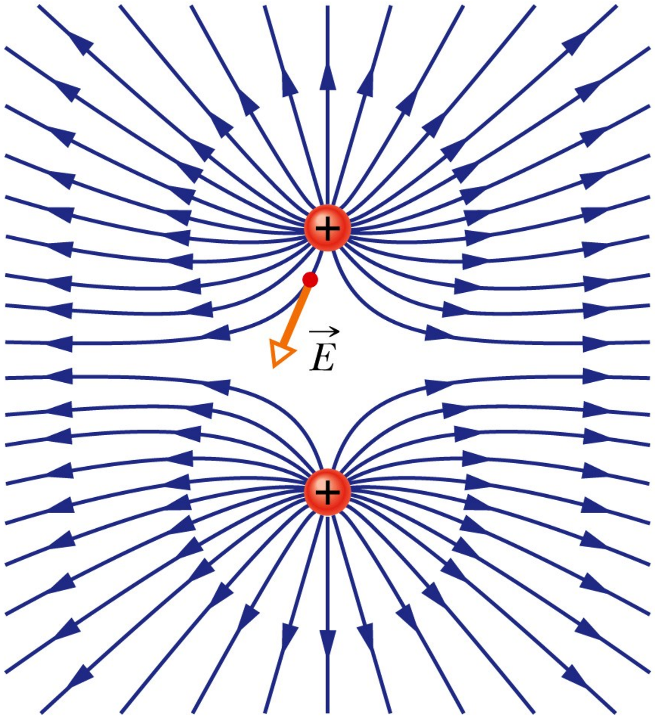
$$\vec{E} = \frac{\vec{F}}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$$

- We can define the electric field at some point near the charged object, such as point *P* in figure (a), as follows:
  - A positive test charge q_0, placed at the point will experience an electrostatic force, **F**.
  - The electric field, **E**, at point *P* due to the charged object is defined as shown to the right.
  - The SI unit for the electric field is the newton per coulomb (N/C) or volt per meter (V/m).
- The direction of **E** is directly away from the point charge if *q* is positive, and directly toward the point charge if *q* is negative.

Electric Field



Field lines for an **electric dipole**, a positive and negative charged pair.



Field lines for two positive charges.

Concept Question

A positively charged object is located to the left of a positively charged object as shown. Electric field lines are shown connecting the two objects. The five points on the electric field lines are labeled A, B, C, D, and E. At which one of these points would a test charge experience the smallest force?

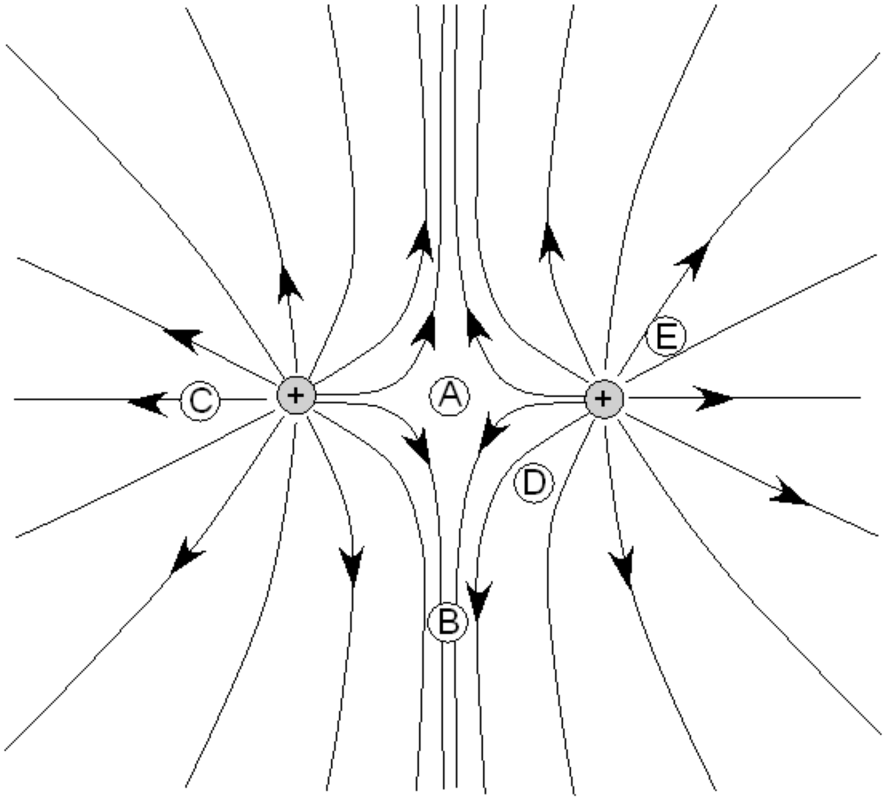
a) A

b) B

c) C

d) D

e) E



Example Problem

An electric force of 30 N is applied to a charge of q = +15 mC. What is the magnitude of the electric field produced?

What is the electric field 15 m from the charge?

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Let's start with our givens:

F = 30 N

q = +15 mC = 0.015 C

E = F/q = 30 N/ 0.015 C = 2,000 N/C

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What is the electric field 15 m from the charge?

Remember the $k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9 \, \mathrm{N \cdot m^2/C^2}.$

and $E = k\,q/r^2$

So, $E = 8.99 \times 10^9 * 0.015\ \mathrm{C}/(15^2) = 599{,}000\ \mathrm{N/C}$

Electric Potential

- The potential energy per unit charge at a point in an electric field is called the **electric potential *V (or simply the potential)*** at that point. This is a scalar quantity.
- The *electric potential difference V* between any two points *i* and *f* in an electric field is equal to the difference in potential energy per unit charge between the two points. Thus,

$$\Delta V = V_f - V_i = \frac{U_f}{q} - \frac{U_i}{q} = \frac{\Delta U}{q} = -\frac{W}{q} \quad \text{(potential difference defined).}$$

- The potential difference between two points is thus the negative of the work done by the electrostatic force to move a unit charge from one point to the other.
- The SI unit for potential is the joule per coulomb. This combination is called the *volt (abbreviated V).*

Concept Question

A uniform electric field is directed in the negative *x* direction. If you were to move a positive charge in the positive *x* direction, how would the total energy of the positive charge and the electric field system change, if at all?

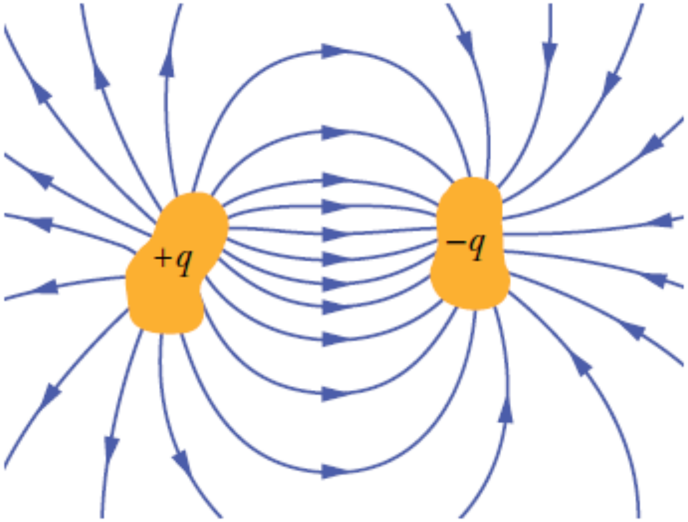
a. The total energy of the system would increase.

b. The total energy of the system would decrease.

c. The total energy of the system would remain unchanged.

Capacitance

- What is a capacitor?
  - Two conductors electrically isolated from each other
  - When charged, the charges on the conductors, or <u>plates</u>, have the same magnitude *q* but opposite sign, +q and –q
  - However, we refer to the charge of a capacitor as being *q*, the absolute value of these charges on the plates.



- The charge *q* and the potential difference *V* for a capacitor are proportional to each other:

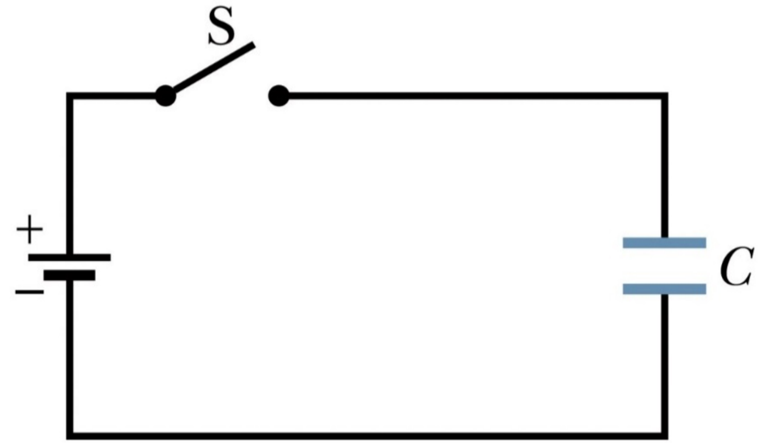
$$q = CV.$$

- The proportionality constant *C* is called the **capacitance** of the capacitor. Its value depends only on the geometry of the plates and not on their charge or potential difference.

- The SI unit is called the *farad (F):* **1 farad (1 F)= 1 coulomb per volt =1 C/V.**

Example Problem

The capacitor in the schematic has a capacitance of 25 mF and is initially uncharged. The battery provides a potential difference of 120 V. After switch *S* is closed, how much charge will pass through it?



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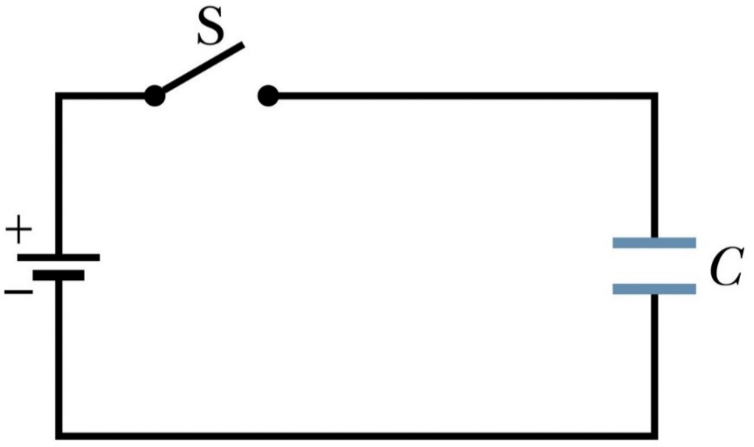


Let's write down out givens

C = 25 mF = 0.025 F

V = 120 V

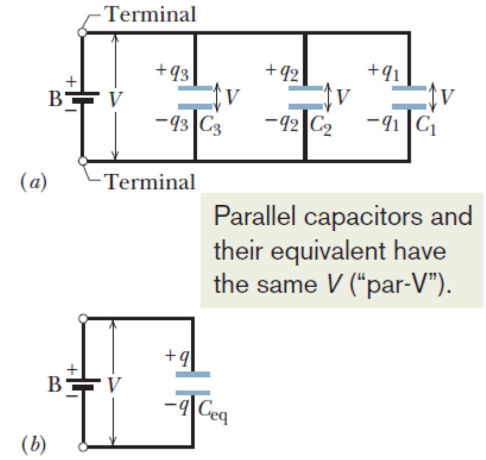
Q = CV

Q = 0.025 F* 120 V

Q = 3 C

Capacitors in Parallel

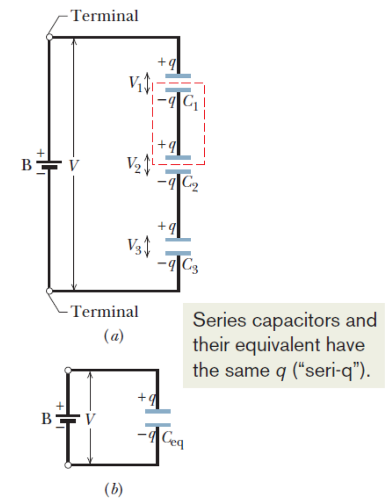
- When a potential difference *V* is applied across several capacitors connected in parallel, that potential difference *V* is applied across each capacitor.
- The total charge *q* stored on the capacitors is the sum of the charges stored on all the capacitors
- Capacitors connected in parallel can be replaced with an equivalent capacitor that has the same total charge *q* and the same potential difference *V* as the actual capacitors, figure (*b*)



$$C_{eq} = \sum_{j=1}^{n} C_j \qquad (n \text{ capacitors in parallel}).$$

Capacitors in Series

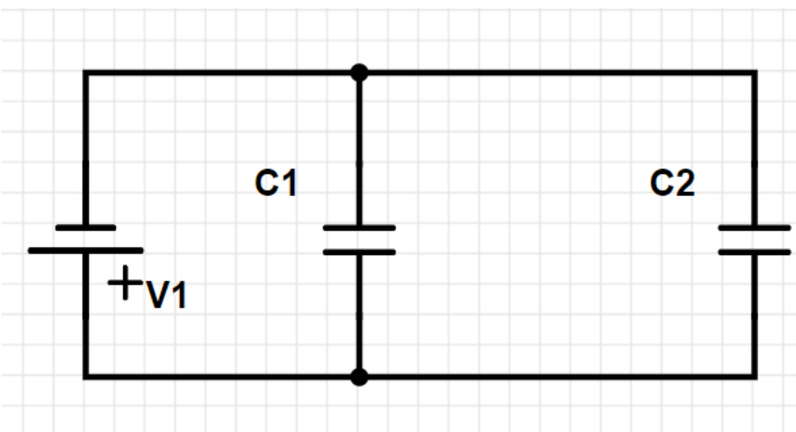
- When a potential difference V is applied across several capacitors connected in series, the capacitors have identical charge q
- The sum of the potential differences across all the capacitors is equal to the applied potential difference V
- Capacitors that are connected in series can be replaced with an equivalent capacitor that has the same charge q and the same total potential difference V as the actual series capacitors, figure (b)
- C_{eq} will be less then the sum of the individual capacitors.

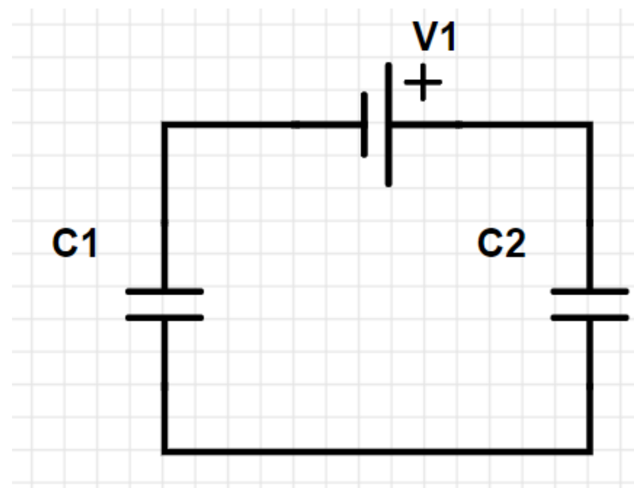


$$\frac{1}{C_{eq}} = \sum_{j=1}^{n} \frac{1}{C_j} \qquad (n \text{ capacitors in series}).$$

Example Problem

Find the equivalent capacitance for the combination of capacitors shown, across which potential difference *V* = 10 V is applied. Assume the C1 = 10 F and C2 = 25 F.





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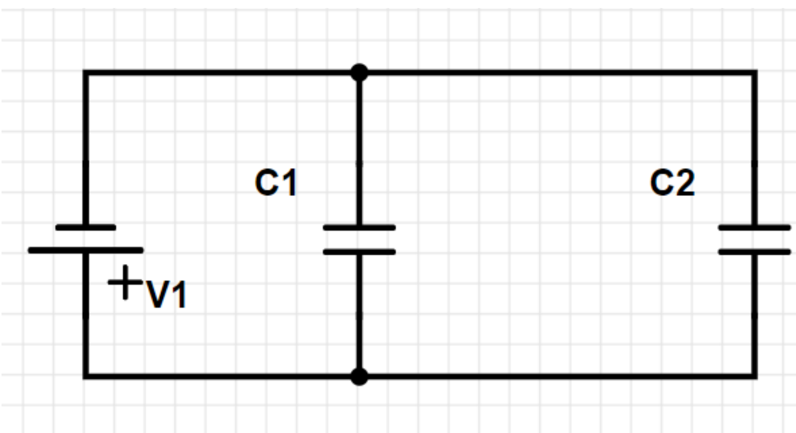
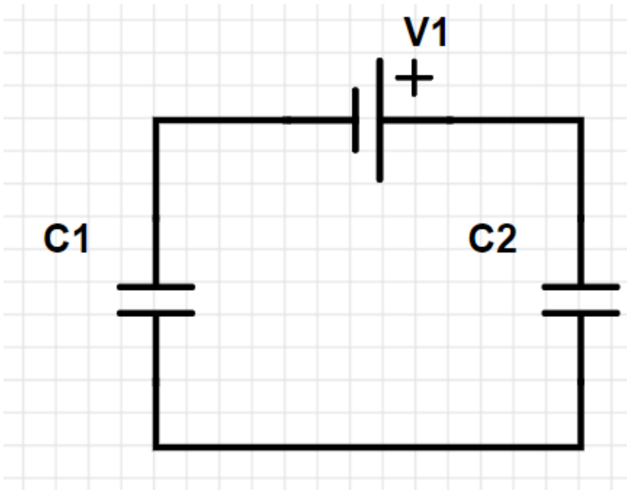
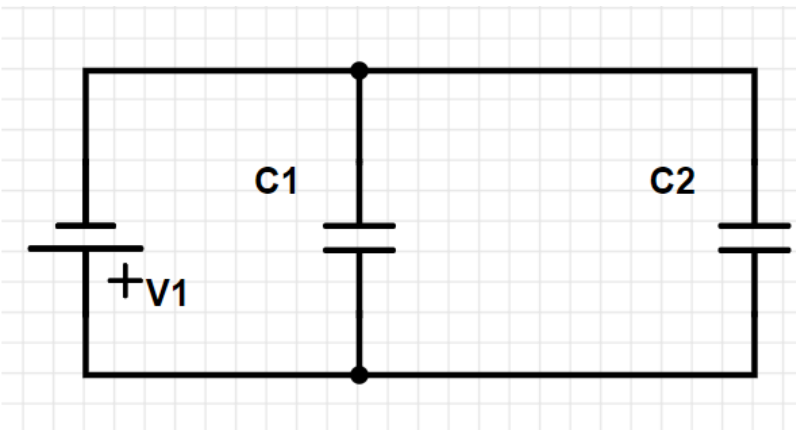


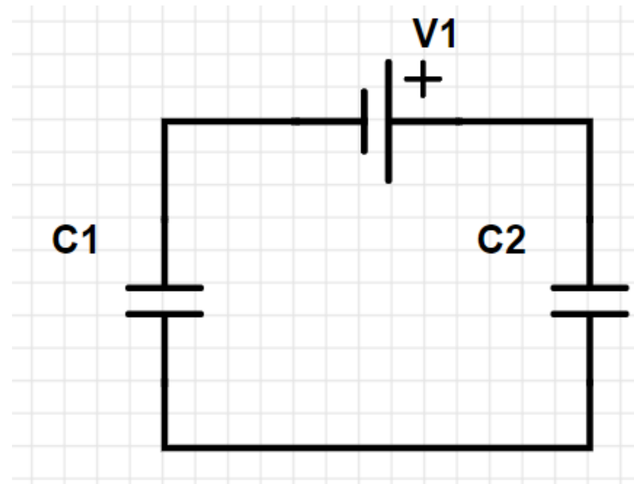


C_{eq} = C1 + C2 = 35 Ω

Example Problem

Find the equivalent capacitance for the combination of capacitors shown, across which potential difference V = 10 V is applied. Assume the C1 = 10 F and C2 = 25 F.





C_{eq} = C1 + C2 = 35 Ω

$1/C_{eq}$ = 1/C1+1/C2

$1/C_{eq}$ = 1/10 +1/25 = 0.10+0.04

$1/C_{eq}$ = 0.14

C_{eq} = 7.14 F

Energy Stored in an Electric Field

The potential energy of a charged capacitor may be viewed as being stored in the electric field between its plates.

$$U = \frac{q^2}{2C} \qquad \text{(potential energy).}$$

$$U = \tfrac{1}{2}CV^2 \qquad \text{(potential energy).}$$

Example Problem

An isolate conducting sphere has a capacitance of 50 mF and a charge q = 1.25 C. How much potential energy is stored in the electric field of this charged conductor?

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Remember that $U = q^2/(2*C)$ and 1000 mF = 1 F

So $U = (0.050\ F)^2 / (2*1.25\ C) = 0.001\ J$

Electric Current

- Although an electric current is a stream of movin charges, not all moving charges constitute ar electric current.

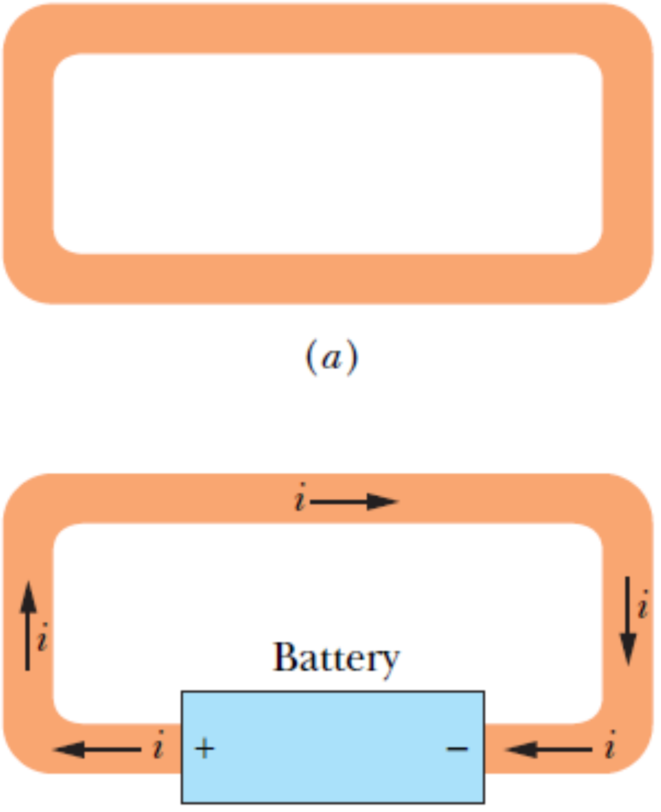
- If there is to be an electric current through a giver surface, there must be a net flow of charge through that surface.

- Example of free electrons (conduction electrons) in an isolated length of copper wire .

- The unit of electric current is the Ampere or Amp (A).

- The power associated with an electric current is

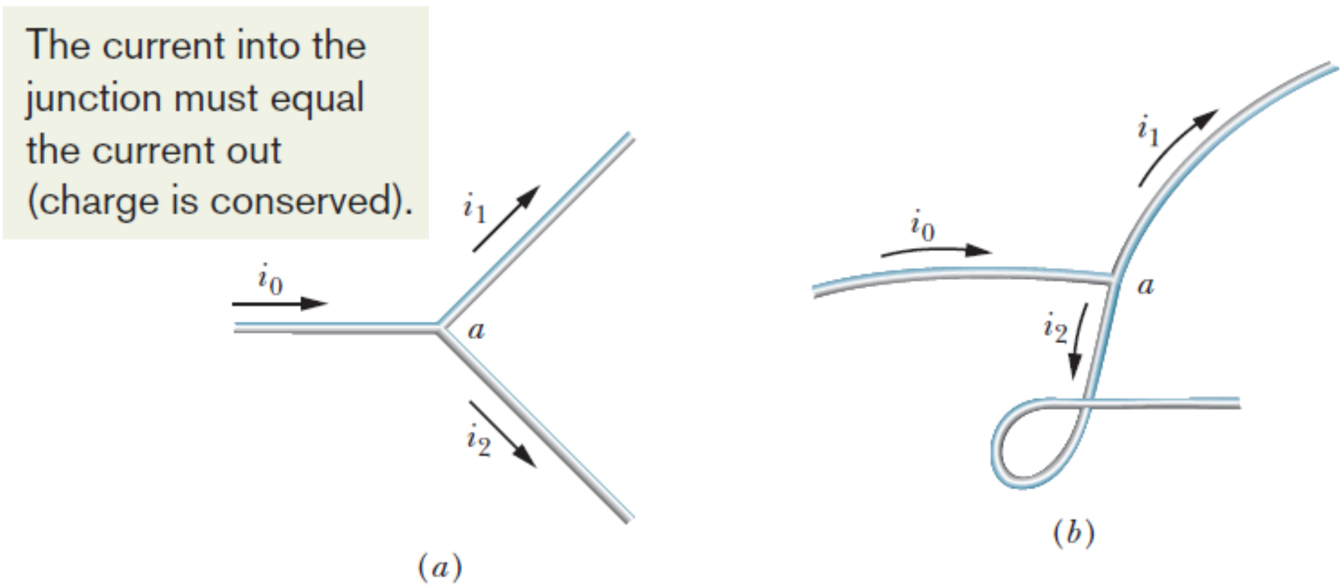
$$P = iV$$



(a) (b)

Electric Current

A current arrow is drawn in the direction in which positive charge carriers would move, even if the actual charge carriers are negative and move in the opposite direction.



Resistance and Current

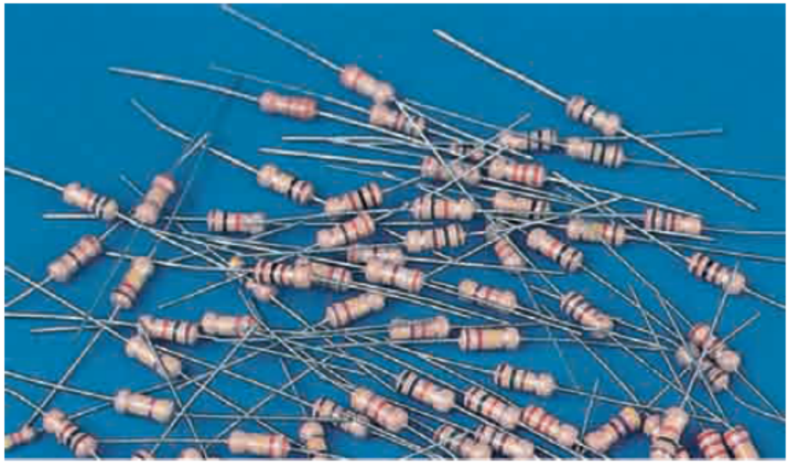
- We determine the resistance between any two points of a conductor by applying a potential difference *V* between those points and measuring the current *i* that results. The resistance *R* is then

$$R = \frac{V}{i} \qquad \text{(definition of } R\text{)}.$$

- The SI unit for resistance is the volt per ampere. This has a special name, the **ohm** (symbol Ω):

$$1 \text{ ohm} = 1\ \Omega = 1 \text{ volt per ampere}$$
$$= 1 \text{ V/A}.$$

- In a circuit diagram, we represent a resistor and a resistance with the symbol 



Concept Question

By which of the following methods could the current in a given circuit be doubled?

a. Either double the resistance or double the voltage.

b. Reduce either the voltage or the resistance to half of the initial value.

c. Either double the voltage or reduce the resistance to half of its initial value.

d. Either double the resistance or reduce the voltage to half of its initial value.

e. None of the above answers are correct.

Example Problem

A circuit contains a battery and a resistor of resistance *R*. For which one of the following combinations of current and voltage does *R* have the smallest value?

a. V = 9 V and I = 0.002 A

b. V = 12 V and I = 0.5 A

c. V = 1.5 V and I = 0.075 A

d. V = 6 V and I = 0.1 A

e. V = 4.5 V and I = 0.009 A

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Remember V = IR, which means R = V/I

a. V = 9 V and I = 0.002 A R = 9 V/0.002 A = 4500 Ω

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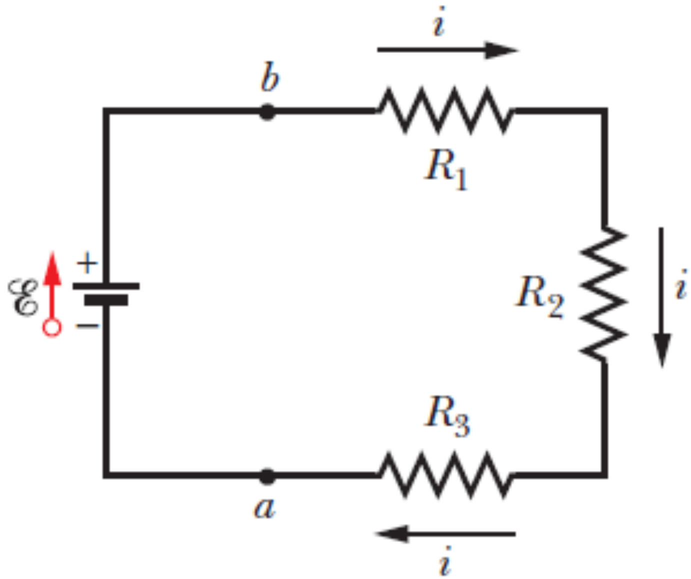
b. V = 12 V and I = 0.5 A R = 12 V/0.5 A = 24 Ω

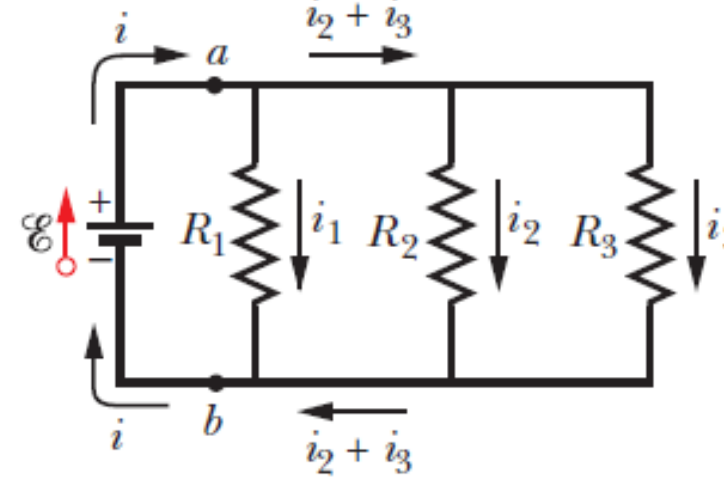
c. V = 1.5 V and I = 0.075 A R = 1.5 V/0.075 A = 20 Ω

d. V = 6 V and I = 0.1 A R = 6 V/0.1 A = 60 Ω

e. V = 4.5 V and I = 0.009 A R = 4.5 V/0.009 A = 500 Ω

Resistors in Series and Parallel



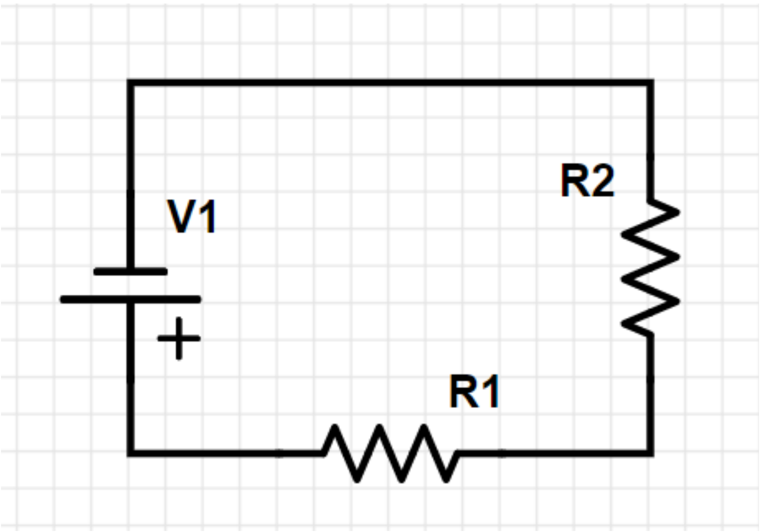


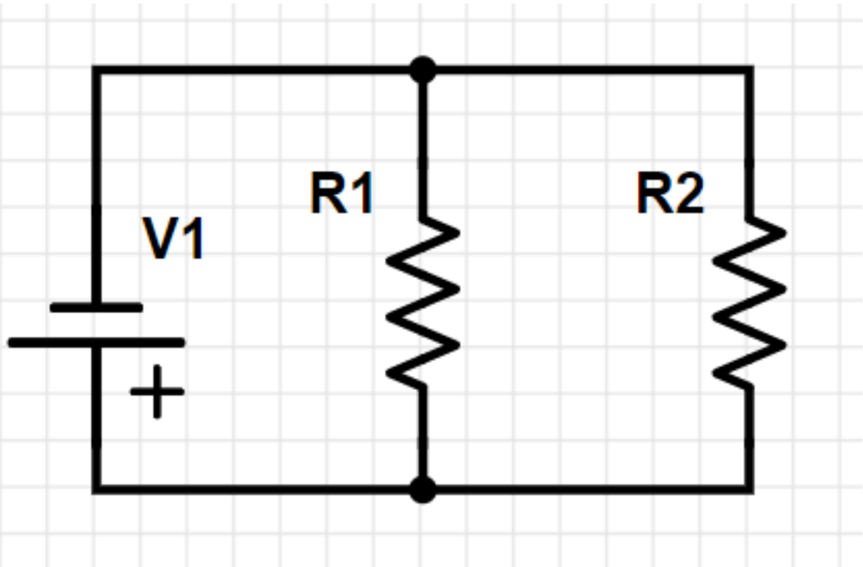
$$R_{eq} = \sum_{j=1}^{n} R_j \qquad (n \text{ resistances in series}).$$

$$\frac{1}{R_{eq}} = \sum_{j=1}^{n} \frac{1}{R_j} \qquad (n \text{ resistances in parallel}).$$

Example Problem

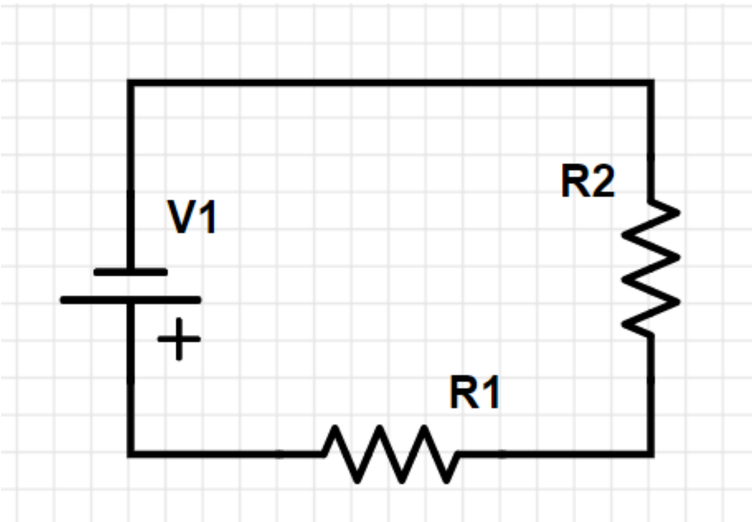
Find the equivalent resistance for the combination of resistors shown, across which potential difference V = 10 V is applied. Assume the R1 = 15 Ω and R2 = 35 Ω.



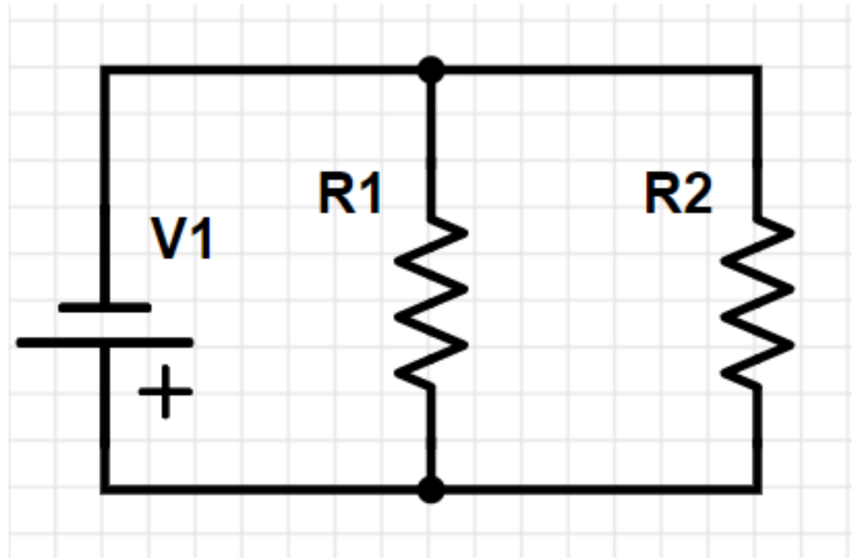


Example Problem

Find the equivalent capacitance for the combination of capacitances shown, across which potential difference V = 10 V is applied. Assume the R1 = 15 Ω and R2 = 35 Ω.



R_{eq} = R1 + R2 = 50 Ω



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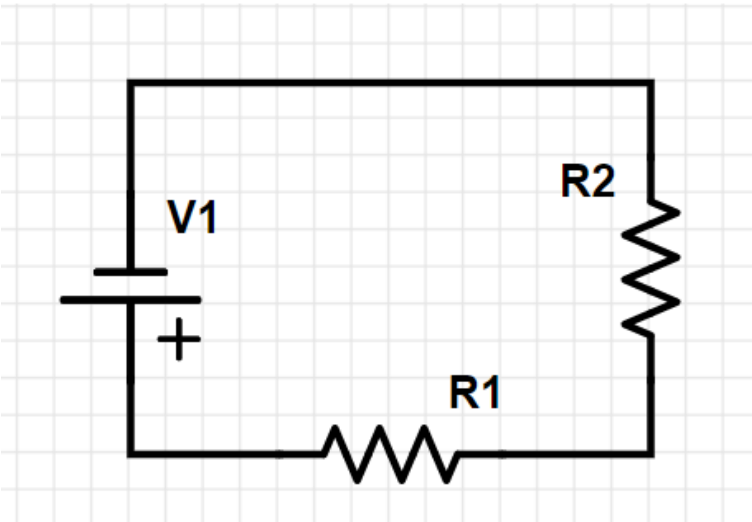

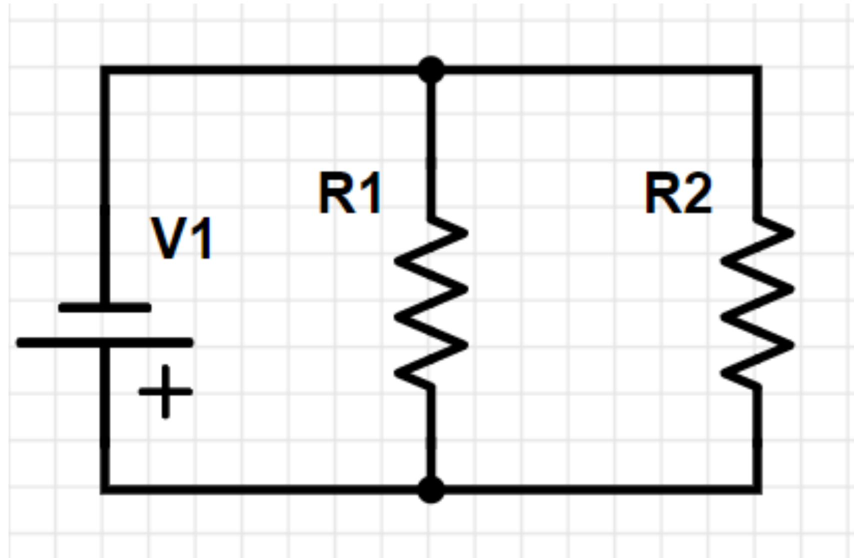

R_{eq} = R1 + R2 = 50 Ω

$1/R_{eq} = 1/R1+1/R2$

$1/R_{eq} = 1/15 + 1/35 = 0.0667+0.0286$

$1/R_{eq} = 0.0953$

R_{eq} = 10.5 Ω

What Produces a Magnetic Field?

- One way that magnetic fields are produced is to use moving electrically charged particles, such as a current in a wire, to make an **electromagnet**. The current produces a magnetic field that is utilizable.

- The other way to produce a magnetic field is by means of elementary particles such as electrons, because these particles have an *intrinsic magnetic field* around them.

- The magnetic fields of the electrons in certain materials add together to give a net magnetic field around the material. Such addition is the reason why a **permanent magnet**, has a permanent magnetic field.

- In other materials, the magnetic fields of the electrons cancel out, giving no net magnetic field surrounding the material.

Definition of the Magnetic Field

Some Approximate Magnetic Fields

At surface of neutron star	10^8 T
Near big electromagnet	1.5 T
Near small bar magnet	10^{-2} T
At Earth's surface	10^{-4} T
In interstellar space	10^{-10} T
Smallest value in magnetically shielded room	10^{-14} T

- We can define a **magnetic field, *B*,** by firing a charged particle through the point at which is to be defined, using various directions and speeds for the particle and determining the force that acts on the particle at that point.
- ***B*** is then defined to be a vector quantity that is directed along the zero-force axis.
- The magnetic force on the charged particle, $\boldsymbol{F_B}$, is defined to be:

$$F_B = |q|vB\sin\phi,$$

- Here ϕ is the angle between vectors ***v*** and ***B***.
- The SI unit for ***B*** that follows is newton per coulomb-meter per second. For convenience, this is called the **tesla (T)**, after Nikola Tesla
- An earlier (non-SI) unit for ***B*** is the *gauss (G),* and

$$1\text{ tesla} = 10^4\text{ gauss}.$$

Concept Question

Complete the following sentence: When a positively-charged particle is released from rest in a region that has a magnetic field directed due east, the particle will

a) remain at rest.

b) be accelerated due east.

c) be accelerated due north.

d) be accelerated upward.

e) be accelerated downward.

Example Problem

A charge of 13 mC is moving into a magnetic field of magnitude of 50 T. If the speed of the charge is 7.0×10^3 m/s and the angle of entry is 90°, what is the magnetic force produced on the charge?

A second charge follows the first one into the same field at a speed of 2.5×10^3 m/s. If the magnetic force on the second charge is 7,500 N, what is its charge?

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A charge of 13 mC is moving into a magnetic field of magnitude of 50 T. If the speed of the charge is 7.0×10^3 m/s and the angle of entry is 90°, what is the magnetic force produced on the charge?

Let's start by writing down what we are given:

$q = 13$ mC $B = 50$ T $v = 7.0 \times 10^3$ m/s $\phi = 90°$

Remember that $F = qvB\sin\phi$ and that 1000 mC = 1 C.

So, $F = 0.013\ C*7.0 \times 10^3\ m/s *50\ T *\sin(90°) = 4{,}550$ N

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Let's write down our givens:

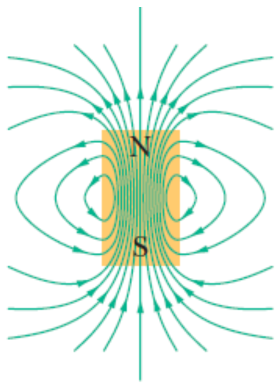
F = 7,500N B = 50 T $v = 2.5 \times 10^3$ m/s ϕ = 90°

Rearranging the force formula from before to solve for q, we get

q = F/(vBsin ϕ) = 7500 N/(50 T*2.5×10^3 m/s * sin(90°)) = 0.06 C or 60 mC

Magnetic Field Lines

- The direction of the tangent to a magnetic field line at any point gives the direction of ***B*** at that point.
- The spacing of the lines represents the magnitude of ***B*** —the magnetic field is stronger where the lines are closer together, and conversely.



(*a*)


(*b*)

Opposite magnetic poles attract each other, and like magnetic poles repel each other.

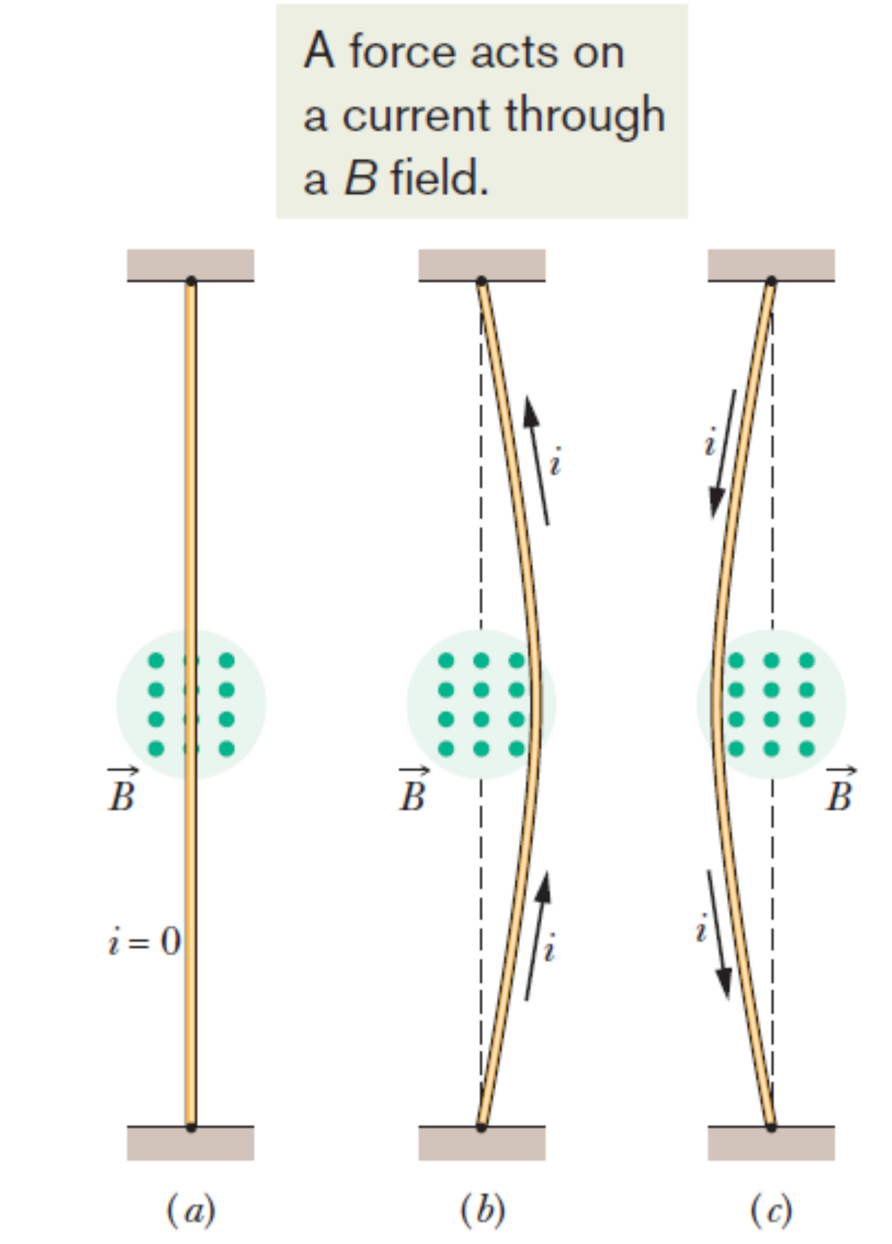
Magnetic Force on a Wire

A flexible wire passes between the pole faces of a magnet.

- Without current the wire is straight
- With upward current, the wire id deflected right-ward
- With downward current the wire is deflected leftward.

The force that causes this wire to bend is the magnetic force which is given by

$$F_B = iLB.$$



Concept Question

Which one of the following parameters is not used to determine the magnetic force on a current-carrying wire in a magnetic field?

a) length of the wire

b) radius of the wire

c) the strength of the magnetic field

d) the magnitude of the electric current