

PEO STRI

Engineering Internship

How Everything Works



SCIENCE, TECHNOLOGY, ENGINEERING, AND MATHEMATICS (STEM)

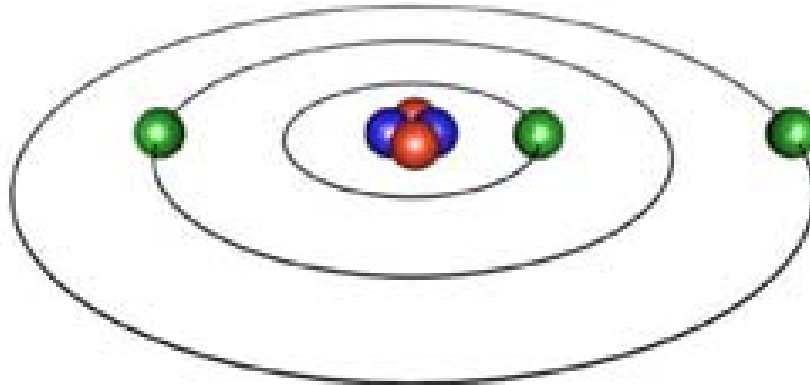
Electricity

Electricity Overview

Electricity is all about moving really tiny stuff, really fast. It is contained in almost everything around you all the time.

Your computer, lights, telephone, and even your own cells, are all charged with electricity at this very moment.

The Atom



An Atom

The atom is the building block of the universe. Everything is made of them, everything uses them, and everything would disappear without them.

So what is an atom made of?

Electrons, protons, and neutrons, really tiny stuff, connected together with magnetism and electric fields, in a volume of space. But before this turns into a description of matter, let's stop and focus on the relevant parts of atoms to electricity.

The component we are interested in is the **electron**, the charged particle that helps define the material the atom is going to make.

Depending on how many electrons there are in an atom, how densely packed they are, and how free they are to move around, an atom and the material it makes can be hard or soft, flexible or rigid, and conductive or nonconductive (conductivity is the measure of whether or not electricity will travel through the material). Since we are interested in electricity, not material properties, we will look at what makes a material more conductive at the atomic level.

Conductivity

Conductivity is the measure of how easily electricity moves through a material. Materials like copper, gold, and iron are easy to pass electricity through, while materials like wood, glass, and plastic are not.

Why is this?

It is all about freedom of movement of electrons. From the human perspective, a grey piece of plastic is not all that different from a piece of aluminum. Both are hard, can be dented, can bend a little then break, can be shiny or not, and can come in any shape or size.

So why is it that the aluminum is a good conductor -

But the plastic is not?

You have to look at it from an atomic level to understand this.

The electrons in the atomic view of the plastic are stuck in place and have no ability to move around, and the electrons of the metal can move around freely. This is the fundamental difference between something that will carry electricity, and something that won't.



It works a lot like dominoes. If you line up 1000 dominoes on end back to back with no space in between (analogous to the plastic) and tap the first domino in line....

What will happen?

Nothing.

The dominoes are not free to move and they just stand there as though nothing happened. Now if you were to line them up again on end, but leave an inch or so between each domino (analogous to the aluminum) and then tap them again.....

Would they just stand there?

No, they would obviously fall down, one after another, until the last domino has fallen over at the end of the line.

This is how electricity works, and understanding this will make understanding the rest of the topic much easier. Electricity happens when a force moves the first electron on a surface where electrons are free to move, and this moving electron bumps into the next electron, and so on until the last free electron moves, and since the electrons can't fall over, they are instantly ready to repeat this process. If the last electron happens to come in contact with the initial pushing force, the cycle continues until there is no energy left.

Voltage, Current, and Table Top Games

Current and voltage are the primary descriptors of an electric circuit, but what exactly are they?

Voltage is similar to a pump; it creates an electrical "pressure" that can apply a force on electrons.

In the domino example, voltage is the initial force that pushes the first domino over, starting the chain reaction. Imagine if the domino chain were to have one part that went up a hill. As each domino falls over going up the hill, they will slow down since it takes extra work to go up hill (just like a car will slow down when coasting up a hill). If the hill is large, or the speed and force of the domino is low, there may not be enough power to push all of the dominoes over, and you will have to exert another force at the place they stopped falling over, or try again and make the initial force stronger. This is just like voltage. If you are simply trying to send electricity from one side of a battery to the other, there will always be enough energy regardless of the voltage to do this. However, if you put a hill (a power consuming device such as a light) in the path of electricity, you will need to have a strong enough initial push to ensure that the energy can make it up the hill.

Current is a measure of how many electrons pass through cross section of a material in a second, where one **amp** is equal to 6.24×10^{18} (624 followed by sixteen zeros) electrons per second. That's a lot of electrons.

The other aspect of dominoes you can observe and control is how many dominoes fall over in a given amount of time. If you have one column of dominoes, no matter how hard you push the initial domino, they will fall over at about the same rate as a result of how gravity works. If you want more to fall over in the same amount of time, you will need to have additional parallel columns of dominoes. This is analogous to current.

Electric Circuits

Electric circuits are the exploitation of the way current and voltage work. More voltage will push you higher up an electrical hill, and more current will send more energy through a wire. A switch works like removing a domino from the path, and a motor or a light is equivalent to the electrical hill.

The basic rule of electric circuits is that energy that leaves a power source (ie a battery) must return. This is why batteries and plugs have two terminals, one positive, and one negative. If the positive and negative terminals of a battery or other power source are connected, you have made a circuit, and can use this to engage electrical devices as long as the rule is followed; negative connects to positive, and vice versa. If you install a lamp in the circuit, assuming there is the correct amount of voltage as specified by the lamp designer, the lamp will glow yellow, and if you install a motor with the correct voltage, it will spin.

Want to control when it spins?

Add a switch. The **switch** connects and disconnects power as the toggle switch is flipped from on to off.

How does electricity make a light glow and a motor spin?

Moving electrons have energy (as does any moving mass) as indicated by Einstein's law, $E=MC^2$. Since an electron has a mass (M) of 9.10×10^{-31} (a decimal point followed by thirty zeros, then 91) and the speed of light (C) is 299,792,458 meters per second, the energy of an electron is 8.18×10^{-14} (a decimal point with thirteen zeros followed by 818) joules.

What is a joule?

A measure of how much energy something has or needs.

A 100 watt lamp for example, requires 100 joules of energy every second. And since we know how much energy is in an electron, we know we need to provide 1.22×10^{15} electrons per second. Again, that's a lot of electrons.

Circuit diagram

A circuit diagram is a simplified conventional graphical representation of an electrical circuit. A pictorial circuit diagram uses simple images of components, while a [schematic diagram](#) shows the components of the circuit as simplified standard symbols; both types show the connections between the devices, including power and signal connections. Arrangement of the components interconnections on the diagram does not correspond to their physical locations in the finished device.

A circuit diagram shows the actual wire connections being used. The diagram does not show the physical arrangement of components. A drawing meant to depict what the physical arrangement of the wires and the components they connect is called "artwork" or "layout" or the "physical design."

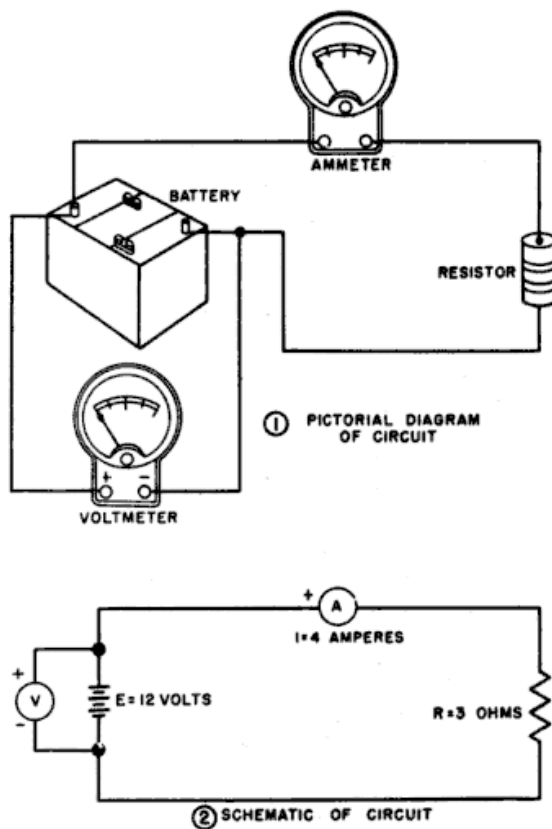



Figure 48. Diagram of a basic circuit.

Circuit diagrams are pictures with symbols that have differed from country to country and have changed over time, but are now to a large extent internationally standardized. Simple components often had symbols intended to represent some feature of the physical construction of the device. For example, the symbol for a resistor shown here dates back to the days when that component was made from a long piece of wire wrapped in such a manner as to not produce inductance, which would have made it a coil. These wire wound resistors are now used only in high-power applications, smaller resistors being cast from carbon composition (a mixture of carbon and filler) or fabricated as an insulating tube or chip coated with a metal film.

 Diode

 Capacitor

 Inductor

 Resistor

 DC voltage
source

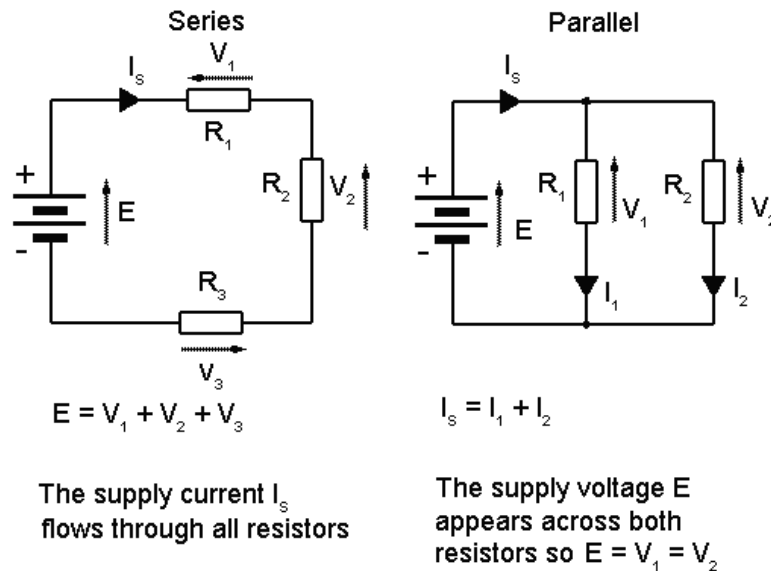
 AC voltage
source

The rules of electricity

- The laws of parallel and series voltages and currents
- Electricity must create a complete circuit to work, and will dissipate all of the voltage by the end, but none of the current

The first rule, parallel and series voltages and currents, describes how electricity travels based on the shape of its path. If electricity travels down a wire, splits into two wires, and then becomes one wire again, and there are similar light bulbs installed on each leg of the split, each bulb will receive the same voltage as was applied to the single wire before the wire split, but only half of the current available.

If one wire does not split, but still contains two light bulbs in a row, each light bulb will receive the same amount of current, but only half of the voltage.



The rule of the completed circuit is that at the end of a circuit, there is always the same exact amount of current flowing as there was at the beginning, but the voltage drops to zero as it has been dissipated as electrical energy in the form of light, motion, or heat. That is why a wire heats up if you connect it between the positive and negative side of a battery with no other load. The voltage must be **zero** at the end of the circuit, and heat is the only load available to dissipate the energy.

Ohm's Law

The first, and perhaps most important, relationship between current, voltage, and resistance is called Ohm's Law, discovered by Georg Simon Ohm and published in his 1827 paper, *The Galvanic Circuit Investigated Mathematically*. Ohm's principal discovery was that the amount of electric current through a metal conductor in a circuit is directly proportional to the voltage impressed across it, for any given temperature. Ohm expressed his discovery in the form of a simple equation, describing how voltage, current, and resistance interrelate:

Ohm's Law can be stated as mathematical equations:

V is voltage measured in **volts**

I is current measured in **amperes**

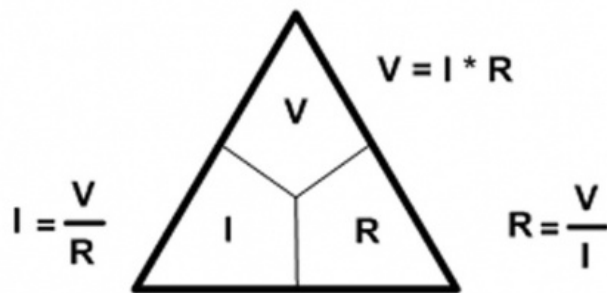
R is resistance measured in **ohms**

$$V = I \times R \text{ (Voltage = Current multiplied by Resistance)}$$

$$R = V / I \text{ (Resistance = Voltage divided by Current)}$$

$$I = V / R \text{ (Current = Voltage Divided by Resistance)}$$

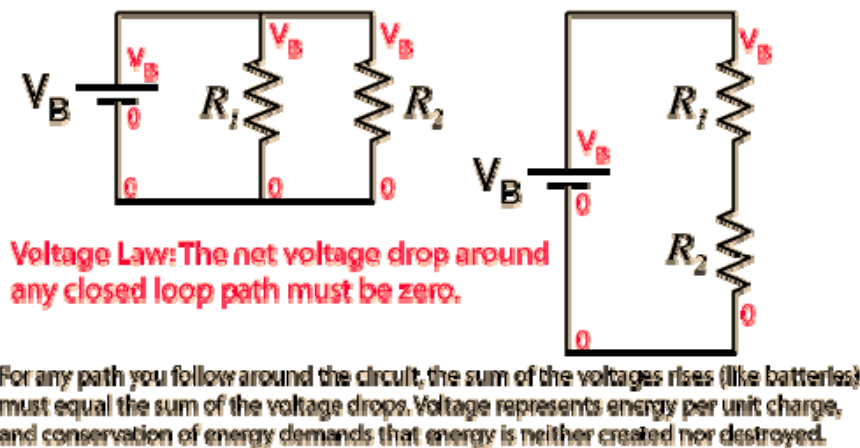
Knowing any two of the values of a circuit, one can determine (calculate) the **third**, using Ohm's Law.



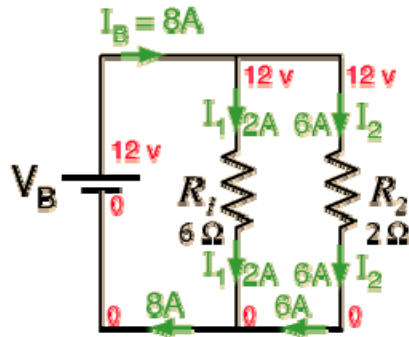
Voltage Law

The voltage changes around any closed loop must sum to zero. No matter what path you take through an electric circuit, if you return to your starting point you must measure the same voltage, constraining the net change around the loop to be zero. Since voltage is electric potential energy per unit charge, the voltage law can be seen to be a consequence of conservation of energy.

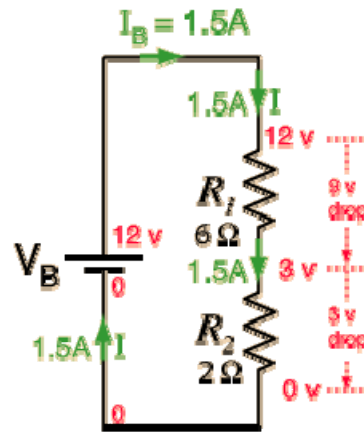
The voltage law has great practical utility in the analysis of electric circuits. It is used in conjunction with the current law in many circuit analysis tasks.



The voltage law is one of the main tools for the analysis of electric circuits, along with Ohm's Law, the current law and the power relationship. Applying the voltage law to the above circuits along with Ohm's law and the rules for combining resistors gives the numbers shown below. The determining of the voltages and currents associated with a particular circuit along with the power allows you to completely describe the electrical state of a direct current circuit.



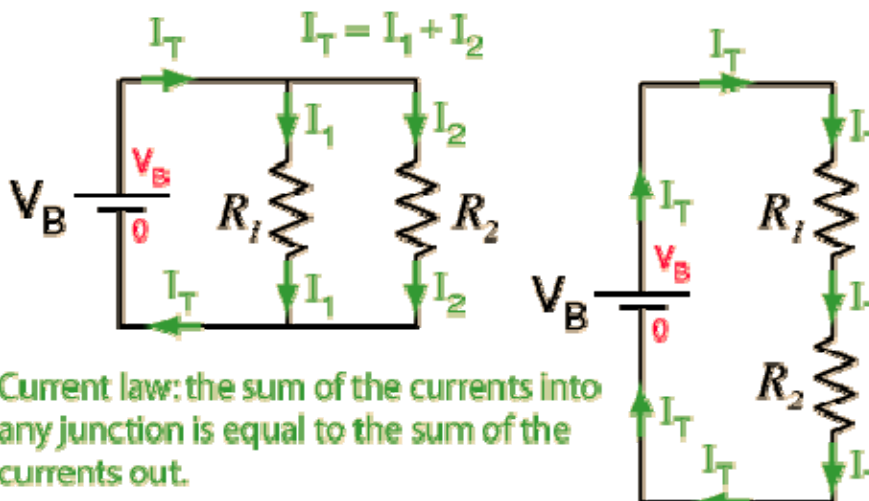
The voltages across elements in parallel are equal. This is one of the implications of the voltage law - since the change across either R_1 or R_2 must be equal to the battery voltage V_B , then they are equal to each other.



For a series combination, the sum of the voltage drops across R_1 and R_2 must sum to equal V_B .

Current Law

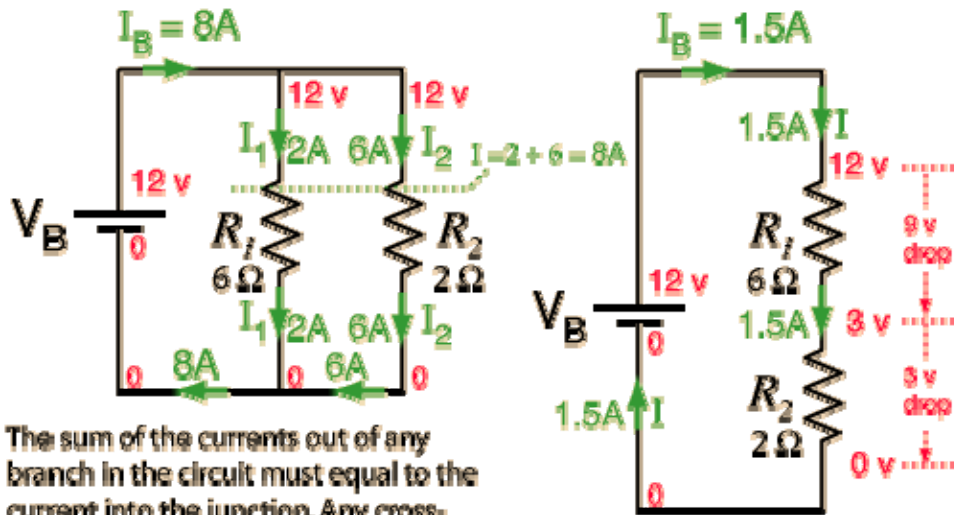
The electric current in amperes that flows into any junction in an electric circuit is equal to the current which flows out. This can be seen to be just a statement of conservation of charge. Since you do not lose any charge during the flow process around the circuit, the total current in any cross-section of the circuit is the same. Along with the voltage law, this law is a powerful tool for the analysis of electric circuits.



Current law: the sum of the currents into any junction is equal to the sum of the currents out.

For any branch of the circuit, the current out of the branch must be equal to the current into the branch. This is required by the conservation of electric charge. Any cross-section of the circuit must carry the total current. For a series circuit, the current is the same at any point in the circuit.

The current law is one of the main tools for the analysis of electric circuits, along with Ohm's Law, the voltage law and the power relationship. Applying the current law to the above circuits along with Ohm's law and the rules for combining resistors gives the numbers shown below. The determining of the voltages and currents associated with a particular circuit along with the power allows you to completely describe the electrical state of a direct current circuit.



The sum of the currents out of any branch in the circuit must equal to the current into the junction. Any cross-section containing all the conductors must have the same total current.

For a series combination, the current is the same at any point in the circuit. It is like water flow through a single pipe.

Calculating Resistance



$$R_{\text{equivalent}} = R_1 + R_2 + R_3 + \dots$$

$$R_{\text{equivalent}} = \frac{V}{I} = \frac{V_1 + V_2 + V_3 + \dots}{I} = \frac{V_1}{I_1} + \frac{V_2}{I_2} + \frac{V_3}{I_3} + \dots = R_1 + R_2 + R_3 + \dots$$

Series key idea: The current is the same in each resistor by the current laws.



$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$

Parallel:
$$\frac{V}{R_{\text{equivalent}}} = I = I_1 + I_2 + I_3 + \dots = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \dots$$

$$\frac{1}{R_{\text{equivalent}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$

Parallel key idea: The voltage is the same across each resistor by the voltage laws.

Useful Equations

Voltage = Current X Resistance

$$(V = I * R)$$

Power = Current X **Voltage**

$$(P = I * V)$$

Therefore,

Power = Current² X Resistance

$$(P = I^2 * R)$$

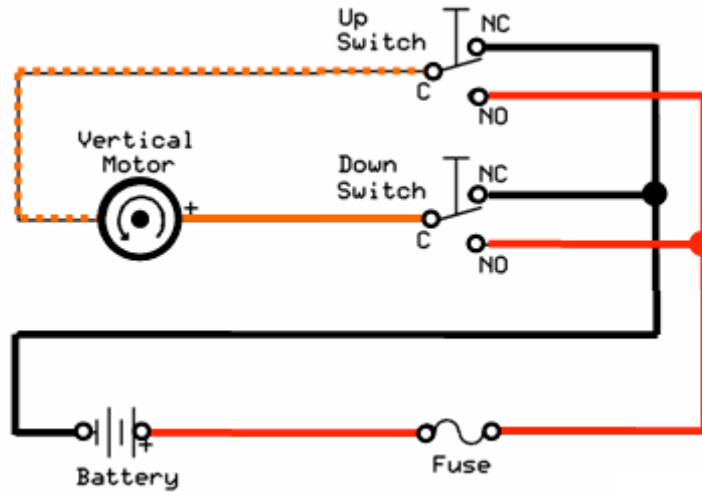
Energy = Mass X [Speed of light]²

$$(E = M * C^2)$$

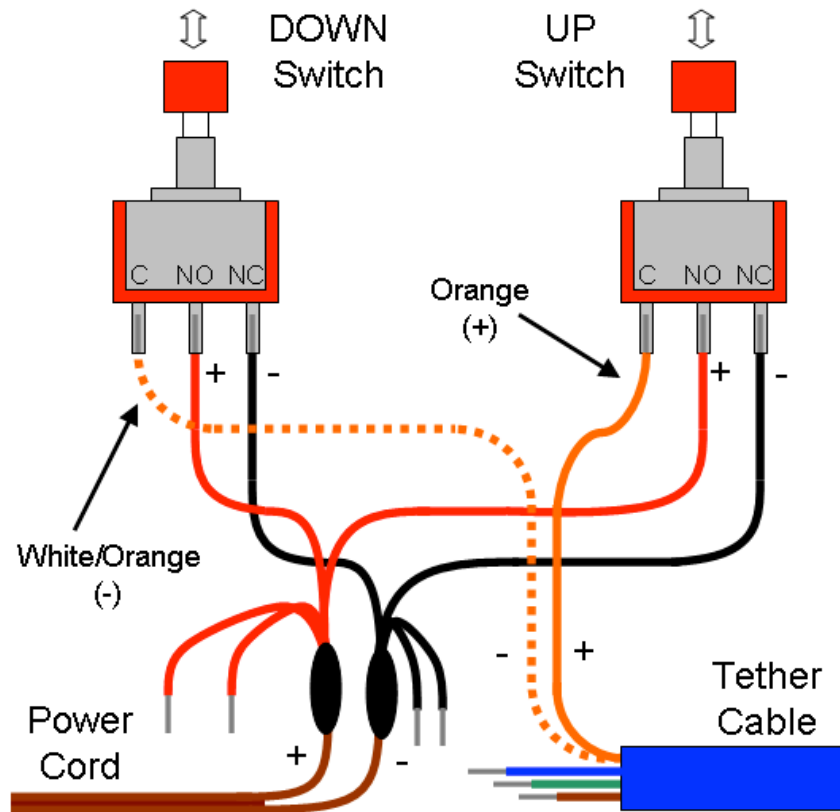
Power = **Energy** / Time

$$(P = E / T)$$

*1 Watt of **Power** = 1 Joule/Second*



Vertical thruster circuit diagram.



Vertical thruster control / pushbutton switch wiring diagram.

Electric Motors

How do electric motors work?

The short answer to this question is that electric motors convert electrical energy into magnetic energy, and then into rotational force. But it is clearly not that simple. An electric motor is the fundamental electro-mechanical energy converter that uses the forces of electricity, magnetism, angular momentum, and inertia, as well as electro-magnetic theory, Faradays theories of electric current, and Tesla's theories of alternating current.

Magnets? I thought you use electricity?

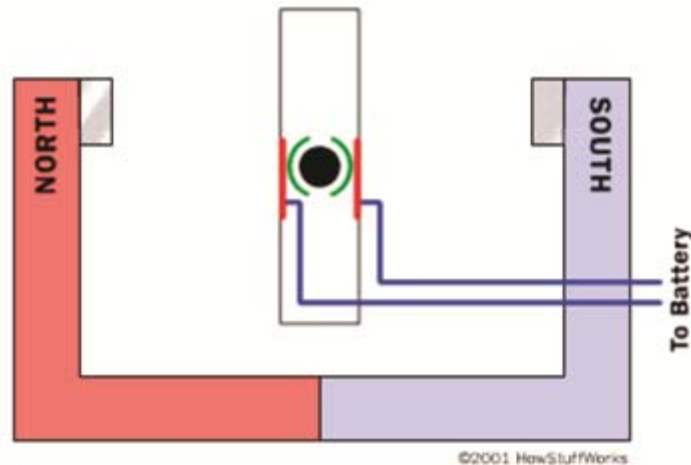
You do, but electricity alone will not create rotation. The fundamental principle at work in an electric motor is magnetism. Imagine you have a paper clip on a table and you slowly move a magnet towards it. As the magnet comes close to the paper clip, one of two things will happen. The paper clip will either jump toward the magnet, sticking firmly, or it will slide away from the magnet until it gets far outside of its magnetic field. If you turn the magnet around in your hand, the opposite will happen. This is called the magnetic moment, and regardless of its shape, size or material, the magnet will always have a "pulling" force on one side and a "pushing" force on the other.

Now imagine replacing the paper clip with a magnet. What would happen if the "pushing" side of the magnet in your hand were pointed at the table magnet? Again, it depends on the orientation of the magnet on the table. If the same side of this magnet (the "pushing" side) were pointed at the magnet in your hand, the magnet on the table would slide away from you just as you would expect. However, if the magnet on the table had the "pulling" side pointed at the same "pushing" side of the magnet in your hand, the magnet would then jump off of the table and stick to the magnet in your hand. The point here is that by changing the polarity (or pushing/pulling side) of the magnet, you can change the direction that the magnet moves.

But how does that apply to motors?

A motor works exactly the same way, by controlling the orientations of the magnets inside it for a specific result. Inside of a motor, there are essentially four magnets. Two are on opposite sides of the outer casing

(the stator), with one that is "pulling" and one that is "pushing." Two other magnets are on opposite sides of the spinning shaft; these switch between one "pulling" and one "pushing" at the same time.



The idea is that the one of the shaft magnets is set to "push" and the other to "pull," so they are pushed away from the closest stator magnet and pulled towards the next magnet. Just as they get to the halfway point between the two stator magnets, they switch to polarity and are attracted to the next stator magnets. At the exact second that the shaft magnets are closest to the stator magnets, they switch again and are then repelled by the closest magnet and attracted to the next, and continue to rotate. This happens forever as long as the mechanism exists to switch the polarity of the shaft magnets, which we will get to in a little bit.

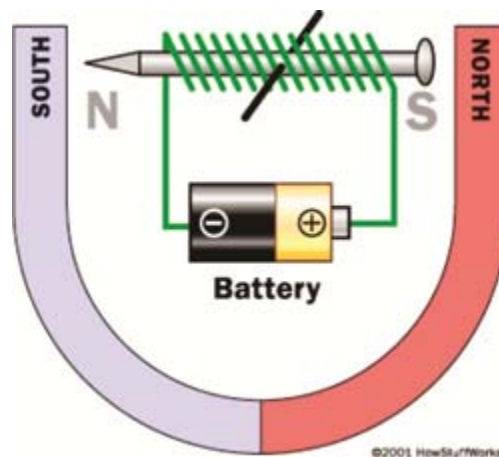
[But why does the shaft continue to spin in the same direction? Why doesn't it get stuck in the middle or spin the other way when the polarity changes?](#)

The shaft continues to rotate in the same direction because of angular momentum and inertia. Inertia is the force that keeps you moving once you start, and what makes it difficult to start, if you are stopped. Imagine riding a bicycle. It is hard to start moving, easy to continue moving once you have started, and then hard to stop once you are going. Angular momentum is the force that makes a pendulum work, making a heavy thing on a string spin. As you rotate the object through the air on a string, it spins around your hand. When you stop moving your hand, the object continues to spin. It is because of this that the magnets on the shaft, called the armature, keep going in the same direction after they have started moving.

They don't get stuck because, well, real motors actually have three armature magnets and only two stator magnets, called permanent magnets. In this case, there is always an imbalance of magnetic force as two of the armature magnets pull toward one permanent magnet, while only one repels it. This guarantees that the motor never gets stuck on one position.

But what about that polarity switching mechanism and all this talk of electricity?

The magnets in the armature aren't exactly your standard type of magnets. These are called electromagnets and work by a principle of electromagnetism that states that when electricity flows through a loop of wire, a magnetic field is generated. You can build one of these. You will need a non-magnetic screwdriver or iron nail, a battery, and some bare copper wire. Wrap the wire around the shaft of the nail a dozen or so times, then connect the ends of the wire to a battery. Your nail is now magnetic.



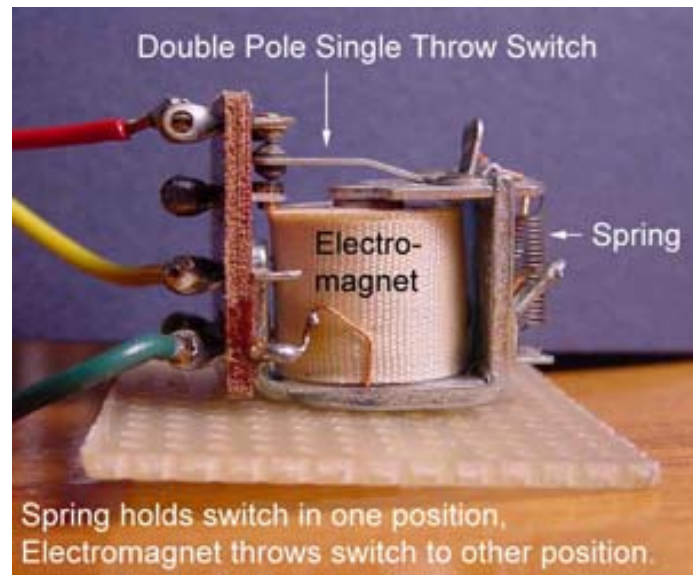
If you turn the battery around, you can see that your nail begins to repel metal objects. This is how the armature magnets work. A coil of wire is connected to the incoming power of the motor. As the power enters the loop, a magnetic field is generated for a moment in one direction. As the motor spins, the coil is disconnected from the power at the commutator and then reconnected backwards, thus creating the opposite polarity. This happens simultaneously with three coils of wire, some of which are connected forwards, and some backwards, creating rotation and a switching of the magnetic field.

Relays

How do I turn on a switch without being at the switch?

What you need is a relay. A relay is an electromechanical switch that is activated by electricity and uses magnetism to turn the switch either on or off. The purpose of a relay is to switch high power items that can draw too much current to safely come in contact with the switch itself, or to enable you to run high currents through one wire and connect and disconnect them with low current through another wire. Basically, a relay is a switch that keeps you away from dangerous amounts of power, or lets you use smaller wires to run things.

How does it do that?



A relay has two main parts: the contacts and the electromagnet. The contacts work exactly the same way as a mechanical switch's contacts. You attach the incoming wire to one contact, and the outgoing wire to the other contact. The switch either connects the two contacts, allowing electricity to pass through, or it disconnects them, breaking the path from the power source to the ground and stopping the power in its tracks. The electromagnet in a relay takes the place of human fingers. When current is run through the relay's electromagnet (from a different circuit than the one you are turning on and off with the relay), energy is forced through a coil of copper wire. This energy creates a magnetic pull on one of the contacts, physically bending it until it touches the other contact, creating a closed

circuit. When the current stops flowing through the coil, the magnetism disappears and the contact restores to its original position, no longer touching the other contact.

[Where does this magnetism come from? I don't see any magnets!](#)

As Maxwell and Faraday deduced in the mid 1800's, when electricity runs through a coil of wire, a proportional magnetic field is generated around the coil of wire in a perpendicular direction to the coil. Basically, the coil of wire converts electrical energy to magnetic energy, instantaneously creating a magnetic field.

[Why do I need a relay?](#)

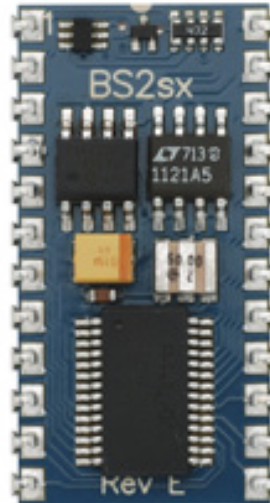
You don't. If you are supplying power to a small electric motor through thin 24 gauge wire, you need nothing more than a battery, wire, motor, and a switch. The motor will draw at most a half amp of electricity, which will pass through the thin wire just fine. If you upgrade the motor to something larger, you will draw more amps to provide the added boost, and therefore need a larger wire. Think of people in a hallway. If too many people try to get through at the same time, the hallway gets clogged. And if they stay there for a while, because they are moving more slowly, the room can get a little warmer from everyone's body heat. The same is true for electricity. If too much electricity tries to go through a wire that is too small, the electricity backs up, and the wire heats up. As a result, with the larger motors, you need a larger wire.



Once you need larger wires, you will need larger switches that can handle the added power. And if you have several motors, you will need several large switches and several less flexible larger wires. All of this begins to become too big and unwieldy to be very useful, so it's a good idea to use relays to change the way things work. With relays, you can still use small wires and small switches to turn the relays on and off. And you can run just one pair of big wires to the relays, which can split up the one wire into several short lengths of large wire that go between the relays and the motors. This will make the control box a more manageable size and the cabling going between the control box and the motors more flexible and easier to work with.

Microcontroller

What is this "Microcontroller" anyway?



A Microcontroller is essentially a one-board computer or a PC on a chip. Your home computer uses many different modules for memory and processing that plug into a motherboard and stack up to be the large computer tower sitting next to your monitor. In contrast, a microcontroller has tiny versions of all of those individual boards built on one single board that can be the size of a postage stamp or smaller.

How do they do that?

This is accomplished when an electrical engineer miniaturizes the components that are used in the PC size board to a single component the size of a grain of rice.

How is this done?

Your computer is large because it does anything you ask it to do. If you need to write a paper, you can use a document editor. If you want to edit photos, it can do that too. In the quest to make chips small, the electrical engineer will remove this ability from the microcontroller chips so that they are only able to perform a few simple dedicated functions. And this is what a microcontroller does best: listen to and respond to the environment.

Several of these minimalistic rice-size components are then assembled to make one of those small black computer chips (called Integrated Circuits or IC's) that you have probably seen in a broken calculator or other electrical device.

Several of these IC's-one for processing, one for data storage and some to regulate what gets plugged in-are attached or soldered to a computer board. This board, when completed, looks like a centipede with between 8 and 32 wire legs, each of which can be used to input data, output data, count button pushes, turn on a switch, make a sound or anything else you can imagine.

But why do you want to measure things anyway?

Why the need to push a button with a computer or to count how many times something happened?



Imagine if the cable for your mouse didn't have the USB or PS/2 fitting on the end - there would just be four wires sticking out that needed to be attached to the computer (one to measure how far forward the mouse moves, one to measure how far to the side the mouse moves, and two for power).

In the microcontroller world, the two power cables would be attached to a plug or battery, and the two measurement wires would be attached to two of the "legs" of the microcontroller. Every time the mouse moves a certain distance, a signal (think of a playing card in a bicycle wheel) is sent to the microcontroller and counted. If 100 of these signals or clicks is equivalent to one mouse ball rotation, and the microcontroller has received 100 clicks in the forward direction and 50 clicks in the sideways direction, the computer, with the aid of some simple programming, can understand that the mouse has moved one ball rotation forward, and a half rotation sideways.

That's how a computer works?

Using some very basic logic and good programming, you can tell a computer to do anything. As for the computer program, well, this is where a software engineer would write a piece of code in a language of his or her choice that very logically tells the computer what the signals mean.

An example for the mouse would be:

PROGRAM	EXPLANATION
PIN 1 = Input Y Direction	Tells the chip pin 1 is an input to measure the Y movement
PIN 2 = Input X Direction	Tells the chip pin 2 is an input to measure the X movement
If PIN 1 = CLICK	Asks, "Did I receive a click signal from pin 1? If I did, perform the following line, if not, skip the following line
Counter add 1	If pin 1 received a click, increment the counter by 1
If PIN 2 = CLICK	Asks, "Did I receive a click signal from pin 2? If I did, perform the following line, if not, skip the following line
Counter2 add 1	If pin 2 received a click, increment the counter by 1
LOOP	Go to the beginning until no more signals are transmitted, then go to the next line
Output "your mouse moved"	Display the text "your mouse moved"
Output Counter	Display the numerical value of counter
Output "clicks in the Y direction"	Display the text "clicks in the Y direction"
Output "your mouse moved"	Display the text "your mouse moved"
Output Counter2	Display the numerical value of counter2
Output "clicks in the X direction"	Display the text "clicks in the X direction"

If the mouse moved the previously stated amount, the output of this program looks like this:

"Your mouse moved 100 clicks in the Y direction"
"Your mouse moved 50 clicks in the X direction"

If you wanted more useful data, you could write a mathematical function in the program that converts clicks to mouse rotations and then to inches, if you knew the diameter or radius of the mouse ball (about a half inch) and the formula for the circumference of a circle ($C=\pi*D$). An example of this program for the Y direction would be:

PROGRAM	EXPLANATION
Pi=3.14159	Defines the value of Pi as 3.14159
D=.5	Defines the Diameter (D) as .5 inches
Yrotation = counter/100	Converts counter into revolutions (one revolution is 100 clicks)
Ycircumference = pi*D*Yrotation	Calculates the circumference of the ball in inches ($C=D*\pi$) and multiplies that by revolutions
Output "your mouse moved"	Displays "your mouse moved"
Output counter	Displays the value of counter
Output "clicks"	Displays "clicks,"
Output Yrotation	Displays the value of Yrotation
Output "revolutions"	Displays "revolution, or"
Output Ycircumference	Displays the value of Ycircumference
Output "inches"	Displays "inches"

If the mouse moved the previously stated amount, the output of this program would look like this:

"Your mouse moved 100 clicks, 1 revolution, or 1.5708 inches"

Using this logic, you can have a microcontroller perform any task you can think of by adding different sensors, buttons, motors and lights. The microcontroller can even do several things like this at once-as many measurements and commands as there are input and output pins on the controller.

So why is my computer so big when this microcontroller computer can do anything the large PC can do?

There are a lot of reasons, but it comes down to storage and input and output pins. If a mouse uses 2 pins, just imagine how many a printer or a keyboard may use. And if a microcontroller usually has no more than 32 pins, you will quickly run out of places to plug things in. Additionally, there is only a very small storage device on a microcontroller. It is just large enough to store the program that controls it, and about 15 extra words or numbers (variables). That means you could only write one- or two-sentence reports on a microcontroller computer. The benefit of this is that, because the microcontroller has fewer abilities and parts, it is significantly cheaper and smaller than a desktop PC. This is no good if you want a computer that can do anything. But if you want a computer to do one or two specific things very well, there is no better option than a microcontroller.

So if you need more than a few inputs and outputs, and want to store large documents and print things, you should probably stick to a large PC; but if you are looking for a small inexpensive computer that can fit in a tight space to control a simple electronics project or remote control vehicle, a microcontroller is for you.

To summarize a **microcontroller** is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. Program memory in the form of ROM is also often included, as well as a typically small amount of RAM. Microcontrollers are designed for embedded applications, in contrast to the microprocessors used in personal computers or other general purpose applications.

Microcontrollers are used in automatically controlled products and devices, and other embedded systems. By reducing the size and cost compared to a design that uses a separate microprocessor, memory, and input/output devices, microcontrollers make it economical to digitally control even more devices and processes.

Switches

How is it that by moving a small lever or pushing a button I can make a motor spin forward or backwards, or not at all?

Switches and buttons work via the same principle, by mechanically connecting the power wire when you want the motor to run, and disconnecting it when you want it to stop. Essentially they switch between providing power or not, hence the name switch.

Imagine the simplest circuit possible: a battery connected to a light. In this example, power comes out of one side of the battery, goes into the light, then comes out and returns to the battery. As long as this loop is connected and the battery is charged, the light turns on. You can build this circuit with an LED, battery and some wire.

Now imagine if you were to remove the wire between the battery and the bulb. The light would turn off because power can no longer get to the bulb or from the bulb, depending on which wire you removed. This is exactly how a switch or button works. It mechanically disconnects the wire from the light.

But my button has places for three wires, and my switch has six!

The previous example of a switch is for a type known as a Single Pole Single Throw (abbreviated SPST). This means that one wire, the pole, can be connected or disconnected to only one other wire, the throw. The Push Button fits in a category of switches called Single Pole Double Throw (abbreviated SPDT). It is Single Pole because one wire (the pole) can be switched between two connections (the Throw)-in this case either to the ground of the battery when the button isn't pressed, or to the positive side of the motor when it is pressed. These types of switches usually have three terminals, the center being the Common (C) or Pole, and the other two designated as either Normally Open (NO) or Normally Closed (NC). NO designates the terminal that will not be connected to the battery when the button is left alone, i.e., this circuit is open, whereas NC designates the terminal that will be connected when the button is left alone, i.e., the part of the circuit that is closed.

If you are confused, you may want to check out the video on how to use a multimeter to see how a switch works before you continue reading.

The toggle switch is in a category of switches called Double Pole Double Throw (DPDT). This means that there are two poles each of which has two throws. This enables you to simultaneously turn two independent circuits on or off at the same time.

Can't you do that with two SPDT switches?

Yes, you can.

It would work perfectly, except for the fact that you need more than one finger to turn on both switches, and as you build a more complex circuit, like a remote control, you will quickly run out of fingers if you use only single pole switches. So, to minimize finger strain, it is advantageous to use multiple pole switches to turn on or off all of the circuits that should turn on or off at the same time.

What else can I make with a switch?

Anything! Once you can use a switch effectively and choose the right switch for the right job, you can make just about anything. As an example, computers use nothing more than millions and millions of switches to remember what your photos look like and what your music sounds like, even if you turn it off and unplug it. The computer has an amazing ability to code information in a language called binary, which is switch language for on or off. Everything on earth can be represented in this form, but the easiest form to understand is numbers. For example, the number 24 is a number written using standard decimal notation (also called base 10). If you convert this to binary (called base 2) you will see that it is equal to 11000.

What? How is 24 the same as 11000?

24 is a number in base 10. The way base 10 works (and this may seem unnecessary to explain) is by indicating with the numbers 0-9 how many sets of 1's, 10's, 100's, 1000's, etc., there are. So for 24, there are no 1000's, no 100's, two 10's, and four 1's. It could also be represented as having 2.4 10's, or 24 1's, but that is not allowed because in base 10, the numbers must be below 10, and you are only allowed to count in whole integers. The key thing that is often not understood is where the 1, 10, 100, and 1000 come from. You may think that each number ends in one more 0 than the previous number, and although that is correct, it is not how we

arrive at those numbers. Each number comes from taking 10, and multiplying it by itself 0 times (not by 0 which would equal 0), then 1 time, then 2 times, then 3 times, and so on. You get the picture. This looks like this in mathematical notation:

$$10^0, 10^1, 10^2, 10^3, \text{ which is equal to } 1, 10, 100, \text{ and } 1000$$

This is read as ten to the 0th power, 10 to the 1st power, 10 to the 2nd power, and 10 to the 3rd power. If you replace the 10 with a 2, you get binary counting, or:

$$2^0, 2^1, 2^2, 2^3, 2^4, 2^5, \text{ which equals } 1, 2, 4, 8, 16, \text{ and } 32$$

Understanding this and applying the same theory of how to represent 24 in base 10, we can obtain 24 in base 2. There are no 32's in the number 24, so we will skip that. There is one 16 in 24, so we will make note of that and the remainder, 8. Next we check to see whether there are any 8's in the remainder, which is 8; there is one, which leaves us with a remainder of 0. Now even though there is no remainder left, we will continue checking the rest of the numbers. Are there any 4's in 0? No. Are there any 2's in 0? No. What about 1's? No. We are left with the understanding that there is one 16, one 8, zero 4's, zero 2's, and zero 1's, or 11000 in binary.

Why did I just do that ?

To answer this, it is essential to understand a few things. First, look at the number 11000. You should notice that there are only 1's and 0's. This is the key concept to understand. Try other numbers and you will see that any number you can come up with will be equal to a binary number with only 1's and 0's. In the electronic world, the number 1 is equivalent to "on," and 0 is equivalent to "off."

Really. Go look at the power switch on the back of your computer, or the power switch of a vacuum cleaner.

1 means the device is running, 0 means it is not. Now that you believe this, think about what a number like 11000 could mean.

How about "on, on, off, off, off?"

Do you see how this applies to switches?

If a computer wants to remember the number 24, it just turns the first two switches on and the next three off. That way, when the computer checks to see what number it was remembering, there are 5 switches in the pattern-"on, on, off, off, off"-that tell it the number was 24.

Okay, that seems reasonable, but this picture of my friends has no numbers in it. How does that work?

It may not seem like it, but your picture is actually a collection of millions of numbers in just a few categories. These categories include color, intensity, and position. If you are familiar with how light works, you will know that there are three primary colors of light (these operate differently from primary colors of paint): red, green, and blue. If you look really close at a screen or carefully put just one drop of water on a screen to act as a magnifying glass, you will see thousands of little red green and blue dots that make up the image you are looking at right now. The important feature of using three colors to make the full spectrum of colors you can see on the screen is blending. If you use red, green and blue light at full power, you will end up with the color white. (Again, it works differently than paint, which if mixed in these colors, would yield a brown-black hue.) Instead of showing you only white, red, blue, and green, the computer is able to turn each of the three lights on partially if needed. Thus, to make the color light yellow, it turns on the red and green lights to full power, and the blue to about 1/3 power. It does this by assigning each of the three colors a numerical value between 1 and 256 (or 1 and 100,000,000 in binary) that is proportional to the required brightness.

So light yellow would be in the form [red][green][blue] represented as:

[256][256][100] in decimal, or in binary, [100000000][100000000][1100100]

The only other parameter is the location on the screen where this light yellow dot should appear, which is indicated by counting the number of dots or pixels from the top right corner of the screen you want to move your color to the right and down. If you want to move one inch right and one inch down, and there are 300 pixels per inch, you would move 300 pixels to the right, then 300 pixels down, and then apply your color. The full numerical command for this one yellow dot would like this:

[300] [300] [256] [256] [100] in decimal or

[100101100] [100101100] [100000000] [100000000] [1100100] in binary

That means for one yellow dot in a picture you would need 43 switches, and you need to do this for every dot on your screen at all times!



Sensors

What is a sensor?

A sensor is an input device. It converts the tangible world into a series of signals that a processor can understand. Be it the sense of smell with a nose sensor and its processing by the human brain, distance with sonar and a bat brain, or electrical current with an ammeter and a computer, it all works by measuring the property of interest with a tool, then converting it into an electrical signal that the brain of the animal or computer processes. With this processed information, the animal or computer can better understand its surroundings and environment.

There are an infinite number of sensor types in the world, and if a sensor doesn't exist but is needed, one can be built custom. Some standard sensors include:

- Available light (photo diode, eyes)
- Distance (infrared range sensor, acoustic range sensor)
- Magnetic heading (digital compass)
- Acceleration (accelerometer, gyroscope, inner ear)
- Temperature (thermocouple, skin)
- Touch (pressure sensitive switch, hair)
- Electrical current (ammeter)
- Angle (inclinometer, inner ear, eyes)

And they all work by measuring the parameter of interest and converting it into an electrical signal the appropriate processor can understand.

Can a computer understand its environment?

Humans are optimized for sensing; each of us is built with eyes, ears, a nose, highly receptive and reactive skin, and a tongue. We also have the ability to learn from experience, so if we sense something we are not familiar with, it is possible for us to determine what it is, how dangerous it is, how far away it is, or what its material properties are - we can make sense of what we sense. We even have the ability to describe sensations to other humans or even computers.

But can we get a computer to do all the sensing itself?



The short answer is no. While computers are amazing machines with the ability to process anything and run programs, they have two major flaws: they crash when programmers have forgotten to tell them even minor details about their work and they must rely on digital copies of everything that exists in the real world. In other words computers don't have any sense if you don't give it to them and they can't make sense of the real world, only simulations of it.

Digital, what's that?

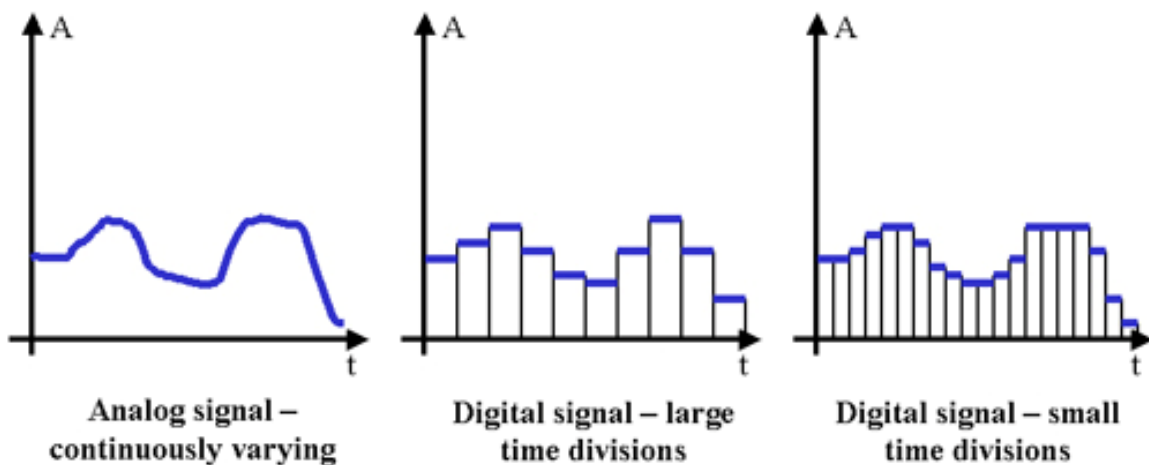
Before analyzing digital items, let's first look at what isn't digital. The opposite of a digital item is an analog item. An analog item is something that can be described using partial values, in other words, something that exists between a maximum and minimum measurable value. For example, a person's body weight throughout the day changes or fluctuates up to 1 – 3 lbs. The body weight could vary up to 5-6 lbs during the month. The range of measurement taken at different times would be an analog value.

Digital items work a lot differently. A digital item is binary, it has only two values, completely on, or completely off, yes absolutely or absolutely no. Some examples of this are the switch on the lamp, eating, and being in one place. The lamp is either on, or off, but never in the middle; in the act of eating, you are either doing it or not; and by being in one place, you are either there, or somewhere else. Since computers can only understand

binary input (read "how switches work" to learn about binary) they are very well suited to understanding digital inputs, but since they only take in on/off values it is very difficult to describe an analog experience in digital terms.

So how do you input analog values into a digital computer?

It starts with logic. First you need to choose exactly what analog parameters are needed to accurately describe the real item (i.e. size, color, texture). Next you need to determine how big the range of each parameter is. So if the parameter is size, what is the biggest it can be, and what is the smallest it can be, and how many different size ranges should exist between the two. Obviously there are an infinite number of size options between the biggest thing and the smallest thing, but computers need a discrete integer value as their input (i.e. the number could be 7 on a scale of 0 to 256, but could not be 8.56 from 0 to 10).



After you have your parameters and ranges, you need to describe your item. If the item is a cell phone, the parameters may be how much blue color exists, how much red color exists, how much green color exists, size, distance, altitude, and weight, and the ranges could be 0 to 256 for all of these parameters.

If it is a teal green phone on a counter, the parameters may look like the following table:

PARAMETER	RANGE	VALUE
Blue	0-256 (off to on)	256 (bright blue)
Red	0-256 (off to on)	0 (no red)
Green	0-256 (off to on)	256 (bright green)
Size	0-256 (1in ³ to 10in ³)	40 (3 in ³)
Distance	0-256 (0 ft to 5 ft)	100 (2 ft way)
Altitude	0-256 (0 ft to 5 ft)	200 (4 feet off ground)
Weight	0-256 (0 lb to 1 lb)	128 (0.5 lb)

But how do those get into the computer?

First, they need to be converted into binary numbers, or a representation of the number using several ones and zeros. If you need more info on this, check out "how switches work". Once you have these numbers in binary, you can send them through a serial port on the computer and the computer will store them in a file. Once there, the file can be accessed, read, and manipulated, and the computer can now tell you all of the details about the phone you had measured.

Printed circuit board

A printed circuit board, or PCB, is used to mechanically support and electrically connect electronic components using conductive pathways, tracks or signal traces etched from copper sheets laminated onto a non-conductive substrate. It is also referred to as printed wiring board (PWB) or etched wiring board. Printed circuit boards are used in virtually all but the simplest commercially produced electronic devices.

A PCB populated with electronic components is called a printed circuit assembly (PCA), printed circuit board assembly or PCB Assembly (PCBA). In informal use the term "PCB" is used both for bare and assembled boards, the context clarifying the meaning.

Alternatives to PCBs include wire wrap and point-to-point construction. PCBs must initially be designed and laid out, but become cheaper, faster to make, and potentially more reliable for high-volume production since production and soldering of PCBs can be automated. Much of the electronics industry's PCB design, assembly, and quality control needs are set by standards published by the IPC organization.



Serial Port

The **serial port** Considered to be one of the most basic external connections to a computer. It has been an integral part of most computers for more than 20 years. Although many of the newer systems have done away with the serial port completely in favor of USB connections.

In computing, a serial port is a serial communication physical interface through which information transfers in or out one bit at a time. Throughout most of the history of personal computers, data transfer through serial ports connected the computer to devices such as terminals and various peripherals.

While such interfaces as Ethernet, FireWire, and USB all send data as a serial stream, the term "serial port" usually identifies hardware more or less compliant to the RS-232 standard, intended to interface with a modem or with a similar communication device.

Modern computers without serial ports may require serial-to-USB converters to allow compatibility with RS 232 serial devices. Serial ports are still used in applications such as industrial automation systems, scientific instruments, shop till systems and some industrial and consumer products. Server computers may use a serial port as a control console for diagnostics. Network equipment (such as routers and switches) often use serial console for configuration. Serial ports are still used in these areas as they are simple, cheap and their console functions are highly standardized and widespread. A serial port requires very little supporting software from the host system.

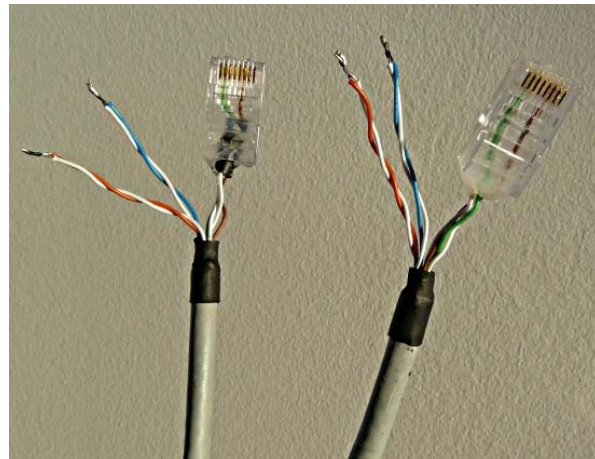


Power over Ethernet (PoE)

Power over Ethernet technology describes a system to pass electrical power safely, along with data, on Ethernet cabling. The IEEE standard for PoE requires Category 5 cable or higher for high power levels, but can operate with category 3 cable for low power levels. Power is supplied in common mode over two or more of the differential pairs of wires found in the Ethernet cables and comes from a power supply within a PoE-enabled networking device such as an Ethernet switch or can be injected into a cable run with a midspan power supply.

PoE provides both data and power connections in one cable, so equipment doesn't need a separate cable for each need. For equipment that does not already have a power or data connection, PoE can be attractive when the power demand is modest. For example, PoE is useful for IP telephones, wireless LAN access points, cameras with pan tilt and zoom (PTZ), and remote Ethernet switches. PoE can provide long cable runs (e.g., 100 meters (330 ft)) and can deliver an isolated 12 W of power.

There are competing technologies. The Universal Serial Bus (USB) provides both data and power, but it is designed for short cables (5 meters (16 ft) maximum length) and provides less than 2.5 W of non-isolated power. It is less expensive than PoE, and works well for low power peripherals such as a computer mouse, a headset/microphone, or a serial port.



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End of Electronics Section

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Practical Applications Activities:

Soldering

Using a Multimeter

Reading circuit diagram

Implementing a switch

Assembling components onto a PCB

Implementing a PoE

Buoyancy

How things float - Overview

Things float when they are positively buoyant, or less dense than the fluid in which they are sitting. This does not mean that an object has to be lighter than the fluid, as in the case of a boat; objects just need to have a greater ratio of empty space to mass than the fluid. In order to understand floating, it is essential to understand a few different concepts, including buoyancy, density, fluids, and the Archimedes Principle.

Buoyancy

Buoyancy, first and foremost, is a force. Just as gravity, drag, and acceleration are all forces that move you in one way or another, buoyancy too moves a body in a direction-which happens to be up.

This upward force occurs only when a few criteria are met. First, you need to be in a fluid. This can be a liquid or a gas, some medium with moving electrons, but not a solid, as the electrons are held in place.

The other requirement is that fluid has to have a measurable density. This is a fairly useless point as the only fluid with little to no density is the vacuum of space; but it is a requirement.



With these criteria met, it is now possible for things to be buoyant, but don't assume that means everything will start floating.

There are a few types of buoyancy:

1. A **NEGATIVELY-buoyant** item, or a body that will sink in a fluid :: Even with the buoyant force pushing the body up (which it always does), a negatively buoyant mass will have the force of gravity pull the body downward until it reaches a solid surface below it, such as the floor. Even though buoyancy lost the battle against gravity, this body still has the upward lift of the force working in its favor. If you measure the weight of the body before it is placed in the fluid, it will weigh more than it does after it has sunk to the bottom of the fluid. This is because even though the item has sunk down, buoyancy is still trying to push it upward.
2. A **NEUTRALLY-buoyant** item, or a body that will stay where it is placed in the vertical direction in a tank of fluid :: In this case, the buoyant force is equal to the gravitational force, so the body neither sinks nor floats. This is the ideal model for a submarine, as a neutrally buoyant item takes the least amount of force to keep it submerged in a position or to be moved in any direction in a fluid.
3. A **POSITIVELY-buoyant** item, or an item whose buoyant force is so great that it can push a body upward and fight the pull of gravity :: When this type of buoyancy exists, it can be said that the body is floating. If it were to be held at the bottom of the fluid and weighed, it would weigh a negative value and be constantly pushed up and away from the scale.

Density

Density is the measure of how much mass is contained in a measured volume, or how much stuff there is in one spot. Clearly, if you have a sponge and a rock that are the same size, there will be more material in the rock, because the sponge has hundreds of holes in the same volume of space.

Density (designated by the Greek symbol rho, ρ) is mathematically defined by the division of **mass (M)** by **volume (V)**, or:

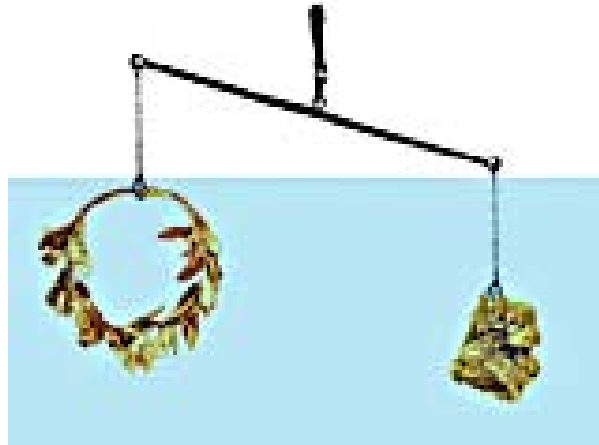
$$\rho = M / V$$

One thing to remember about density is that the mass you are measuring is that of EVERYTHING inside of the volume. Thus, in the case of the sponge, you are measuring the mass of the squishy sponge material as well as the air that fills the holes of the sponge. This explains why a boat hull full of air will float, but a hull full of water will sink. If you weigh the air-filled boat hull and divide by volume, you will get a number that is significantly smaller than if you did the same with a hull full of water.

Fluids

The key thing to understanding the meaning of fluids is that in the discussion of buoyancy, aerodynamics and other scientific topics, fluids refer to more than liquids. It is common to describe liquids such as water, juice, coolant, and other wet items as a fluid, and air, nitrogen, propane and other "invisible" intangible items as a gas. But since they behave the same way in scientific equations and conversations, they get lumped into the category of fluids in scientific situations. The defining characteristic of a fluid, whether it is gas or liquid, is the ability for its electrons to freely move around in a volume of that fluid. This is in contrast to a solid, whose electrons are somewhat fixed to a location in its volume. You would never see the corner of a desk move to the middle of a desk; it just can't happen.

Archimedes Principle



The story goes that Archimedes, a famous Greek scientist, was given the task of determining whether the king's golden wreath, a gift to the gods, was made of real gold or some alloy. Archimedes wanted to melt the gold material into a known volume and weigh it, thus determining the density. But the king would not allow this. So Archimedes thought about this for some time, until one day while bathing, he noticed the water level increased as he entered the tub, proportionally to his volume. This meant that he could put the difficult-to-measure crown in water, and instantly know the volume of the crown by measuring the displacement of water. At this point, Archimedes leapt up from the tub and ran naked through the streets shouting "Eureka! Eureka!"

What Archimedes came up with was a relationship between the volume of a solid and the volume of a fluid, which directly relates through the density equation, to a relationship between the density of a solid and a fluid, and the mass of a solid and a fluid. He also determined that the buoyant force, the mass of an object out of the fluid minus the mass of the object in the fluid, is equal to the weight of liquid displaced by the object, or:

Mass out of fluid - Mass in fluid = Density of fluid * Volume of solid, or,

$$\text{Buoyancy} = \rho * V$$

Archimedes determined that by measuring the weight of the water increase when the wreath was submerged, he was actually measuring the buoyant force acting on the wreath. And from this, he could divide by the density of water, and find the volume of the crown.

PVC

How does molten plastic become a pathway for water travel and a structural member?

Polyvinyl Chloride, or as it is commonly referred to, PVC, is a thermoplastic polymer which simply means that the material can be heated to its melting point, then formed into a shape and allowed to cool to a brittle but rock solid material at room temperature. The manufacturing of PVC relies on this transformation from molten plastic to hard plastic to create a variety of shapes that can withstand a multitude of environmental stresses.

These stresses include:

- Heat (up to 60° C or 140° F)
- Pressure
- Collisions
- Acidic material
- Physical deformation

This specific set of material properties allows PVC to:

- Bend small amounts under stress before it breaks
- Resist corrosion from acids
- Resist fracture when dropped
- Hold a lot of pressure before bursting
- Work in a variety of temperatures

With this diverse set of material properties, PVC is an ideal material to hold and move water and act as a structural member. If you want more information on material properties of PVC, check out [Lenntech's PVC webpage](#).

But why PVC?

Although there are thousands of materials in the world, it is essential to choose the best match of material properties for your application and design criteria.

In the case of plumbing, the criteria are that the material must:

- Be able to hold pressurized hot water
- Withstand the environment of a construction site
- Not contaminate drinking water
- Resist being dropped or impacted
- Cost an appropriate amount to provide a good value

In the case of a structural material, the properties of interest are:

- Cost effectiveness
- Rigidity (resistance to bending)
- Availability
- Resistance to dropping or impact
- Safe handling
- Waterproofing

Although there are many materials that meet most of these requirements or even all (like steel and acrylic), only one meets all of the requirements and costs the least, and that is PVC. As a result, the industry standard for plumbing for many years has been PVC, and many low cost low force structures can use PVC as well.

How do they make it?

PVC is made of salt and oil. Salt provides the chlorine by adding energy to the salt crystal (sodium chloride) that breaks all of the internal bonds and releases the chlorine from its grasp.

The oil is heated and cooled rapidly and repeatedly, which breaks the large molecules of hydrocarbons (the molecules that make oil) into smaller molecules, some of which are known as ethylene (small forms of hydrocarbons). These ethylene molecules are filtered out using pressure and distillation.

Once these two molecules are extracted and contained, they are mixed together in high temperature baths resulting in a new molecule known as ethylene dichloride, which at high temperatures becomes vinyl chloride. This vinyl chloride is then polymerized (forced to bond with more of the same molecule) to create polyvinyl chloride.

This is where the fun begins. PVC is not the final step. Depending on what material properties you want the PVC to have, you can add materials during the heating stage to get a more flexible material, a different colored material, a less flammable material, or a more impact resistant material. As a result, it is possible to design a plastic that is an exact match to your design criteria.

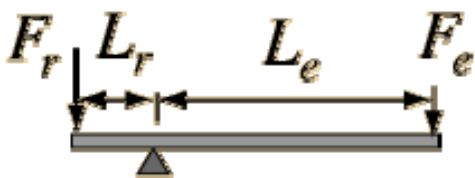
Simple Machines

- They are machines from which more complex machines can be fashioned.
- They have no internal source of energy.
- They are very useful since they multiply the input force to accomplish a task.

The factor by which Simple Machines multiplies the input force is often called the "mechanical advantage". If you idealize the machine by neglecting friction, then you can state an "ideal mechanical advantage" or **IMA** for the machine. A typical grouping of simple machines will be covered below.

The expressions for the ideal mechanical advantages of the following simple machines were obtained by determining what forces are required to produce equilibrium, since to move the machine in the desired direction you must first produce equilibrium and then add to the input force to cause motion. Both force equilibrium and torque equilibrium are applied.

The Lever



$$IMA = \frac{L_e}{L_r}$$

The lever is one of the so-called "simple machines" from which many more complex machines are derived. With a lever, one can obtain a multiplication of force, but of course not a multiplication of energy. The multiplication of force can be seen to arise from the equilibrium of torques, where an input force F_e with a long lever arm L_e can balance a larger resistance force F_r with a short lever arm L_r .

A rigid lever can approach an ideal machine since there is very little loss. From torque equilibrium we see that a resistance force F_r can be balanced by a smaller effort force $F_e = (L_r/L_e)F_r$. This is often stated in terms of the ideal mechanical advantage $F_r/F_e = L_e/L_r$ shown in the illustration.

Since we know by conservation of energy that no machine can output more energy than was put into it, the ideal case is represented by a machine in which the output energy is equal to the input energy. For simple geometries in which the forces are in the direction of the motion, we can characterize the ideal machine in terms of the work done as follows:

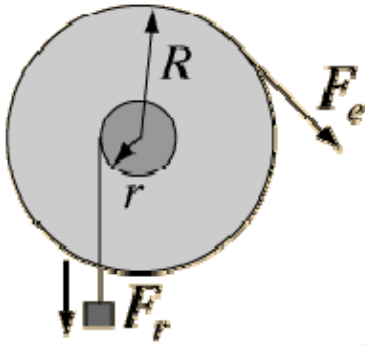
Ideal Machine: Energy input = Energy output

$$\text{Work input} = \mathbf{F}_e * \mathbf{d}_{\text{input}} = \mathbf{F}_r * \mathbf{d}_{\text{output}} = \text{Work output}$$

From this perspective it becomes evident that a simple machine may multiply force. That is, a small input force can accomplish a task requiring a large output force. But the constraint is that the small input force must be exerted through a larger distance so that the work input is equal to the work output. You are trading a small force acting through a large distance for a large force acting through a small distance. This is the nature of all the simple machines above as they are shown.

Of course it is also possible to trade a large input force through a small distance for a small output force acting through a large distance. This is also useful if what you want to achieve is a higher velocity. Many machines operate in this way.

Wheel and Axle

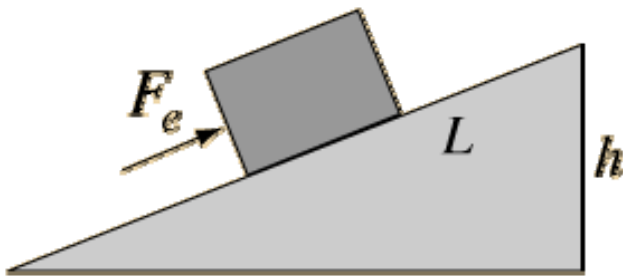


Wheel and axle $IMA = \frac{R}{r}$

The wheel and axle combination constitutes one of the so-called "simple machines" from which many more complex machines are derived. The principle of operation is essentially a lever, since it depends upon the effort force F_e having a longer lever arm than the resistance force F_r . The ideal mechanical advantage is just the ratio of those lever arms R/r .

The clear advantage of the wheel and axle over a simple lever is that the distance of travel is limited only by the amount of rope or cable that you can wrap around the wheel or axle.

The Incline



Incline $IMA = \frac{L}{h}$

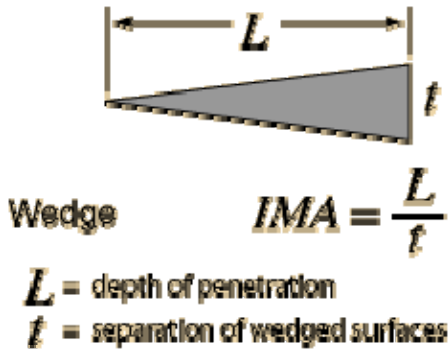
The incline is one of the so-called "simple machines" from which many more complex machines are derived. By pushing an object up a slanted surface, one can move the object to height h with a smaller force than the weight of the object. If there were no friction, then the mechanical advantage could be determined by just setting the input work (pushing the object up the incline) equal to the output work (lifting the object to height h).

The resistance force $F_r = m \cdot g$, the weight of the object. It takes work $m \cdot g \cdot h$ to overcome that resistance force and lift the object to height h . By doing work on it we give it gravitational potential energy $m \cdot g \cdot h$. By exerting F_e to

push the object up the incline, we do the same amount of work in the ideal frictionless case. So setting the works equal $F_e \cdot L = F_r \cdot h$, we arrive at the ideal mechanical advantage $F_r/F_e = L/h$ shown in the illustration.

Another approach to the incline is just to calculate the amount of force F_e required to push the object up a frictionless incline. If the forces are resolved as in the standard incline problem, you find that the required force is $F_e = m \cdot g \cdot \sin\theta = m \cdot g \cdot h/L = F_r (h/L)$.

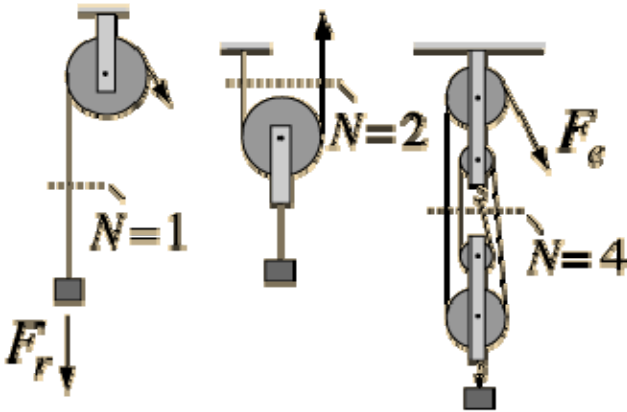
The Wedge



The wedge is one of the so-called "simple machines" from which many more complex machines are derived. The wedge embodies the same principles as the incline in the sense that a smaller force working over a longer distance can produce a larger force acting through a small distance. As a double incline, its ideal mechanical advantage is the ratio of the depth of penetration L to the amount of separation achieved t . Note that the input force for a simple incline works along the incline, i.e., the hypotenuse of the triangle. For the wedge, the working force drives the wedge inward, and the driving force times the depth of penetration is the input work to the machine.

The ideal mechanical advantage has little meaning in this case since in practical use, there is usually a large amount of friction. Nevertheless, the wedge is of great usefulness. A thin wedge of steel can create enormous forces for lifting or splitting when driven into a crack or crevice.

The Pulley

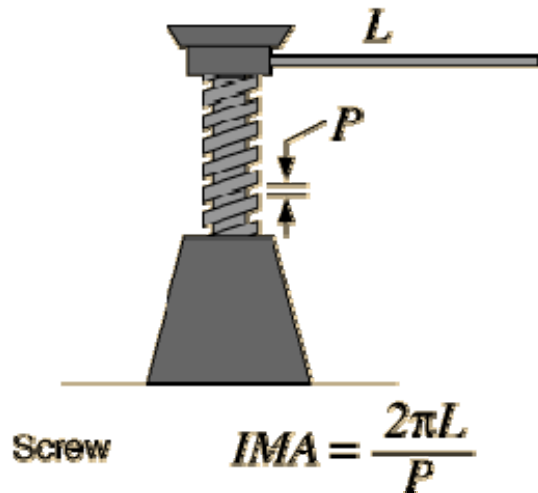


Pulley $IMA = N$

The pulley is one of the so-called "simple machines" from which many more complex machines are derived. With a single fixed-axis pulley, the ideal mechanical advantage is just $N=1$. You get the convenience of being able to redirect the effort force F_e , so that you can stand clear of the load. With a suspended pulley as in the middle illustration, the upward forces in the two ropes is equal, and therefore each supports half of the load, giving an IMA of $N=2$.

With a four-pulley set as shown, you have four ropes supporting the load, so the effort force F_e that establishes the rope tension is just one-fourth of the load in the ideal case, so $IMA=4$. All these force relationships are obtained from the force equilibrium condition, which in this case just amounts to "forces up = forces down" at any cross-section of the system.

The Screw



The screw is one of the so-called "simple machines" from which many more complex machines are derived. A screw is essentially a long incline wrapped around a shaft, so its mechanical advantage can be approached in the same way as the incline.

When a screw is turned once, it advances by the distance between adjacent screw threads. This distance is commonly called the "pitch" of the thread. As depicted in the illustration, the handle also adds a lever. Analyzed from the point of view of work, the handle is moved one circumference $2\pi L$ to lift the load by the amount P . So the ideal mechanical advantage is $2\pi L/P$.

The ideal mechanical advantage is of little meaning here since there is typically a lot of friction. But the screw is of enormous usefulness for the lifting of heavy loads and for use in screw fasteners which can exert great forces to hold objects together.

**All Simple Machines work on the principle of
"Trading Force for Distance"**

Hydraulic and Pneumatic machines

Both pneumatics and hydraulics are applications of **fluid power**. They use fluid to transmit power from one point to another.

In many ways, hydraulics and pneumatics share the same principles. However, there are a few ways in which they differ. The power in both systems is transferred through fluid.

Hydraulics

The oil that hydraulic systems use is incompressible, similar to a solid.

The motion, which is caused by fluid entering a chamber is slow and smooth.

Because the output follows the motion of the input directly, the position and speed of the output device is easy to accurately control.

The system is self-lubricating because it uses oil.

The pressure generated in a hydraulic system can range from 500 to 5000 psi. Therefore, they are commonly used to lift or move heavy objects.

Pneumatics

With pneumatics that use air, power is transmitted by gas, which is compressible like a spring.

Since compressed air tends to expand quickly, the motion is fast.

The compressed air causes the motion of the output device to be jumpy. Therefore, it is difficult to position objects accurately or at a precise speed.

An oil mist is often added to the air stream to provide lubrication.

Pneumatics systems typically operate at around 100 psi. They are commonly used to operate rotary tools and cylinders for clamps or for pushing mechanisms.

They use Pascal's Principle, which says pressure that is applied to a fluid is transmitted unchanged throughout the whole fluid. Work is performed because the pressure is the same but the area is different or changed; this makes the total pressure multiply.

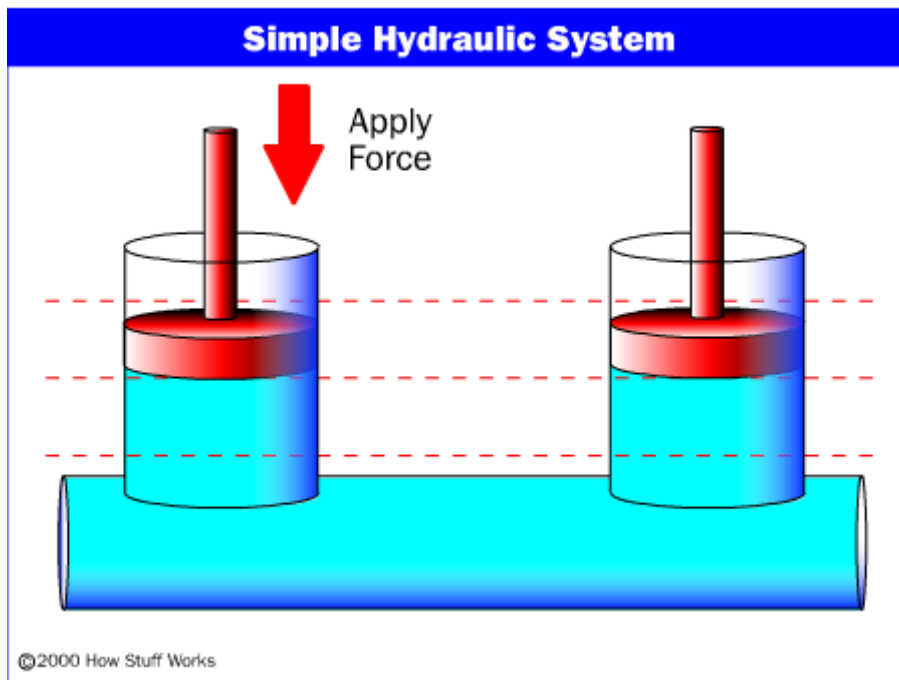
For example: A hydraulic press depends on Pascal's principle: the pressure throughout a closed system is constant. One part of the system is a piston acting as a pump, with a modest mechanical force acting on a small cross-sectional area; the other part is a piston with a larger area which generates a correspondingly large mechanical force. Only small-diameter tubing (which more easily resists pressure) is needed if the pump is separated from the press cylinder.

Pascal's law: Pressure on a confined fluid is transmitted undiminished and acts with equal force on equal areas and at 90 degrees to the container wall.

A fluid, such as oil, is displaced when either piston is pushed inward. The small piston, for a given distance of movement, displaces a smaller amount of volume than the large piston, which is proportional to the ratio of areas of the heads of the pistons. Therefore, the small piston must be moved a large distance to get the large piston to move significantly. The distance the large piston will move is the distance that the small piston is moved divided by the ratio of the areas of the heads of the pistons. This is how energy, in the form of work in this case, is conserved and the Law of Conservation of Energy is satisfied. Work is force times distance, and since the force is increased on the larger piston, the distance the force is applied over must be decreased.

A fundamental feature of fluid systems (hydraulic or pneumatic) is the ability to apply force or torque multiplication in an easy way, independent of the distance between the input and output, without the need for mechanical gears or levers, either by altering the effective areas in two connected cylinders or the effective displacement (cc/rev) between a pump and motor. In normal cases, hydraulic ratios are combined with a mechanical force or torque ratio for optimum machine designs.

The Basic Idea



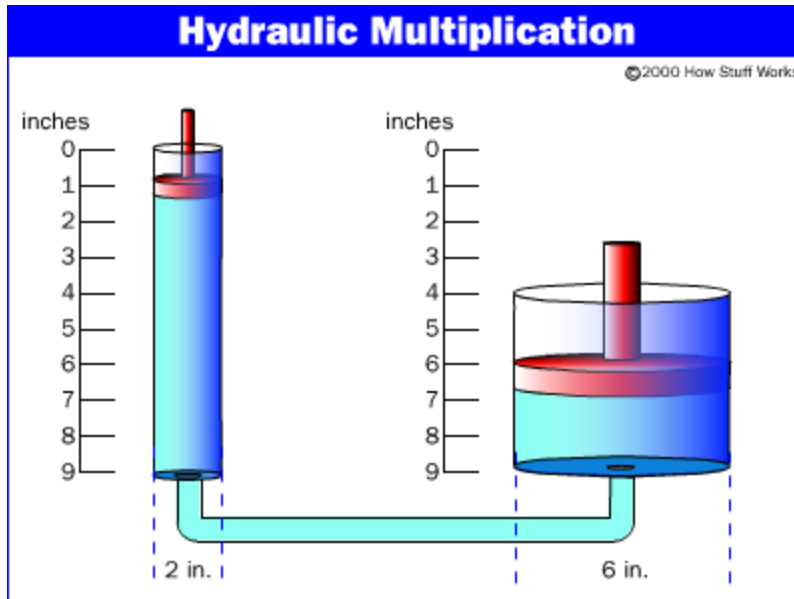
A Simple hydraulic system consisting of two pistons and an oil-filled pipe connecting them. Click on the red arrow to see the animation.

The basic idea behind any hydraulic system is very simple: **Force that is applied at one point is transmitted to another point using an incompressible fluid.** The fluid is almost always an oil of some sort. The force is almost always multiplied in the process. The picture below shows the simplest possible hydraulic system:

Reference to the drawing: If you apply a downward force to one piston (the left one), then the force is transmitted to the second piston through the oil in the pipe. Since oil is incompressible, the efficiency is very good -- almost all of the applied force appears at the second piston. The great thing about hydraulic systems is that the pipe connecting the two cylinders can be any length and shape, allowing it to snake through all sorts of things separating the two pistons. The pipe can also fork, so that one **master cylinder** can drive more than one **slave** cylinder if desired.

The great thing about fluid systems is that it is very easy to add force multiplication (or division) to the system. As we covered earlier, **trading force for distance** is very common in mechanical systems.

In a fluid system, all you do is change the size of one piston and cylinder relative to the other, as shown here:



Hydraulic multiplication: The piston on the right has a surface area nine times greater than the piston on the left. When force is applied to the left piston, it will move nine units for every one unit that the right piston moves, and the force is multiplied by nine on the right-hand piston. Click the red arrow to see the animation.

To determine the multiplication factor:

The piston on the left is 2 inches in diameter (1-inch radius), while the piston on the right is 6 inches in diameter (3-inch radius). The area of the two pistons is $\text{Pi} * r^2$. The area of the left piston is therefore 3.14, while the area of the piston on the right is 28.26. The piston on the right is 9 times larger than the piston on the left. What that means is that any force applied to the left-hand piston will appear 9 times greater on the right-hand piston. So if you apply a 100-pound downward force to the left piston, a 900-pound upward force will appear on the right. The only catch is that you will have to depress the left piston 9 inches to raise the right piston 1 inch.

Hydraulic machines

Hydraulic machines are machinery and tools that use liquid fluid power to do simple work. Heavy equipment is a common example.

In this type of machine, hydraulic fluid is transmitted throughout the machine to various hydraulic motors and hydraulic cylinders and which becomes pressurised according to the resistance present. The fluid is controlled directly or automatically by control valves and distributed through hoses and tubes.

It is important that a hydraulic system contains no air bubbles. If there is an air bubble in the system, then the force applied to the first piston gets used compressing the air in the bubble rather than moving the second piston, which has a big effect on the efficiency of the system.

The brakes in a car are a good example of a basic piston-driven hydraulic system. When you depress the brake pedal in your car, it is pushing on the piston in the brake's master cylinder. Four slave pistons, one at each wheel, actuate to press the brake pads against the brake rotor to stop the car.

Note: In almost all cars on the road today two master cylinders are driving two slave cylinders each. That way if one of the master cylinders has a problem or springs a leak, you can still stop the car.

In most other hydraulic systems, hydraulic cylinders and pistons are connected through valves to a pump supplying high-pressure oil.

Many functions in hydraulic systems are provided by reservoirs. First, a reservoir holds the fluid in a convenient spot for the pump inlet. It supplies extra fluid to the circulating system in the event of leakage or cylinder extension. In addition, most reservoirs are called upon to perform a fluid-conditioning role, in which the turbulent fluid returning from the hydraulic system is allowed to settle and deaerate. And to complete the complex list, many users expect a reservoir to exchange heat with the outside air, thus cooling the heated fluid.

The method for determining reservoir size is to determine the heat balance of the hydraulic system, calculate the amount of heat that will be generated in it through lost work, then determine the amount of space available and the amount of heat that can be dissipated in that amount of reservoir space. Such a calculation will quickly reveal the necessity for a heat exchanger, if it exists. After a decision is made on a heat exchanger, the reservoir size can be determined.

Pneumatic Machines

Pneumatic systems are extensively used in industry, where factories are commonly plumbed with compressed air or compressed inert gases. This is because a centrally located and electrically powered compressor that powers cylinders and other pneumatic devices through solenoid valves is often able to provide motive power in a cheaper, safer, more flexible, and more reliable way than a large number of electric motors and actuators.

Pneumatic Systems comprise a huge number of technologies and integrations that use pressurized air to either power or drive them. In the case of pneumatic controls and instrumentation, pneumatics are used to communicate process variables commands to control valves. Pneumatic logic is used in many machine applications. While being explosion proof and intrinsically non-hazardous for dangerous areas such as in refineries and chemical plants, pneumatics are relatively easy to install and maintain since the signals are carried through simple low pressure tubes.

Pneumatics uses an easily compressible gas such as air or a suitable pure gas, while hydraulics uses relatively incompressible liquid media such as oil. Most industrial pneumatic applications use pressures of about 80 to 100 pounds per square inch (550 to 690 kPa). Hydraulics applications commonly use from 1,000 to 5,000 psi (6.9 to 34 MPa), but specialized applications may exceed 10,000 psi (69 MPa).

Advantages of Pneumatics

- Simplicity of Design And Control
 - Machines are easily designed using standard cylinders & other components. Machines operate by simple ON - OFF type control.
- Reliability
 - Pneumatic systems tend to have long operating lives and require very little maintenance.
 - Because gas is compressible, the equipment is less likely to be damaged by shock. The gas in pneumatics absorbs excessive force, whereas the fluid of hydraulics directly transfers force.
- Storage
 - Compressed gas can be stored, allowing the use of machines when electrical power is lost.
- Safety
 - Very low chance of fire (compared to hydraulic oil).
 - Machines can be designed to be overload safe.

Advantages of Hydraulics

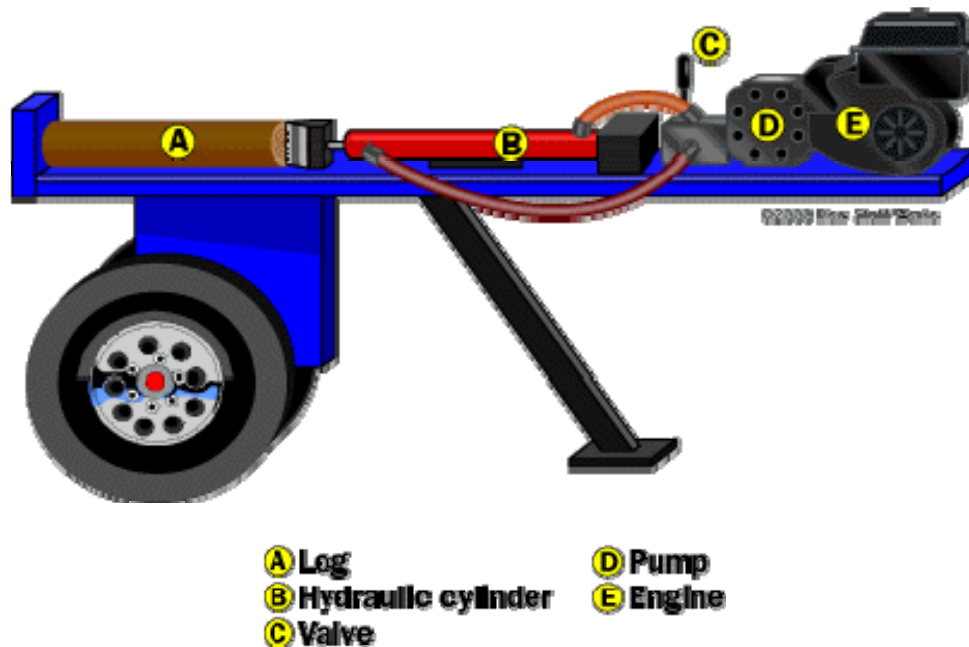
- Liquid (as a gas is also a 'fluid') does not absorb any of the supplied energy.
- Capable of moving much higher loads and providing much higher forces due to the incompressibility.
- The hydraulic working fluid is basically incompressible, leading to a minimum of spring action. When hydraulic fluid flow is stopped, the slightest motion of the load releases the pressure on the load; there is no need to "bleed off" pressurized air to release the pressure on the load

How Log Splitters Work

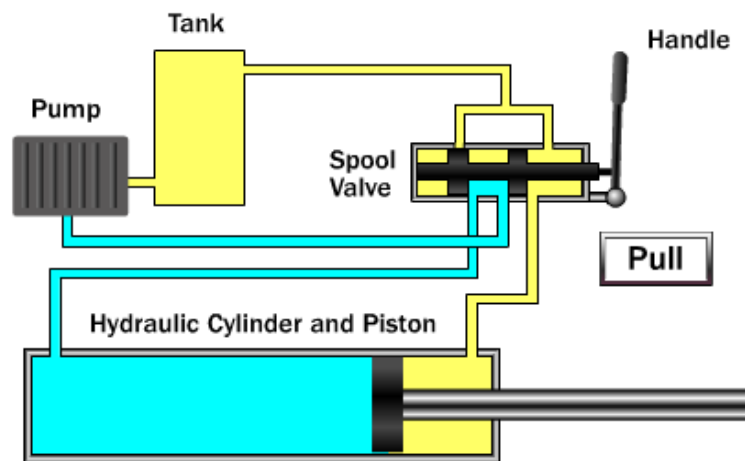
The simplest hydraulic device that you find in common use today is the **log splitter**. It contains all of the basic components of a hydraulic machine:

- An **engine**, normally a small four-stroke gasoline engine, provides the power for the system. The engine is attached to a hydraulic oil pump.
- The **hydraulic oil pump** creates a stream of high-pressure oil, which runs to a valve.
- The **valve** lets the operator actuate the **hydraulic cylinder** to split a log.
- There is also a **tank** to hold the hydraulic oil that feeds the pump and usually a **filter** to keep the oil clean.

The major components of a log splitter are shown below:



High-pressure oil from the pump is shown in light blue, and low-pressure oil returning to the tank is shown in yellow.



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In the figure above you can see how the valve can apply both forward and backward pressure to the piston. The valve used here, by the way, is referred to as a "spool valve" because of its resemblance to a spool from a spool of thread.

A typical backyard log splitter has:

- A 5-horsepower gasoline engine
- A two-stage hydraulic oil pump rated at a maximum of 11 gallons per minute (3 gpm at 2,500 psi)
- A 4-inch-diameter, 24-inch-long hydraulic cylinder
- A rated splitting force of 20 tons
- A 3.5-gallon hydraulic oil tank

A **two-stage pump** is an ingenious time-saver. The pump actually contains two pumping sections and an internal pressure-sensing valve that cuts over between the two. One section of the pump generates the maximum gpm flow rate at a lower pressure. It is used, for example, to draw the piston back out of a log after the log has been split. Drawing the piston back into the cylinder takes very little force and you want it to happen quickly, so you want the highest possible flow rate at low pressure. When pushing the piston into a log, however, you want the highest possible pressure in order to generate the maximum splitting force. The flow rate isn't a big concern, so the pump switches to its "high pressure, lower volume" stage to split the log.

Hydraulic Pumps

One thing you can see is that the advertised "20-ton splitting force" is generous "rounded up" rating. A 4-inch piston has an area of 12.56 square inches. If the pump generates a maximum pressure of 3,000 pounds per square inch (psi), the total pressure available is 37,680 pounds, or about 2,320 pounds shy of 20 tons.

Another thing you can determine is the cycle time of the piston. To move a 4-inch-diameter piston 24 inches, you need $3.14 * 22 * 24 = 301$ cubic inches of oil. A gallon of oil is about 231 cubic inches, so you have to pump almost 1.5 gallons of oil to move the piston 24 inches in one direction. That's a fair amount of oil to pump -- think about that the next time you watch how quickly a hydraulic backhoe or skid/loader is able to move! In our log splitter, the maximum flow rate is 11 gallons per minute. That means that it will take 10 or so seconds to draw the piston back after the log is split, and it may take almost 30 seconds to push the piston through a tough log (because the flow rate is lower at high pressures).

From this discussion you can see that just to fill the cylinder with oil, you need at least 1.5 gallons of hydraulic oil in the system. You can also see that one side of the cylinder has a larger capacity than the other side, because one side has the piston shaft taking up space and the other doesn't. Therefore, big hydraulic machines usually have:

- **Large appetites for hydraulic oil** (100 gallons is not uncommon if there are six or eight large hydraulic cylinders used to operate the machine.)
- **Large external reservoirs** to hold the difference in the volume of oil displaced by the two sides of any cylinder

This example covered the basics of a simple hydraulic system.

Numerical control (NC)

Numerical control (NC) refers to the automation of machine tools that are operated by abstractly programmed commands encoded on a storage medium, as opposed to controlled manually via handwheels or levers, or mechanically automated via cams alone. The first NC machines were built in the 1940s and 1950s, based on existing tools that were modified with motors that moved the controls to follow points fed into the system on punched tape. These early servomechanisms were rapidly augmented with analog and digital computers, creating the modern computer numerical control (CNC) machine tools that have revolutionized the machining processes.

In modern CNC systems, end-to-end component design is highly automated using computer-aided design (CAD) and computer-aided manufacturing (CAM) programs. The programs produce a computer file that is interpreted to extract the commands needed to operate a particular machine via a postprocessor, and then loaded into the CNC machines for production. Since any particular component might require the use of a number of different tools-drills, saws, etc., modern machines often combine multiple tools into a single "cell". In other cases, a number of different machines are used with an external controller and human or robotic operators that move the component from machine to machine. In either case, the complex series of steps needed to produce any part is highly automated and produces a part that closely matches the original CAD design.

Computer Integrated Manufacturing (CIM):

Computer Integrated Manufacturing, known as CIM, is the phrase used to describe the complete automation of a manufacturing plant, with all processes functioning under computer control and digital information tying them together. It was promoted by machine tool manufacturers in the 1980's and the Society for Manufacturing Engineers (CASA/SME).

The heart of computer integrated manufacturing is CAD/CAM. Computer-aided design(CAD) and computer-aided manufacturing(CAM) systems are essential to reducing cycle times in the organization. CAD/CAM is a high technology integrating tool between design and manufacturing. CAD techniques make use of group technology to create similar geometries for quick retrieval. Electronic files replace drawing rooms. CAD/CAM integrated systems provide design/drafting, planning and scheduling, and fabrication capabilities. CAD provides the electronic part images, and CAM provides the facility for toolpath cutters to take on the raw piece.

The computer graphics that CAD provides allows designers to create electronic images which can be portrayed in two dimensions, or as a three dimensional solid component or assembly which can be rotated as it is viewed. Advanced software programs can analyze and test designs before a prototype is made. Finite element analysis programs allow engineers to predict stress points on a part, and the effects of loading.

Once a part has been designed, the graphics can be used to program the tool path to machine the part. When integrated with an NC postprocessor, the NC program that can be used in a CNC machine is produced. The design graphics can also be used to design tools and fixtures, and for inspections by coordinate measuring machines. The more downstream use that is made of CAD, the more time that is saved in the overall process.

Generative process planning is an advanced generation of CAD/CAM. This uses a more powerful software program to develop a process plan based on the part geometry, the number of parts to be made, and information about facilities in the plant. It can select the best tool and fixture, and it can calculate cost and time.

Flexible Manufacturing systems (FMS)

Flexible Manufacturing systems (FMS) are extensions of group technology and cellular manufacturing concepts. Using integrated CAD/CAM, parts can be designed and programmed in half the time it would normally take to do the engineering. The part programs can be downloaded to a CNC machining center under the control of an FMS host computer. The FMS host can schedule the CNC and the parts needed to perform the work.

In Simple Terms: Computer-controlled process technology suitable for producing a moderate variety of products in moderate, flexible volumes. This system reduces setup or changeover times and facilitates the production of differentiated products in small numbers. The shift in emphasis is from mass production of a few products to a job-shop environment in which customized orders are manufactured. Automation allows for better quality and scheduling, rapid changes in product lines, and lower inventories and costs

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End of Machine Design Section

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Practical Applications Activities:

Completing the SeaPerch

Implementing the controls to the motors

Designing on a CAD application

Developing/fabricating the prototype

Implementing a prototype

Verification and documentation
