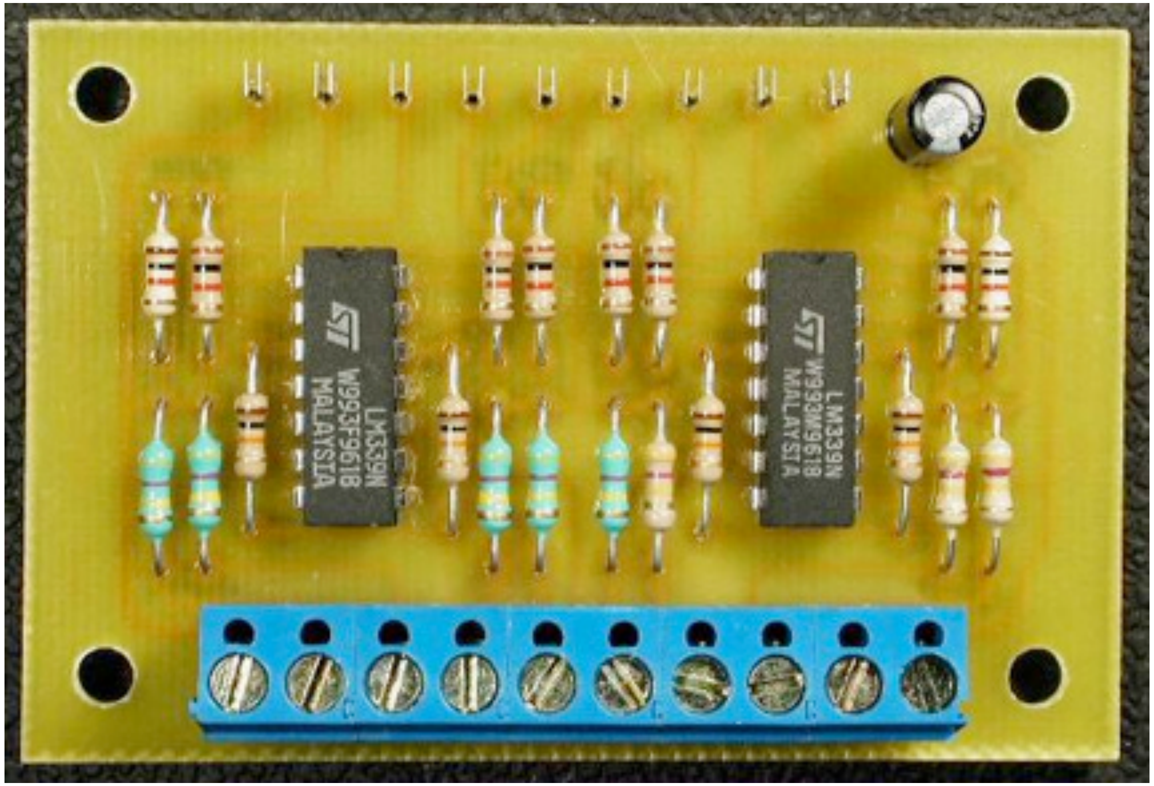
Basic Electronics - Part 2
Electronic Components



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Understanding Electricity

To most people, electricity is a very abstract phenomenon. Difficult to visualise and hence difficult to imagine. In this document, I will try to make it more concrete by drawing many analogies between the flow of electricity and the flow of water. The latter is, after all, totally familiar and intuitively understood by anyone.

Electronic(s) means literally: working with/on Electrons

To understand the behaviour of electrons (and thus electronics!) we need to differentiate three important concepts:

Electric Charge is the amount of electrons involved**.**

As we describe an amount of water in terms of litres, and not as the number of molecules involved, likewise electric charge is measured in Coulomb (C). 1 Coulomb contains 6.022×10^{23} electrons.
Analogous to the amount of charge is the amount of water. (1 l of water contains $55.55 \times 6.022 \times 10^{23}$ molecules!)

Electric Current is the movement of an electric charge.

Anytime electrons move, this is called current. Current is measured in Ampere (A) which is defined as Coulombs per second [1A = 1C / s]. So; when 1C of electrons flow through a wire in 1 sec, the wire carries a current of 1 A.
The maximum current a circuit can handle is determined (among other things) by the thickness of the wires.
With water, the 'current' is the amount of water moving per unit of time. Flow of water is usually measured in litres per minute.

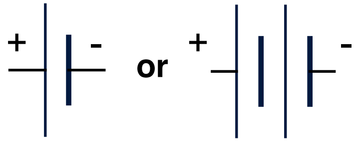
Electric Field or **Potential** is the amount of Energy converted or transferred by the electrons moving.

Like water flowing downhill under the influence of gravity, electrons will flow in the presence of an electric field (or by means of certain chemical reactions..). The electrons themselves are *negative* particles, and so are repelled by the negative pole of the field, and attracted by the positive pole of the field.
In an electric field, **electrons will flow from - to +.**
Potential is measured in Volts (V). When 1C loses 1V of potential, 1 Joule of energy is released.
Equivalent to the Potential (or voltage) is the pressure of the water in the pipe at a given point.

Because electricity and the important relationships between Field, Charge and Current (and similar relations to magnetic fields) were discovered long before the electrons, a very unfortunate discrepancy has come into existence, because the electrons carry a *negative* electric charge:
Electric current is defined as **flowing from + to -**
Electric current is flowing in the **opposite direction** to the electrons that are causing the current in the first place!

Basic Electronic Components

The Battery

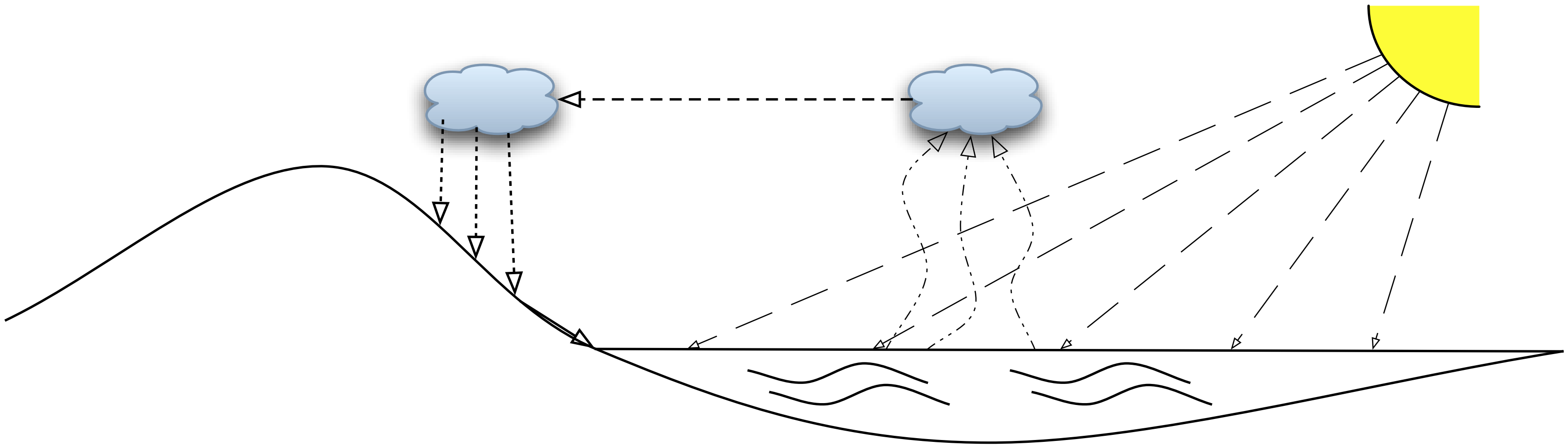


The Battery is a source of electricity. A chemical reaction inside the battery absorbs electrons at the + pole, and delivers electrons to the - pole.

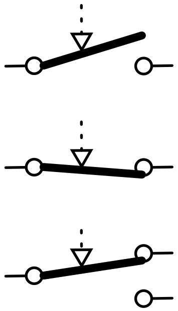
Without external connections to the battery an electric field will build up, because of the difference in charge between the + pole (few electrons) and the - pole (many electrons). This electric field will make electrons want move from the - to the +, so in the opposite direction as the chemical reaction!

When the field-potential reaches a certain voltage, the chemical reaction will stop, but the electric field will persist, holding a constant voltage between the battery poles.
The real power of the battery comes in when an external connection is made between the poles. Then suddenly electrons can flow from - to + (creating a current from + to -), *outside* the battery, without having to face the opposing force of the chemical reaction inside the battery. In fact, as electrons 'escape' along a path external to the battery, the chemical reaction immediately starts up again and starts pushing electrons around inside the battery.

In terms of water-flow, think of a pump using physical force to create a pressure difference between its inlet & outlet. Or the heat of the sun evaporating water from a lake (a point of lowest potential energy) into clouds (very high potential energy) from where it can fall down as rain, running ever downhill until it finds another lake or the sea...



Switches



Normally Open (NO)

Normally Closed (NC)

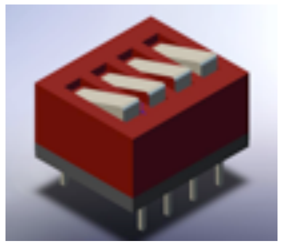
Toggle or **Double Throw (DT)**

Switches are electro-mechanical components that make or break one or more electrical contacts, thereby allowing or disallowing the flow of electrons (i.e. electric current), depending on the state of the switch.

The nomenclature is again somewhat confusing; when a switch is said to be **closed**, current **can** flow through, and when the switch is **open**, current **cannot** flow through.

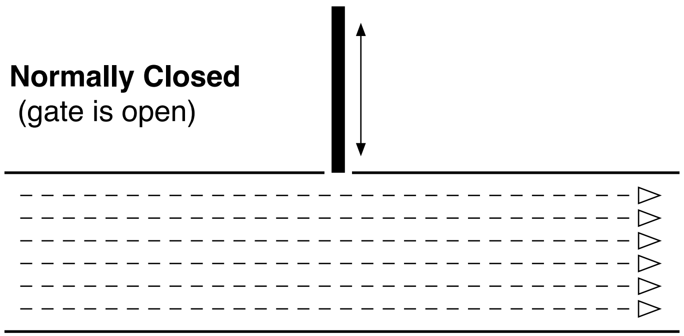
Think of a bridge where, in the raised, open state, no traffic can pass across the bridge, and when it is lowered or closed, traffic can again pass.

Switches come in a great variety of shapes and forms, With 1, 2 or more 'positions' (i.e. stable states), with internal springs that push the switch back into its default state after the external force is removed (momentary switches), and switches actuated by different kinds of external forces (mechanical force, magnetic fields, air-pressure, water-level, etc.). Lever switches, rotary switches, slide switches, rocker switches, pushbutton switches, key activated switches, DIP-switches, etc, etc.

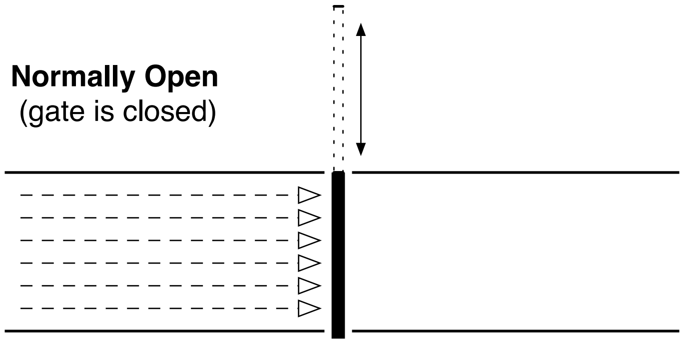


The water-equivalent of a switch is simply a faucet, or a pipe with a valve or gate in it. This is where the confusion of the switch's state-names becomes evident, because an **open** faucet or valve is equivalent to a **closed** switch, and a **closed** faucet or valve is like an **open** switch. One essential difference is that the electric current is always switched <u>completely</u> on or off, there is no gradation of in-between states as with a faucet.

Normally Closed
(gate is open)

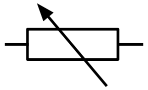


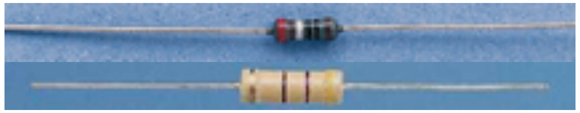
Normally Open
(gate is closed)



Resistors

 **or**  **Fixed Resistor**

 **or**  **Variable Resistor**



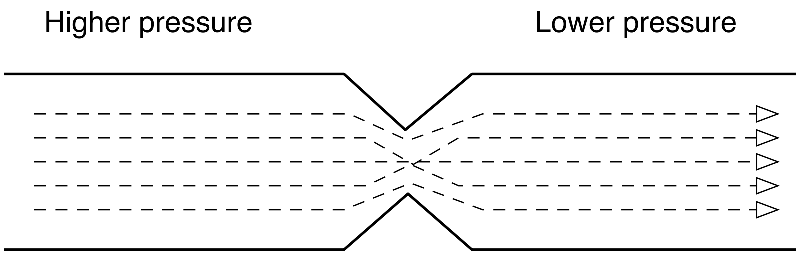
Resistors offer resistance to electric current.

Electrons flowing through a resistor will lose a little bit of their energy, which results in a potential-difference (= electric field) across the resistor, opposite in direction to the flow of current. This field will 'push back' at the electrons flowing through. The electric energy 'lost' in the resistor will be released as heat.

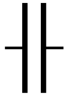
The **Resistance** of a resistor is measured in Ohm (Ω).
Ohm's Law describes the relation between current, resistance and potential:
A * Ω = V or V / Ω = A
When 1mA flows through a 3.3kΩ resistor, there will be 3.3V across it. With 6V across a 120Ω resistor, a 50mA current will flow through it.

A resistor is like a pipe with a kink in it; the kink makes it more difficult for the water to flow through, so the pressure before the kink will be higher than after the kink. The amount of water flowing through (the current) is the same before & after the kink, of course!

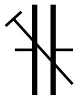
In contrast to a switch, a variable resistor can be seen as a faucet or a valve which is partly closed, thereby resisting the flow of the water. Although a variable resistor can usually be set to 0Ω, completely closed (like a switch) / completely open (like a faucet), it can not usually be set to ∞Ω, completely open (like a switch) / completely closed (like a faucet). At least a small trickle of current can always flow through.



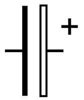
Capacitors



Regular Capacitor



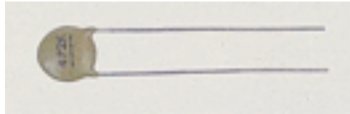
Variable Capacitor

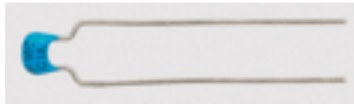


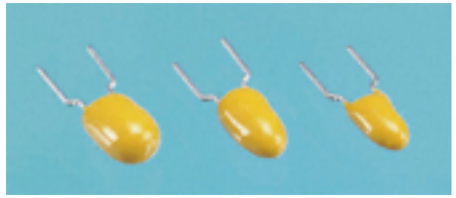
Electrolytic (or **Polarized**) **Capacitor**

Capacitors are storage vessels for electric charge. When current flows into a capacitor the voltage across it will rise **over time**. When a voltage is applied to a capacitor, there will be a peak-current initially, then the current will decrease over time.

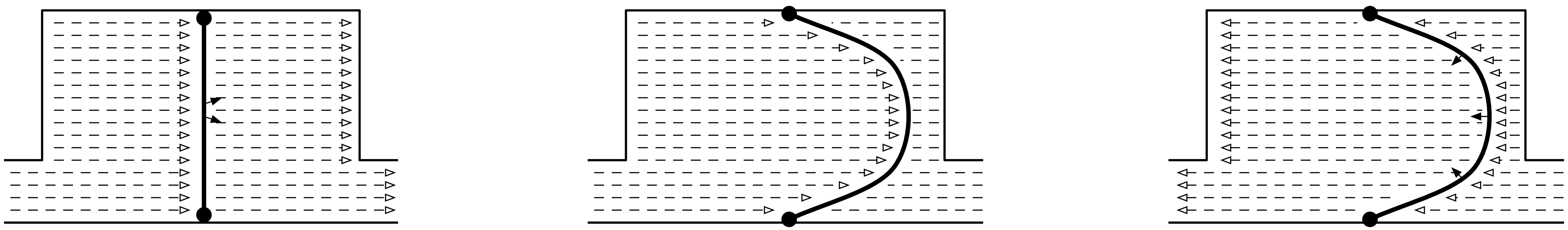
The **Capacitance** of a capacitor dictates how much energy can be stored, and is measured in Farad (F).
A steady current of 1mA will make the voltage across a 1µF capacitor rise with 1V per msec (= 1kV / sec).



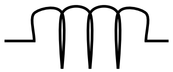




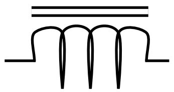
Imagine a closed tank or barrel, already filled with water, with a pipe at either end and a rubber membrane stretched across the middle; The pressure of the water flowing into one half of the barrel will at first stretch the membrane and push water out the other end.
Note that it is <u>different</u> water being pushed out, the two halves of the barrel are not actually connected!
But the <u>amount</u> of water (i.e. the electric charge) flowing into the barrel is the same as what flows out, so we can simplify things (at least linguistically) by saying water (current) flows *through* the barrel (capacitor), even though this is not literally what happens.
The stretching of the membrane increases the pressure in the 'input' half of the barrel, until it is equal to the pressure in the pipe. At this point, the pressure on the 'output' side will be zero because all of the pressure form the input-side is counteracted by the membrane, and the flow stops. If the pressure on the input-side then drops, the membrane will spring back into its unstretched state, and water (current) will flow in the <u>opposite</u> direction during this 'discharge'.
The size of the barrel is directly equivalent to the capacitance of the capacitor, and the thickness of the membrane is the 'dielectric strength'. If the voltage across a capacitor gets too high, the capacitor will break. Exactly like the membrane in a barrel would break if the pressure gets too high.



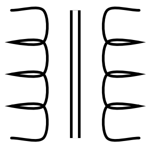
Inductors



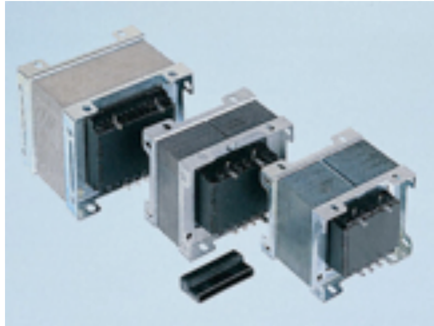
Air Coil



Coil with **magnetic core**



Transformer

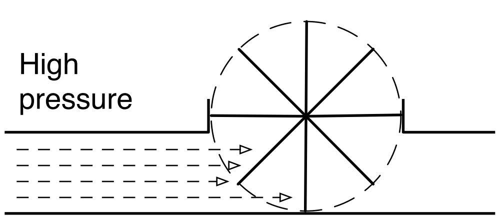


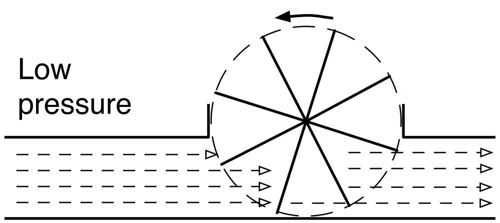
An Inductor (or coil) is simply a wire wound into a coil, usually around some iron or ferrite core. Inductors also store electric energy, but unlike capacitors it's not stored as an electric charge, but as a **magnetic field**. Inductors convert electric energy to magnetic energy, and back again.
Inductors behave like the mirror-image of Capacitors: When a **voltage** is applied to an inductor the **current** through it will rise over time.
When current flows through an inductor, there will be a peak-voltage initially, then the voltage will decrease over time.
When current stops flowing through an inductor, there will be another peak-voltage decreasing over time, but with <u>opposite</u> polarity to the original current.

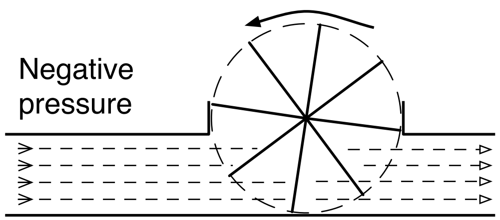
The **Inductance** of an inductor describes how much energy can be stored, and is measured in Henry (H). 1V applied to a 1mH inductor will make the current rise with 1A / msec.

Think of a water-pipe with a heavy impellor-wheel inside;
At first, the inertia of the wheel will resist the water flowing in, making the pressure in the pipe rise. The pressure persists, and the wheel will start turning, allowing more & more water to flow through. When the wheel is up to speed, and the pressure drops, the wheel's inertia 'wants to keep the wheel going' and will *suck* water into the intake-pipe! (suction is negative pressure, i.e, a voltage of opposite polarity to the original voltage that started the wheel turning.) The direction of flow (current) will be <u>the same</u> as the original (charging) flow during this 'discharge'

The mass or inertia of the water-wheel is equivalent to the inductance of the inductor. The limiting factor here is the maximum speed of the wheel, i.e. the maximum current flowing through the wire from which the coil is wound.







Semiconductors

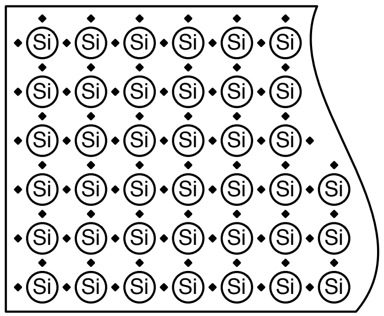
The basic components described previously (the switch, resistor, capacitor and inductor) are often called 'passive' components. In addition, the capacitor and inductor are called 'reactive', because they react (over time) to changes in current or applied voltage. The components described on the following pages however, are not considered to be 'passive'. They are only very rarely referred to as 'active' components, and it is much more common to call these components 'semiconductors' because of the semi-conducting bits of silicon that they are actually made of.

As stated earlier, electric current *is* the flowing of electrons. Conducting materials (or simply 'conductors') are those materials where electrons can move around inside them freely. These include all metals, graphite (a form of carbon) and some fairly exotic materials. On the other hand, non-conductive materials ('isolators') have all of their electrons locked firmly away inside their molecules or crystal-structures. Examples of isolators are; glass, plastics and ceramics.

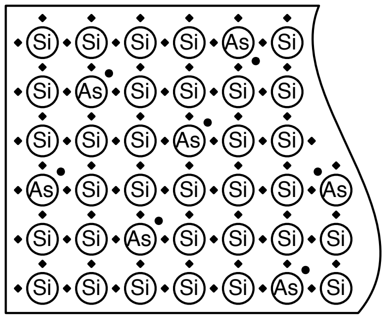
There exists a class of isolators whose crystal-structure can be slightly modified to give them conducting properties. Examples of this kind of isolator are; germanium, silicon and (in theory) diamond. In their pure forms, these materials are perfect isolators and will not conduct electric current. But by purposely polluting the pure crystalline form of these isolators with atoms from the neighbouring columns (III or V) of the Periodic Table of Elements, we can introduce a surplus (**N**-type) or shortage (**P**-type) of electrons into these crystals. Afterward these polluted crystals will contain some free electrons (in N-type semiconductors) or **holes** where electrons should have been (in P-type semiconductors), and they can now conduct electricity, albeit somewhat less effectively than true conductors. Hence the name semi-conductors.

How an N-type semiconductor can conduct electricity is obvious; it contains free electrons. The P-type can also conduct electricity, however, because a non-free (or 'bound') electron can suddenly jump into a hole, leaving its proper place in the crystal and thereby making a new hole appear in its previous location. By this mechanism, the <u>holes</u> can be said to move around freely, and can be viewed as negative electrons (and thus as carriers of a positive charge!). Note however that the holes are *not* positrons (which are true positive electrons in the anti-matter sense). Holes are exactly what the name implies; abstract virtual entities that only denote the <u>absence</u> of an electron where one should have been.

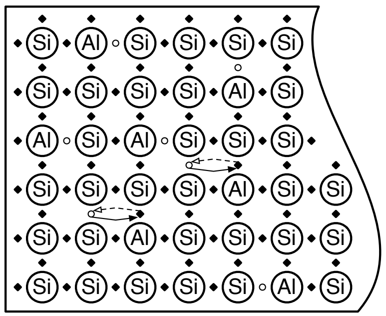
Pure Silicon

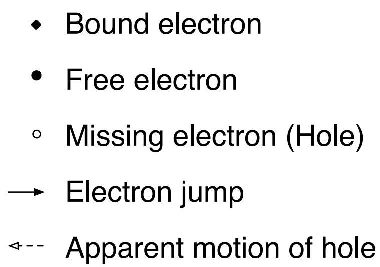


N-Type



P-Type





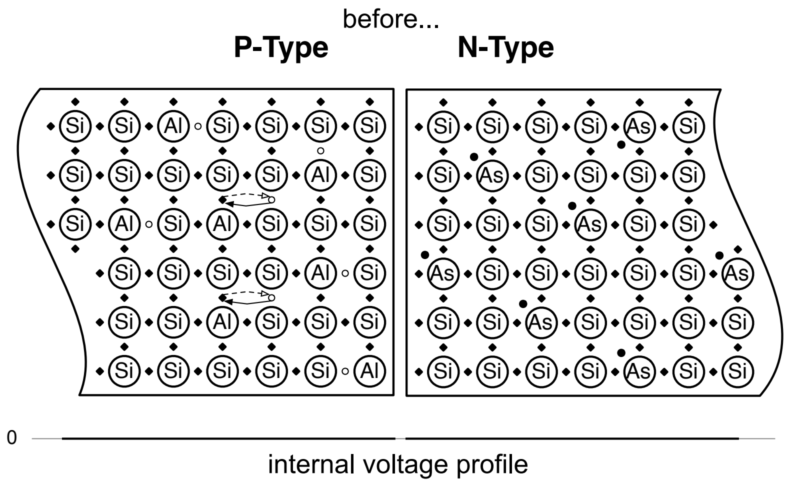
The P-N Junction

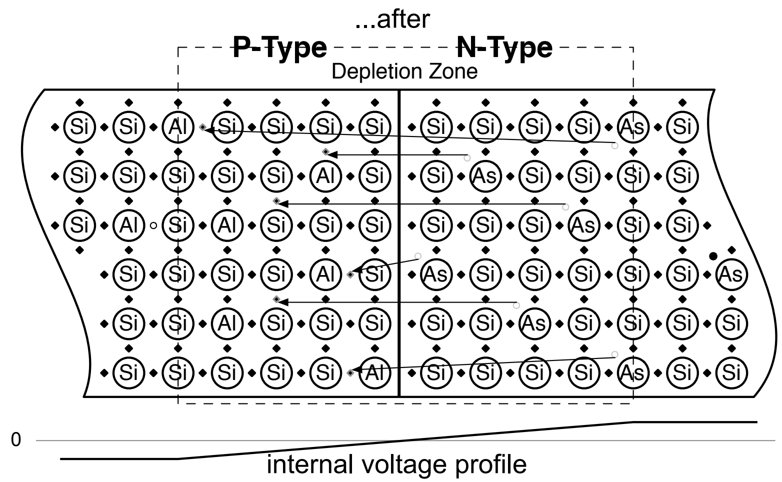
Making semi-conductors out of isolators may seem like a rather pointless exercise. After all, much better conductors can be made with much less effort, so why bother? But truly interesting stuff happens once a bit of P-type and a bit of N-type semiconductor are joined together. At the junction, the free electrons in the N-bit are suddenly attracted by the holes in the P-bit, and because they can cross the boundary, they go and 'recombine' with (i.e. fill up) the holes. This creates a zone at the very edge of the N-bit where the free electrons are all gone (or 'depleted') and, likewise, a zone at the very edge of the P-bit where the holes are depleted. These two zones have suddenly reverted to the pure state the crystal had before it was polluted, and now form an <u>isolating</u> barrier between the two bits of semi-conducting materials. These two zones together are called the 'depletion zone' of the P-N junction.

Contrary to what you might at first expect, this depletion zone does *not* grow indefinitely in both directions, using up all the holes and free electrons that exist in both bits of semiconductor-material. As we've already seen, the movement of electrons constitutes an electric current, and thus the migration of electrons from the N-bit to the P-bit of the semiconductor must necessarily result in the build-up of an electric field! As the P-bit absorbs more electrons, it becomes more negatively charged. Likewise, the N-bit is losing electrons and becomes more positively charged. This difference in charge creates an electric field which counteracts the growing of the depletion zone, until a (dynamic) balance is reached. At this point, the voltage across the depletion-zone is strong enough to prevent any more electrons from making it to the other side, and true isolation is established.

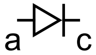
Now, if an external voltage were applied to a P-N junction, two different things might happen. If the **-** of the external voltage is connected to the P-side and the **+** to the N-side, more electrons are introduced in the P-bit, recombining with the holes there, and more free electrons are sucked out of the N-bit. So the depletion-zone will grow bigger.

Conversely, if the external voltage is reversed, the depletion-zone will shrink. If the external voltage is exactly equal (but opposite) to the internal voltage that came into existence when the two bits of semiconductor-material were originally joined, the depletion-zone will <u>disappear</u> completely, and any further increase of the external voltage will result in a current flowing through the P-N junction.



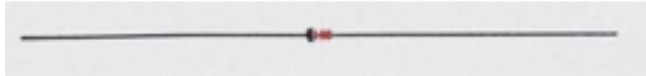


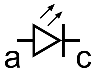
Diodes



A Diode lets current flow through in only one direction. (Hence the arrow in the symbol).

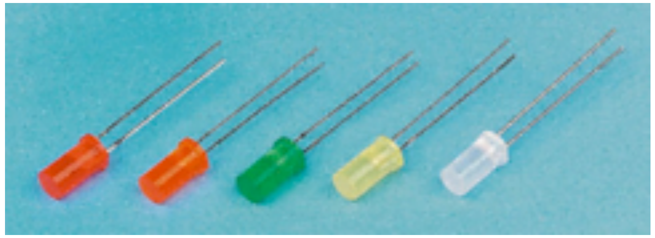
One leg of the diode is marked, usually with a fat black or white line. The marked leg is the 'cathode', where current can flow out of, but not into. (i.e. the **-** end) The other leg (where the current can flow into the diode, the **+** end) is called the 'anode'

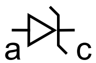




A Light-Emitting Diode (LED) lets current flow through in only one direction, and emits light when current is flowing.

LED's sometimes have the cathode (the **-**) marked with a flattened edge, and usually have the anode (the **+**) leg being longer than the cathode leg.



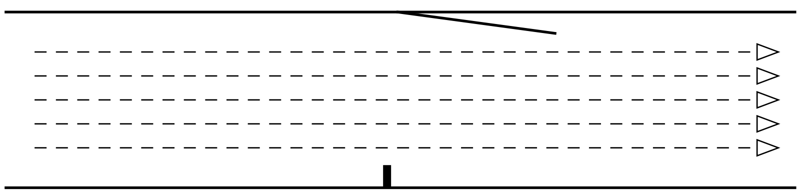


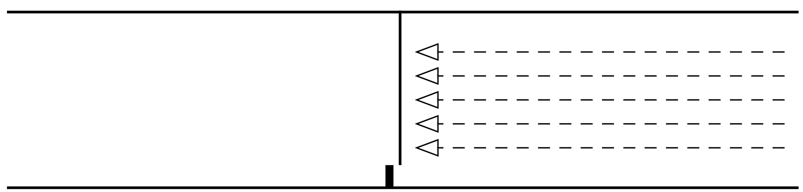
A Zener-Diode lets current flow through in one direction, but <u>also</u> in the other direction if the reverse voltage is above a certain threshold.

This threshold is called the ‘zener-voltage’, and it is constant for a given diode. Zener-Diodes are useful in voltage-regulation applications.

It may or may not be obvious, but all types of diodes mentioned here are, at their core, simply the P-N junction described on the previous page. As such, diodes have a small 'forward voltage' which is required to break down the depletion barrier before they can start conducting. How large this forward voltage is depends on the semiconducting materials used in the diode's construction and, in LEDs, is directly related to the colour of the emitted light.

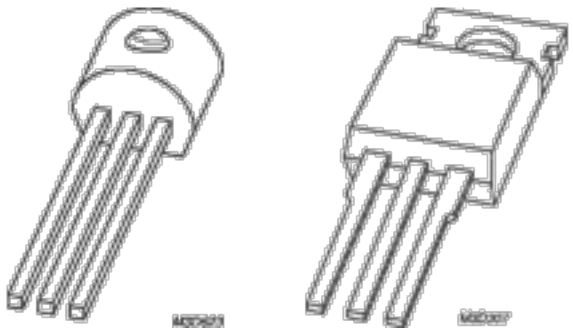
The Diode acts like a pipe with a one-way valve; in one direction the pressure will push the valve open and current can flow. In the other direction, the pressure will push the valve closed. The pressure lost from the effort required to push (and keep) the valve open is equivalent to the diode's forward voltage.



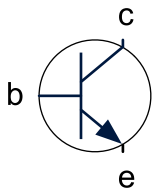


Transistors (in various flavours)

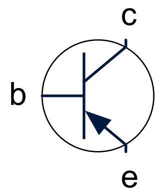
Transistors (short for 'Transfer Resistors') appear in different types or 'families' (see next page) and each family comes in 2 polarities.



Regular Transistors (a.k.a 'Bi-junction' or 'Bipolar' Transistors)



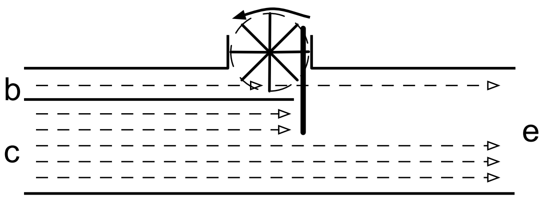
NPN

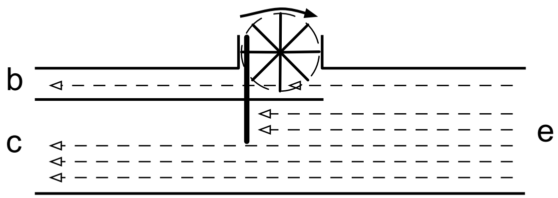


PNP

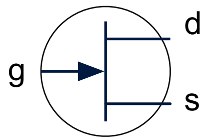
These work as **current-controlled resistors**. The three terminals are; 'e' (for 'Emitter'), is the common terminal. 'b' (for 'Base'), is the controll*ing* terminal. 'c' (for 'Collector'), is the controll*ed* terminal.
Inside the transistor, the path between b and e works like a diode, so current can only flow one way. In NPN-transistors, it can flow from b to e, in PNP-transistors from e to b. (See the arrows in the symbols!). The presence of a small current along this path (the controll*ing* current) allows for a much larger current (the controll*ed* current) to flow along the controlled path; from c to e in NPN-transistors and from e to c in PNP-transistors. So, in a way, the resistance between the c & e terminals is controlled by the **current** flowing into (NPN) or out of (PNP) the b terminal.
Like diodes, transistors need a certain 'forward voltage' to be present on the controlling terminal (between b & e) before they start to conduct. Like resistors, transistors convert the 'lost' electric energy to heat. The material of which transistors are made (silicon, usually) is very sensitive to overheating. Temperatures over 100°C may already be fatal. Transistors designed to handle serious currents have a metal mounting-base which *must* be attached to a heat-sink (a large metal surface, designed to dissipate heat).

Imagine a large pipe (the controlled path) has a shutter inside, which can be raised by the turning of an impellor-wheel. The water needed to turn the wheel flows through a smaller pipe (the controlling path). Some slippage is involved, so the wheel needs to keep turning to keep the shutter opened, and the speed of the wheel (i.e. the controlling current) determines how far the valve will open.
This way, the controlling **flow** controls the resistance of the controlled pipe.

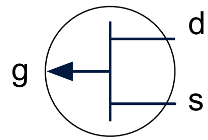




Field-Effect Transistors (FETs)



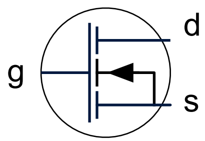
N-Channel



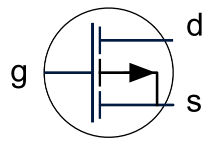
P-Channel

These work as **voltage-controlled resistors**. The three terminals here are a bit more sensibly named; 's' (for 'Source'), is the common terminal. 'g' (for 'Gate'), is the controll*ing* terminal. 'd' (for 'Drain'), is the controll*ed* terminal. Inside the FET, the path between g and s works like a (small) capacitor; current will only briefly flow into or out of the gate, raising or lowering the gate-voltage. N-channel FETs are controlled by a positive voltage, P-channel FETs by a negative voltage. The presence of a small voltage on the gate (the controlling voltage) allows for a large current (the controlled current) to flow along the controlled path; from d to s in N-channel FETs and from s to d in P-channel FETs. So, in a way, the resistance between the d & s terminals is controlled by the **voltage** on the g terminal.

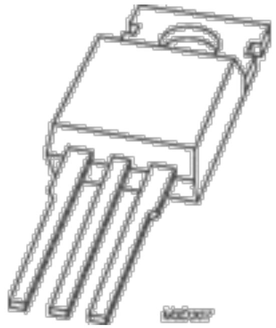
Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs)



N-Channel

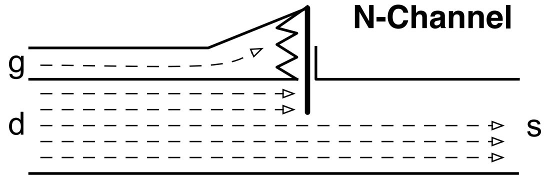


P-Channel

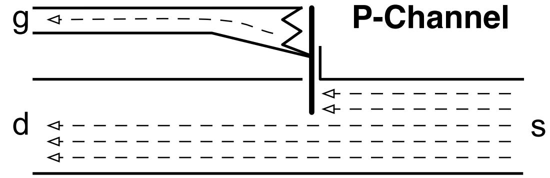


MOSFETs are a slightly more modern version of FET's and most of them are designed to handle very large currents. They function almost exactly like regular FET's. One essential difference is an internal diode formed between the 'substrate' (which is connected to the source) and the drain.
All FETs require a certain 'bias voltage' on the gate, above (N-Ch) or below (P-Ch) which the FET will start to conduct. Unlike regular transistors, however, this bias voltage can be negative (for N-Ch) or positive (P-Ch), in which case the FET is said to operate in 'Depletion Mode' (i.e. an external gate-voltage is required to shut it off!)

The Water-equivalent is very similar to the Transistor model, except here we have the shutter controlled by a balloon or bellows. So, in this case, the **pressure** in the controlling pipe controls the raising & lowering of the shutter.



N-Channel



P-Channel

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