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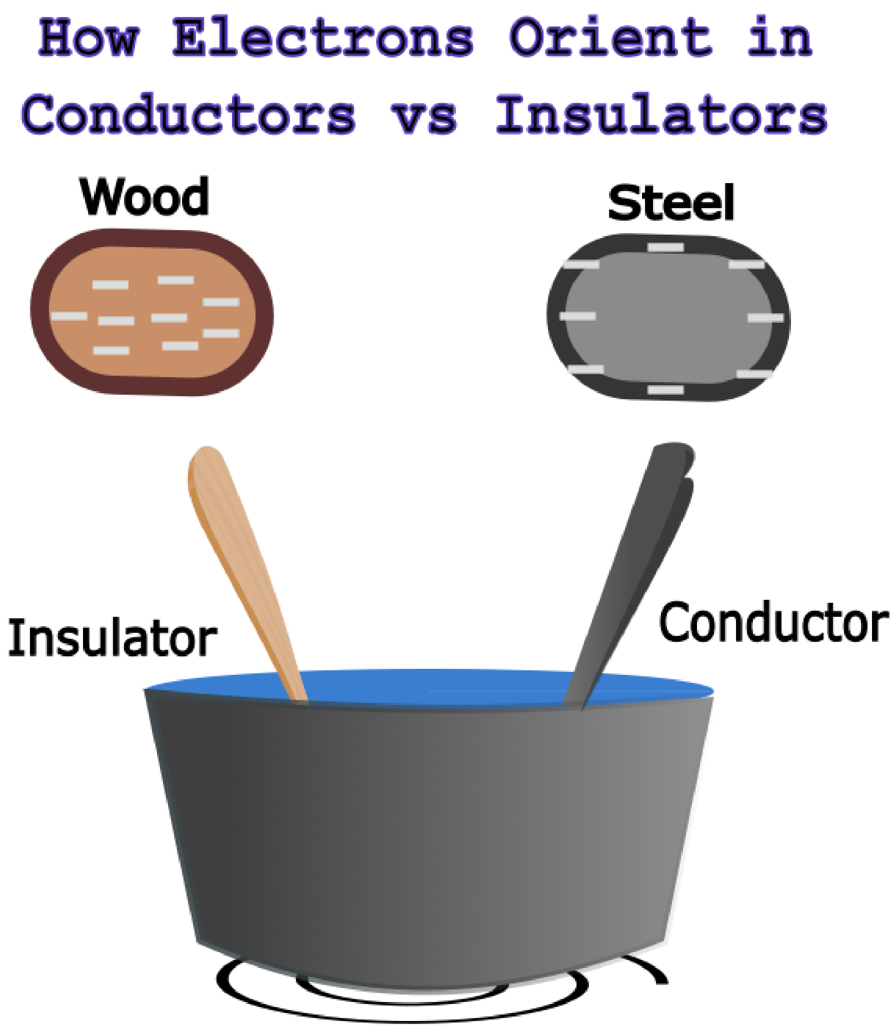
Chapter 1

Introduction to Electricity

What happens when you turn on a flashlight? The battery in the flashlight acts as an electron pump. The electrons flow through the wires to the lightbulb (or LED). As the electrons pass through the lightbulb, they excite the molecules within, which gives off light and heat. (LEDs also give off light and heat, but they give off a lot less heat.) Then the electrons return to the battery to be pumped around again.

When electricity is flowing through a copper wire, the protons and neutrons of the copper stay put while the electrons jump between the atoms on their way from the battery to the lightbulb and back again.

In some materials, like copper and iron, electrons are loosely bound to their nuclei, forming a sea of electrons, which allows energy to flow. These are good *electrical conductors*. In other materials, like glass and plastic, electrons don't leave their nuclei easily. Thus, they are terrible electrical conductors – we call them *electrical insulators*. For example, the plastic around a wire is electrical insulation.



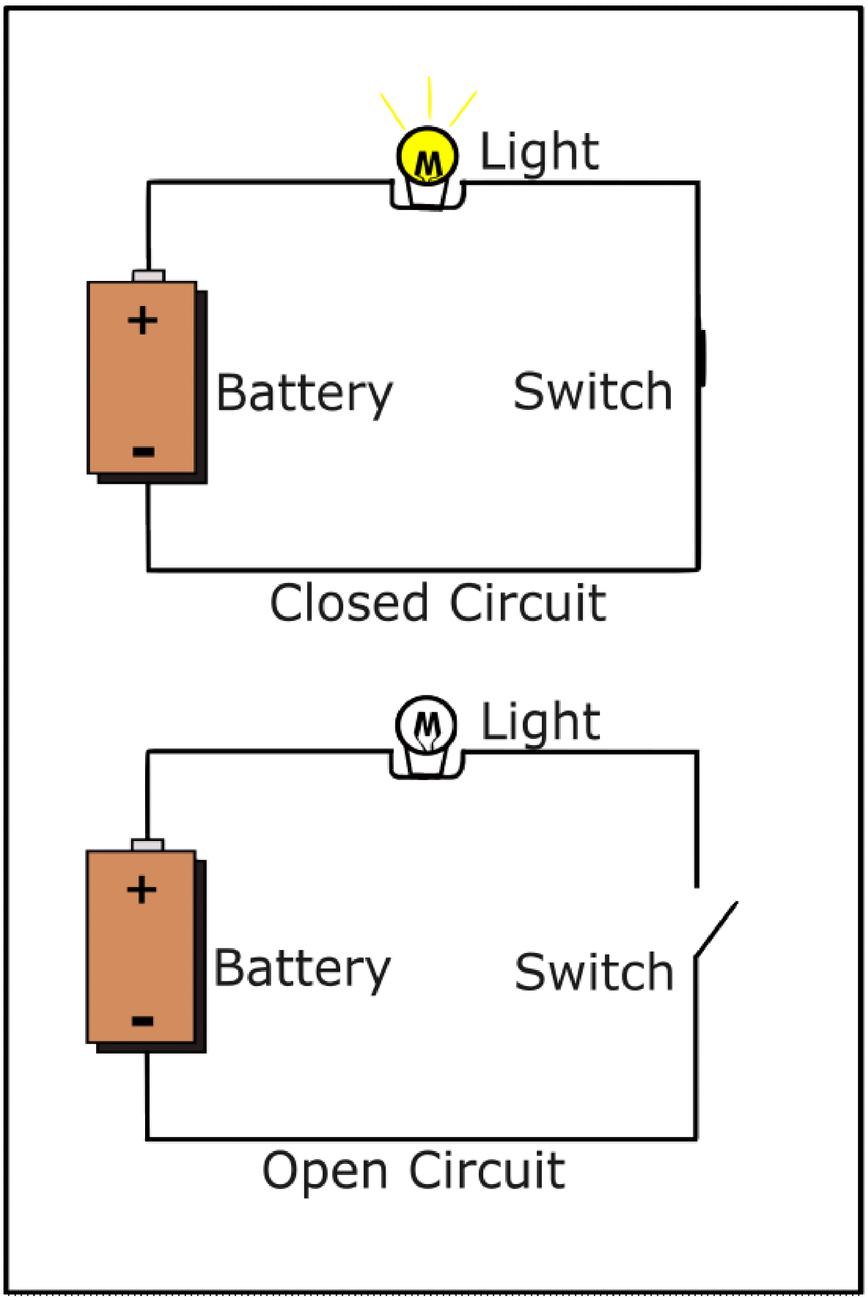
1.1 Units

Electrons are very small, so to study them, scientists came up with a unit that represents *a lot* of electrons. 1 *coulomb* is about 6,241,509,074,460,762,608 electrons. When 5 coulombs enter one end of the wire every second (and simultaneously 5 coulombs exit the other end), we say "This wire is carrying 5 amperes of current."

(Truthfully, we usually shorten ampere to just "amp". This is sometimes a little awkward because we often shorten the word "amplifier" to "amp". You should be able to tell which is which from the context.)

If you look at the circuit breakers or fuses for your home's electrical system, you'll see that each one is rated in amps. For example, maybe the circuit that supplies power to your kitchen has a 10 amp circuit breaker. If for some reason, more than 10 amps tries to pass through that wire, the circuit breaker will turn off the whole circuit.

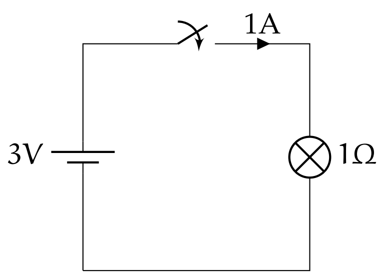
When it is on, your flashlight pushes about 1 amp of current through the lightbulb(When it is off, there is no current in the lightbulb).



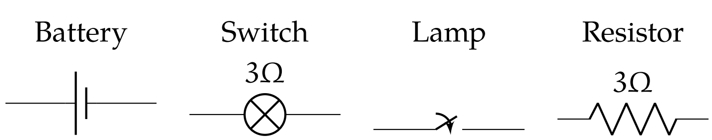
The lightbulb creates *Resistance* that the current pushes through. Think of it like plumbing: The current is the amount of water passing through a pipe. The resistance is something that tries to stop the current – like a ball of hair. The battery is what allows the current to push through the resistance; we call that pressure *voltage*.

1.2 Circuit Diagrams

Here is a circuit diagram of your flashlight:



The lines are wires. The symbols that we will use:



The battery pushes the electrons from one end and pulls them back in at the other, so the circuit must go around in a circle for the current to flow. This is why the current stops flowing when the switch breaks the circuit.

You can think of a switch as having zero resistance when it is closed and infinite resistance when it is open.

For our purposes, a lamp is just a resistor that gives off light.

1.3 Ohm's Law

Resistance is measured in *ohms*, and we use a Greek capital omega for that: Ω

Voltage is measured in *volts*.

Ohm's Law

Whenever a voltage V is pushing a current I through a resistance of I, the following is true:

$$V = IR$$

where V is in volts, I is in amps, and R is in ohms.

1.4 Power and Watts

Joule's Law

When a current I is passing through a resistance R, the power consumed is

$$W = I^2 R$$

where W is in watts, I is in amps, and R is in ohms.

Of course $V = IR$, so we can extend this to:

$$W = I^2 R = IV = \frac{V^2}{R}$$

Your flashlight's batteries provide about 3 volts. How much battery power is the flashlight using when it is on? The power (in watts) produced by the battery is the product of the voltage (in volts) and the current (in amps). So your flashlight is giving off $3volts \times 1amp = 3watts$ of power. Some of that power is given off as light, some as heat.

A watt is 1 joule of energy per second. We say that a watt is a measure of *power*.

When we talk about how much energy is stored in a battery, we use a unit like a kilowatt-hour. A kilowatt-hour is equivalent to 3.6 million joules.

1.5 Another great use of RMS

In many electrical problems, the voltage fluctuates a lot. For example, the fluctuations in voltage makes the sound that comes out of an audio speaker.

You can use the root-mean-squared of the voltage to figure out the average power your speaker is consuming.

Let's say that the RMS of the voltage you are sending to the speaker is V_{rms} and the resistance of the speaker is R ohms, then the power consumed by the speaker is:

$$P = \frac{V_{rms}^2}{R}$$

Similarly, if you know the RMS of the current you are pushing through the speaker is I_{rms}, then the power consumed by the speaker is:

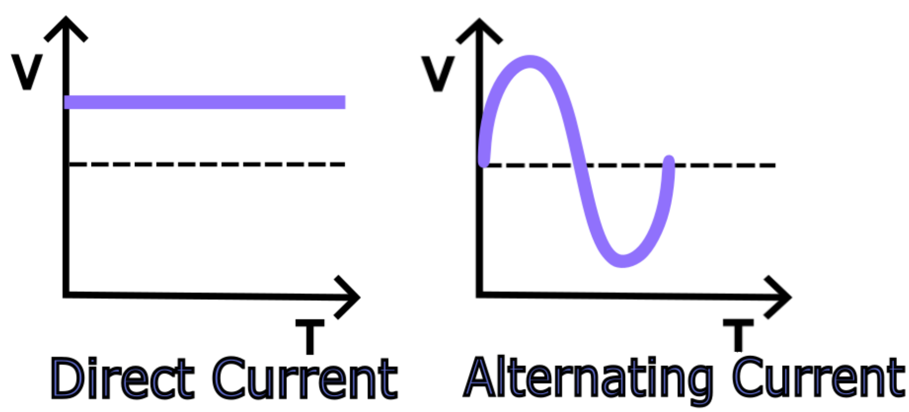
$$P = I_{rms} R$$

1.6 Electricity Dangers

Large amounts of electricity moving through your body can hurt or even kill you. You must be careful around electricity.

However, your body is not a very good conductor, so low-voltage systems (like a flashlight) don't have enough voltage to move significant amounts of current through your body.

However, the electricity in a power outlet has much more voltage. The voltage in these outlets is fluctuating between positive and negative, so we call it *Alternating Current* or AC.

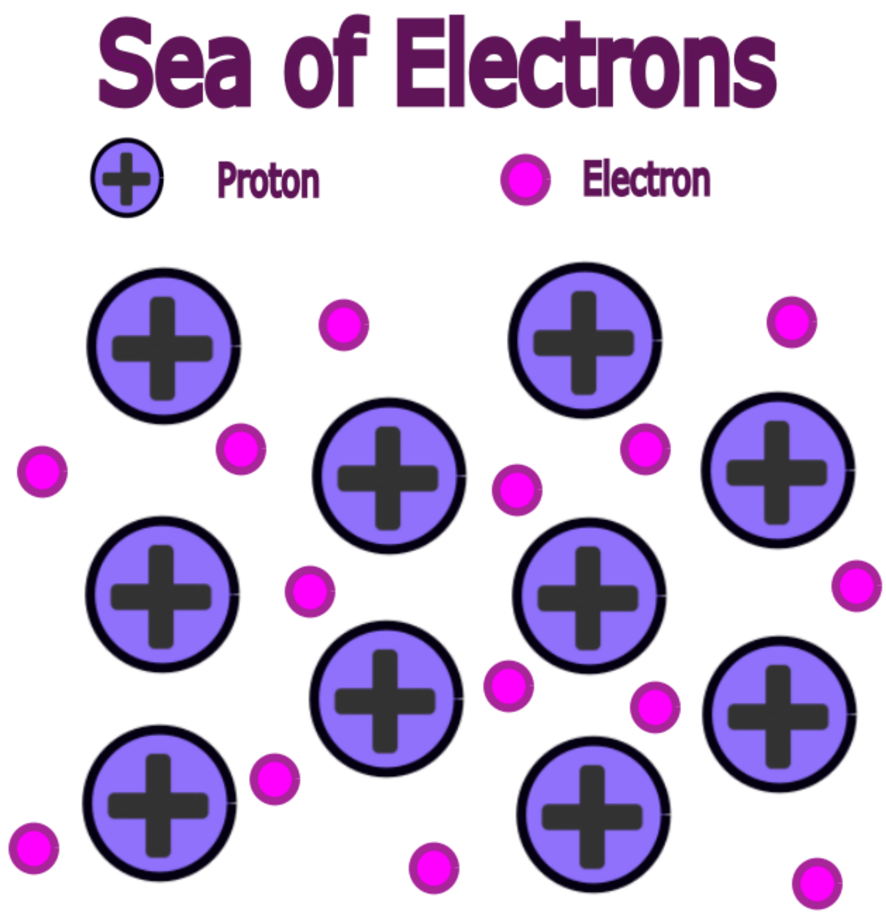


In most countries, the RMS of the voltage between 110 and 240 V. (The peak voltage is always $\sqrt{2}$ times the RMS value. In the US, for example, people say "Our outlets supply 120 V." They mean that the RMS of the voltage difference between the wire and the earth is 120V. The peak voltage is almost 170V.)

How much current can a human handle? Not much. You can barely feel 1 mA moving through your body, but at 16 mA, your muscles will clench and you won't be able to relax them – many people die from electrocution because they grab a wire which pushes enough current through their body to prevent them from letting go of the wire. At 20 mA, a human's respiratory muscles become paralyzed.

The fuse breaker in a house will often allow 20 A to flow through the circuit before it shuts off the power: Always, always, always shut off the power before touching any of the wiring in your house.

While water is actually a mediocre conductor, it can still deliver enough current to kill you. If you see a wire in a puddle, you should not touch the puddle. Interestingly, because of the salt, sea water is more than 100 times better at conducting electricity than the water you drink.

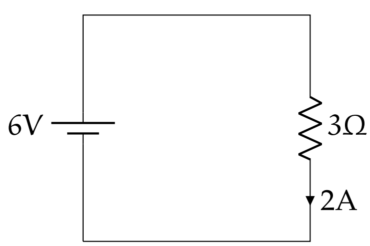


If you hold a wire in each hand, how many Ohms of resistance will your body have? Once it gets past your skin, you will look like a bag of salt water to the electricity. After the skin, your body will have a resistance of about 300Ω. However, the skin is a pretty good insulator. If you have dry, calloused hands, your skin may add a 100,000Ω to the resistance.

Chapter 2

DC Circuit Analysis

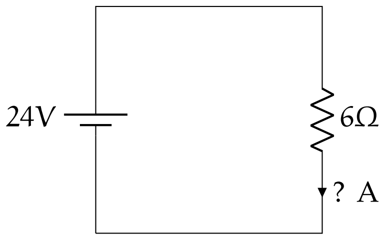
In the most basic circuit, you have only a battery and a resistor:



In this case, you only need Ohm's Law: $V = IR$. In this case, $6V = 3\Omega \times 2A$.

Exercise 1 Ohm's Law

How many amps are going around the circuit?



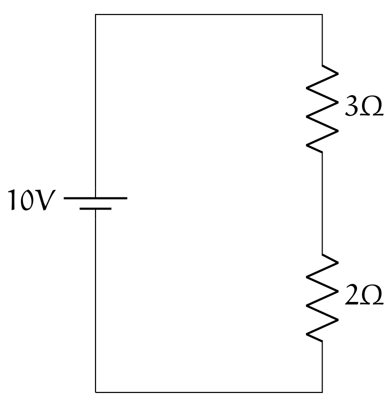
Working Space

Answer on Page 33

2.1 Resistors in Series

When you have two resistors wired together in a long line, we say they are "in series". If you have two resistors R_1 and R_2 wired in series, the total resistance is $R_1 + R_2$.

In this diagram, for example, the total resistance is 5Ω.



The current flowing through the circuit, then, is $10/4 = 2A$.

By Ohm's law, the voltage drop across the upper resistor is $IR = 2A \times 3\Omega = 6V$.

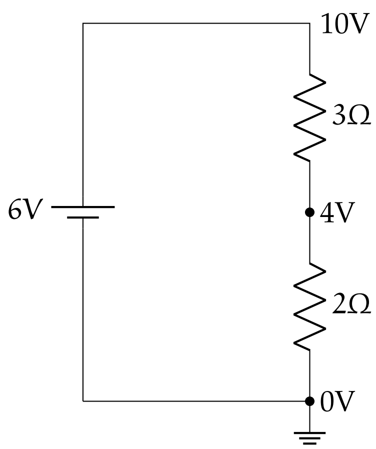
The voltage drop across the lower resistor is $IR = 2A \times 2\Omega = 4V$.

Notice that the battery pumps the voltage up to 10V, then the two resistors drop it by exactly 10V. This is known as "Kirchhoff's Voltage Law":

Kirchhoff's Voltage Law

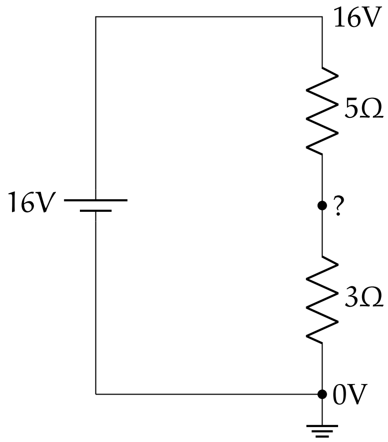
As you make a loop around a circuit, the sum of the voltage increase must equal the sum of the voltage decrease.

The negative end of the battery is connected to "ground" (it has zero voltage), then we can draw a diagram with the voltages(That symbol in the lower right represents a connection to ground).



Exercise 2 Resistors In Series

What is the current going around the circuit?
What is the voltage drop across each resistor?

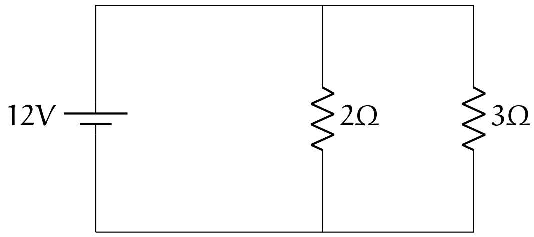


Working Space

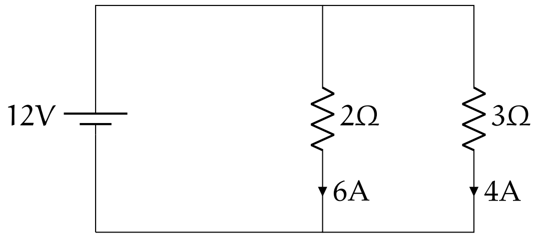
Answer on Page 33

2.2 Resistors in Parallel

Look at this circuit. Note that the current can go two different paths.



There is 12 volts pushing current through both resistors. So 6A will go through the 2Ω resistor and 4A will go through the 3Ω resistor.



Thus, a total of 10 A will be going through the battery.

Imagine you are a battery. You can't see that you have two resistors. What does it feel like to you? $\frac{V}{I} = R$, and $V = 12$ and $I = 10$. So the effective resistance of the two resistors in parallel is $\frac{12}{10}$ or $\frac{6}{5}\Omega$.

Resistance in Parallel

If you have several resistances $R_1, R_2, \ldots, R_n$ wired in parallel, their effective resistance R_t is given by

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$$

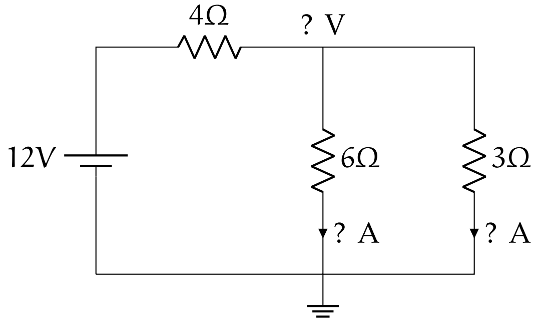
In our example:

$$\frac{1}{R_t} = \frac{1}{2} + \frac{1}{3} = \frac{5}{6}$$

Thus $R_t = \frac{6}{5}\Omega$.

Exercise 3 Resistors In Parallel

What is the current going through the battery? What is the drop over the 4Ω resistor? What is the current in each branch?



Working Space

Answer on Page 34

Chapter 3

Charge

If you rub a balloon against your hair and then place it next to a wall it will stick. We say that it has gotten an *electrical charge*. It stole some electrons from your hair, and now the ballon has slightly more electrons than protons. We say that it has a negative electrical charge.

Objects with slightly more protons than electrons have a positive charge.

This charge is measured in coulombs. The charge of a single proton is about 1.6×10^{-19} coulombs.

An object with a negative charge and an object with a positive charge will be attracted to each other. Two objects with the same charge will be repelled by each other.

Coulomb's Law

If two objects with charge q_1 and q_2 (in coulombs) are r meters from each other, the force of attraction or repulsion is given by

$$F = K\frac{|q_1 q_2|}{r^2}$$

where F is in newtons and K is Coulomb's constant: about 8.988×10^9.

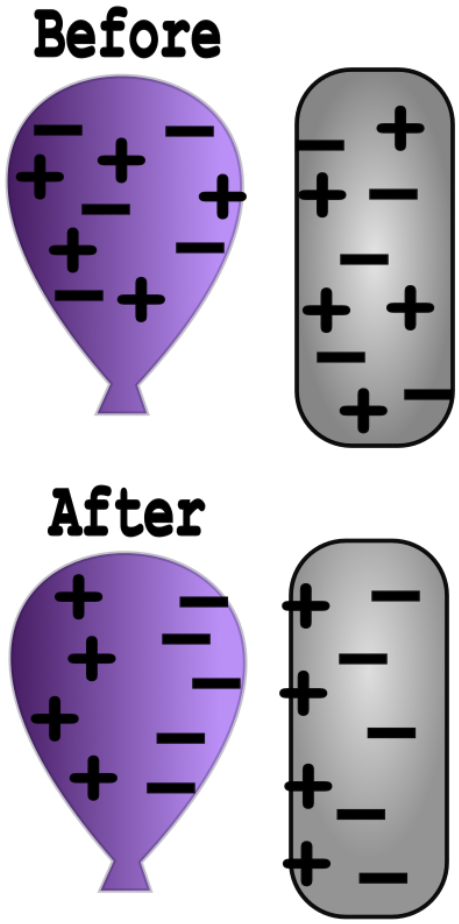
Exercise 4 Coulomb's Law

Two balloons are charged with an identical quantity and type of charge: -5×10^{-9} coulombs. They are held apart at a separation distance of 12 cm. Determine the magnitude of the electrical force of repulsion between them.

Working Space

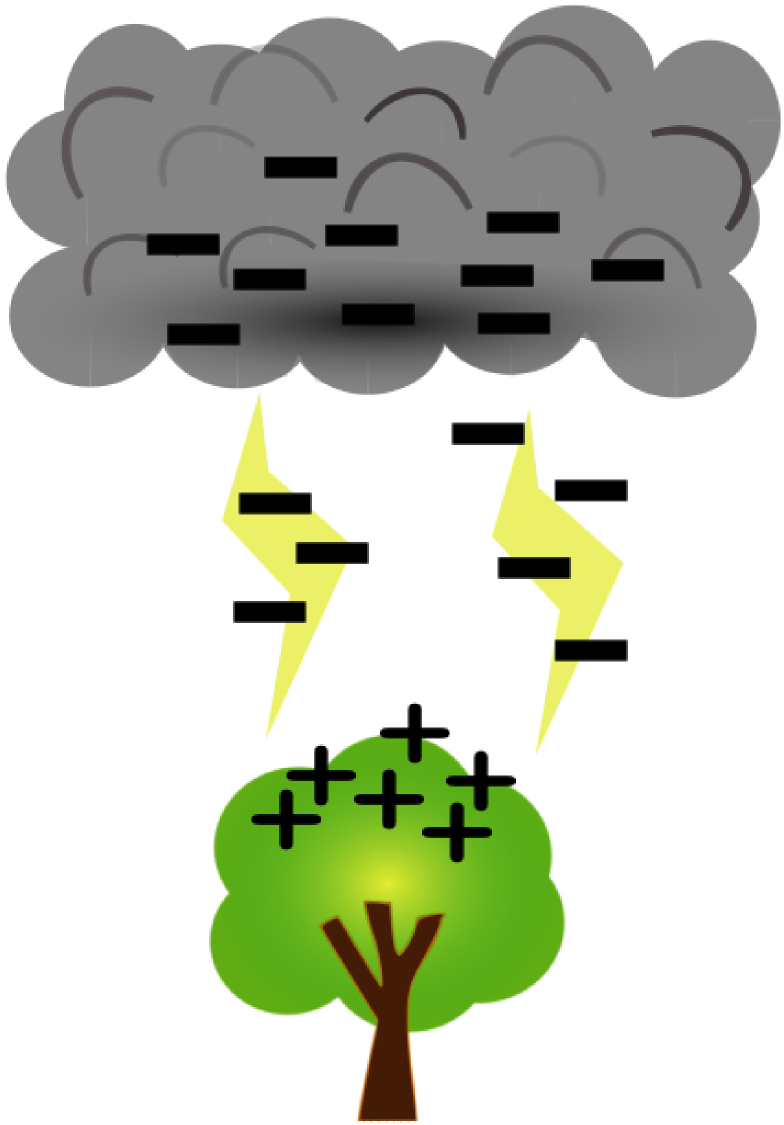
Answer on Page 34

At this point, you might ask "If the wall has zero charge, why is the balloon attracted to it?" The answer: the electrons in the wall move away from the balloon. The negative charge on the balloon pushes electrons into the wall, so the surface of the wall gets a mild positive charge. The surface is close to the balloon, so the attraction is stronger than the repulsion.



3.1 Lightning

A cloud is a cluster of water droplets and ice particles. These droplets and ice particles are always moving up and down through the cloud. In this process, electrons get stripped off and end up on the water droplets at the bottom of the cloud(water droplets collect at the bottom because they are denser). The air between the droplets is a pretty good insulator, and thus the electrons are reluctant to jump anywhere. However, eventually, the charge gets so strong that even the insulating properties of the air is not enough to prevent the jump, causing lightning.



A lot of lightning moves within a cloud or between clouds. However, a few jump to the earth. These bolts of lightning vary in the amount of electrons they carry, but the average is about 15 coulombs.

And thunder occurs because the electrons heat the air they pass through, causing the air to expand suddenly, and the resulting shockwave is the sound we know as thunder.

3.2 But...

This idea that opposite charges attract creates some heavy questions that you do not yet have the tools to work with. So the answer is basically "Don't ask that question now!"

However, you probably have these questions, so I will point you in the direction of the answers.

The first is "In any atom bigger than hydrogen, there are multiple protons in the nucleus. Why don't the protons push each other out of the nucleus?"

We aren't ready to talk about it, but there is a force called *the nuclear force* which pulls the protons and neutrons in the nucleus of the atom toward each other. At very, very small distances it is strong enough to overpower the repulsive force due to the protons' charges.

Another question is "Why do the electrons whiz around in a cloud so far from the nucleus of the atom? Negatively charged electrons should cling to the protons in the center, right?"

We aren't ready to talk about it, but quantum mechanics tells us that electrons like to live in a certain specific energy level. Hugging protons isn't one of those levels.

Chapter 4

Fertilizer

In 1950, there were 2.5 billion people on the planet, and about 65% were malnourished. In 2019, there were 7.7 billion people on the planet, and only 15% are malnourished. How did crop yields increase so much? There were several factors: better crop varieties, reliable irrigation, increased mechanization, and affordable fertilizers.

When a plant grows, it takes molecules out of the soil and uses them to build proteins. It primarily needs the elements nitrogen (N), phosphorus (P), and potassium (K).

When you buy a bag of fertilizer at the store, it typically has three numbers on the front. For example, you might buy a bag of "24-22-4". This means that 24% of the mass of the bag is nitrogen, 22% is phosphorus, and 4% is potassium.

Potassium comes as potassium carbonate (K_2CO_3), potassium chloride (KCl), potassium sulfate (K_2SO_4), and potassium nitrate (KNO_3). Any blend of these chemicals is known as "potash". Potash is dug up out of mines.

Phosphorus is also mined, but is refined into phosphoric acid (H_3PO_4) before it is put into fertilizer.

Nitrogen is an especially interesting case for 2 reasons:

- Worldwide farmers apply more nitrogen to their soil than potassium or phosphorous combined.
- 78% of the air we breathe is nitrogen in the form of N_2, but neither plants nor animals can utilize nitrogen in that form.

4.1 The Nitrogen Cycle

Converting the N_2 in the air into a form that a plant can use is known as *nitrogen fixation*. For billions of years, there were only two ways that nitrogen fixation occurred on earth:

- The energy from lightning causes N_2 and H_2O to reconfigure as ammonia (NH_3) and nitrate (NO_3). This accounts for about 10% of all naturally occurring nitrogen fixation.
- Cyanobacteria are responsible for the rest. They convert N_2 into ammonia.

Let's say that you are eating soybeans. There is a cyanobacteria called *rhizobia* that has a symbiotic relationship with soybean plants. Rhizobia fixes nitrogen for the soybean plant. The soybean plant performs photosynthesis and gives sugars to the rhizobia.

The proteins in the soybeans contain nitrogen from the rhizobia. When you eat them, you use some of the nitrogen to build new proteins. You probably don't use all the nitrogen, so your cells release ammonia into your blood.

Ammonia likes to react with things, so your liver combines the ammonia with carbon dioxide to make urea ($CO(NH_2)_2$). Your kidneys take the urea out of your blood and mix it with a bunch of water and salts in your bladder. When you urinate, the urea leaves your body.

If you urinate on the ground, the nearby plants can take the nitrogen out of the urea.

When you die, the nitrogen in your proteins will return to the soil as ammonia and nitrate.

For centuries, farms got their nitrogen from urine, feces, and rotting organic material. There were two challenges with this:

- Human pathogens had to be kept away from human food.
- There was simply not enough to support 7.7 billion people.

So we had to figure out how to do nitrogen fixation at an industrial level.

4.2 The Haber-Bosch Process

During World War I, two German scientists, Fritz Haber and Carl Bosch figured out how to make ammonia from N_2 and H_2 using high temperatures and pressures. This is how nearly all nitrogen fertilizer is created today.

Where do we get the H_2? From methane (CH_4) in natural gas. Today, 3-5% of the world's natural gas production is consumed in the Haber-Bosch process.

The ammonia is converted into ammonium nitrate (NH_4NO_3) or urea before it is shipped to farms.

4.3 Other nutrients

Healthy plants require several other elements that are sometimes applied as fertilizer: calcium, magnesium, and sulfur.

Finally, tiny amounts of copper, iron, manganese, molybdenum, zinc, and boron are sometimes needed.

Chapter 5

Concrete

To make concrete, you mix cement with water and an aggregate (sand or rock). The cement is usually only about 10 to 15 percent of the mixture. The cement reacts with the water, and the resulting solid binds the aggregate together. In 2019, the world consumed 4.5 billion tons of cement.

Concrete is hard and durable. The mortar between the pyramids at Giza is concrete – it is now 5000 years old. Today we use concrete to build many structures including buildings, bridges, airport runways, and dams.

There are many kinds of cement, but the most common is Portland cement. It is made by heating limestone (calcium carbonate) with clay (for silicon) in a kiln. Two things come out of the kiln: Carbon dioxide and a hard substance called “clinker”. The clinker is ground up with some gypsum before it is sent to market.

The carbon dioxide is released into the atmosphere. Cement manufacture is responsible for about 8% of the world’s CO_2 emissions; it is a major contributor to climate change.

Really hard concrete, like that used in a nuclear power plant, can support 3,000 kg per centimeter without being crushed. However, if you pull on two ends of a piece of concrete it comes apart pretty easily. We say that concrete can handle a lot of *compressive stress*, but not much *tensile* stress.

5.1 Steel reinforced concrete

Many places where we use concrete (like in a bridge), we need both compressive and tensile stress. Often the top of a beam is undergoing compression and the bottom of the beam is undergoing tension.

FIXME Picture here

Steel has tremendous tensile strength, but not as much compressive strength as concrete. To get both tensile *and* compressive strength, we often bury steel bars or cables inside the concrete. This is known as *steel-reinforced concrete*. The concrete generally does a very good job protecting the steel, which keeps it from rusting.

You may have heard of *rebar*. That is just short for "reinforcing bar". Typically rebar has bumps and ridges that keep the bar and the concrete from moving independently.

5.2 Recycling concrete

A lot of concrete structures only last about 100 years. When they are demolished, the concrete can be reused as aggregate in other projects. Often the concrete bits are mixed with cement and made into concrete again.

If the concrete to be reused is reinforced with steel, the steel has to be removed and recycled separately. Then the concrete is crushed into small pieces.

Chapter 6

Metals

Elements that transmit electricity well, even at low temperatures, are called *metals*. Here are some metals that you are probably familiar with: aluminum, iron, copper, tin, gold, silver, and platinum. Aluminum and iron are particularly common; together they make up about 14% of the earth's crust.

An *alloy* is a mixture of elements that includes at least one metal. Brass, for example, is an alloy of copper and zinc. Bronze is an alloy of copper and tin.

6.1 Steel

One of the most common alloys is steel, an alloy of iron and carbon. In pure iron, the molecules slip easily past each other, so pure iron is relatively soft and easily deformed. The carbon in steel prevents that slipping, thus steel is much, much harder than iron.

How much carbon? If you put less than 0.002% by weight, you end up with something very much like pure iron. As you increase the carbon, it gets harder and harder. Once it gets above about 2%, the result is very brittle.

If you add about 11% chromium to steel, you get *stainless steel* which resists rusting.

Exercise 5 Tensile Strength

The tensile strength of steel is usually between 400 MPa and 1200 MPa. A Mega Pascal (MPa) is the strength necessary to hold 1,000,000 newtons of force with a cable that has a 1 square meter cross section. Or, equivalently, to hold 1 newton of force with a cable that has a 1 square millimeter cross section.
If you have are buying a round cable that has a tensile strength of 700 Mpa and must hold a 100 kg man aloft, what the diameter of the smallest cable you can use?

Working Space

Answer on Page 34

Here are some approximate tensile strengths of ather materials:

Material	Tensile strength (MPa)
Iron	3
Concrete	4
Rubber	16
Glass	33
Wood	40
Nylon	100
Human hair	200
Aluminum	300
Steel	700
Spider webs	1000
Carbon fiber	4000

6.2 What metal for what task?

You will see copper used a lot for electrical wires in your house and appliances because it is very efficient at moving electricity (very little power is lost as heat). It is also very good a transmitting heat, so you will often see copper pots and pans.

Aluminum is less dense than copper, and is still a pretty good conductor of electricity. Thus, the overhead wires in a power system are often made of aluminum.

Aluminum is not as strong as steel, but considerably lighter. It is often used structurally where weight is a concern: skyscrapers, cars, airplanes, and ships.

Titanium is about as strong as steel, but it weights about half as much. Titanium is very difficult to work with, so it is used in places where weight and strength are very important and cost is not: airplanes and bicycles.

(Carbon fiber, which is light, strong, and very easy to work with, is replacing aluminum and titanium in many applications. 20 years ago, many expensive bicycles were made of titanium. These days the vast majority are made with carbon fiber.)

Zinc and tin are very resistant to corrosion, so they are often used as a coating to prevent steel from rusting. They are also used in many alloys for the same reason. In the United States, the penny is 97.5% zinc and only 2.5% copper.

Appendix A

Answers to Exercises

Answer to Exercise 1 (on page 12)

$V = IR$ so $I = \frac{V}{R} = \frac{24V}{6\Omega} = 4A$.

Answer to Exercise ?? (on page 14)

There is a total resistance of 8Ω, so your 16V will push 2A of current around the circuit.

2A going through a 5Ω resistor represents a 10V drop.

2A going through a 3Ω resitor represents a 6V drop.

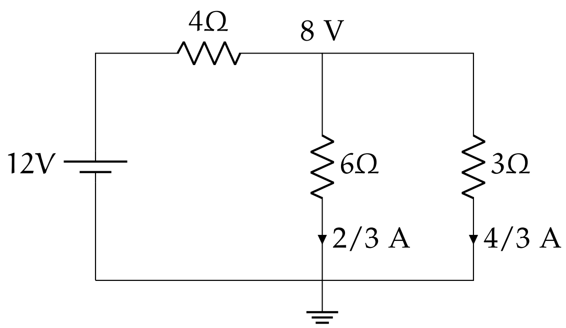
Answer to Exercise 3 (on page 16)

The effective resistance of the 6Ω and the 3Ω is 2Ω because

$$\frac{1}{R_T} = \frac{1}{6} + \frac{1}{3} == \frac{1}{2}$$

So the battery experiences a resistance of $4\Omega + 2\Omega = 6\Omega$. A 12V will push 2A through a resistance of 6Ω.

The voltage drop across the 4Ω resistor is $2A \times 4\Omega = 8V$. Thus there will be a 4V drop across the two resistors in parallel. So 2/3 A will flow through the 6Ω resistor. 4/3 A will flow through the 3Ω resistor.



Answer to Exercise 4 (on page 18)

$$F = K\frac{|q_1 q_2|}{r^2} = (8.988 \times 10^9)\frac{(-5 \times 10^{-9})(-5 \times 10^{-9})}{0.12^2} = \frac{224.7 \times 10^{-9}}{0.0144} = 15.6 \times 10^{-6}$$

15.6 micronewtons.

Answer to Exercise 5 (on page 30)

On earth, holding a 100 kg man aloft requires 980 Newtons of force.

$980/700 = 1.4$, so you need a cable with a cross-section area of 1.4 square millimeters.

$$\pi r^2 = 1.4$$

So $r = \sqrt{1.4/\pi} \approx .67$ millimeters. So the cable would have to have a diameter of at least 1.34 millimeters.

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