Batteries and Circuits

Two things are needed to make a an electricity do something useful:
1) a source of *electrical potential* to provide the power,
2) a complete circuit round which electricity can flow.

We are going to use a battery to provide the electrical potential. A chemical reaction inside the battery works like a pump to push electricity. The amount of "push" is the voltage – measured in *Volts*.

The circuit for the electricity to flow round needs to be built of electrical conductors and must provide a loop from the positive to the negative terminal of the battery. Metals are by far the most common electrical conductors, but there are also all kinds of other materials that can be used to create special behaviours.

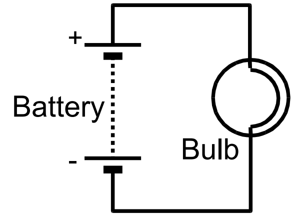
When a circuit is connected a *current* will flow round the circuit. The current is like the amount of water flowing through a pipe. The current is measured in *Amps*, or more usually for electronics a 1/1,000th of an Amp or milliamp (mA).

To understand electronic circuits it is normal to draw a *circuit diagram* or *schematic*. This diagram is like the London Underground map – it shows how things connect in a way that allows you to see the underlying pattern without the complexity of how things are physically laid out in the real world.

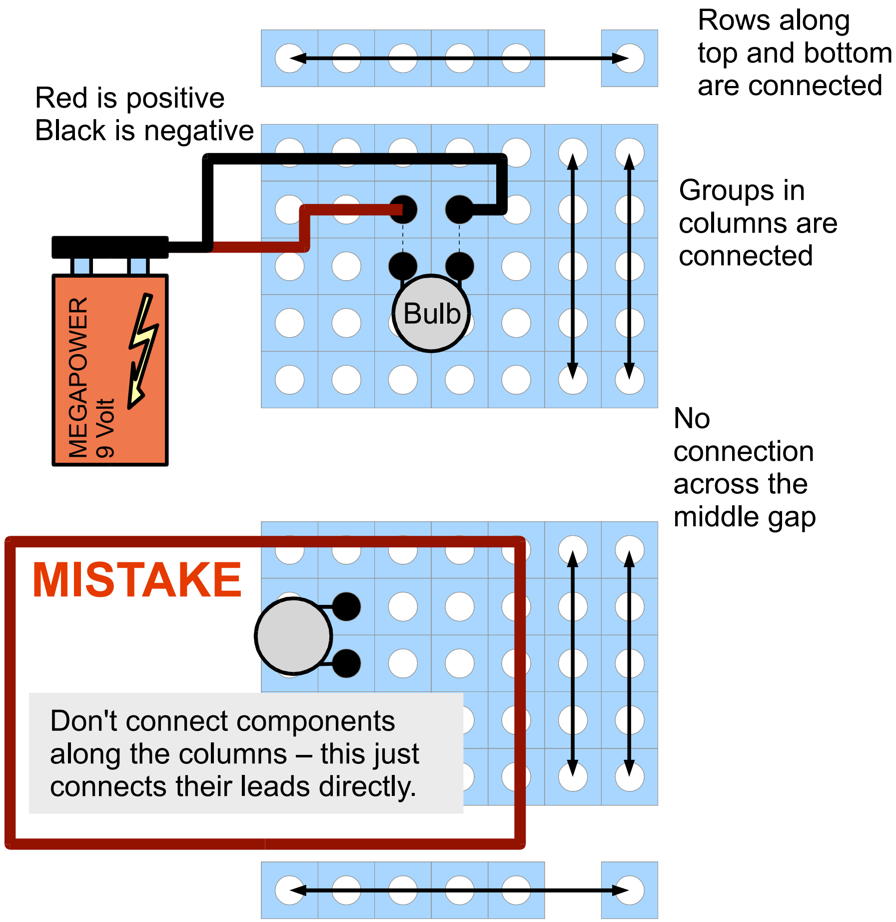
Count Alessandro Volta

1745 – 1827
Developed the first battery

Schematic



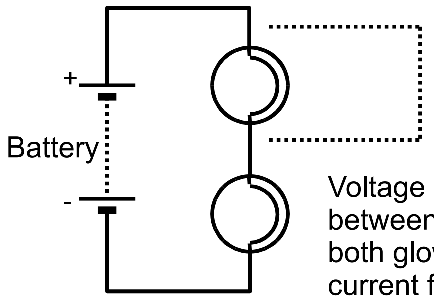
Build on Breadboard



Experiments with Series and Parallel Circuits

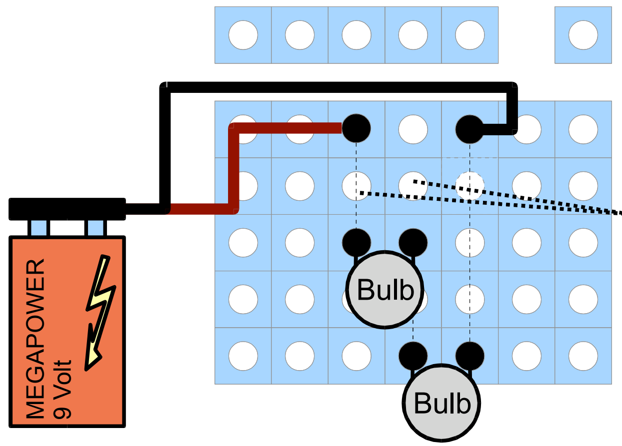
Bulbs in Series

Like Christmas tree lights



What happens if you short-circuit one bulb with a loop of wire?

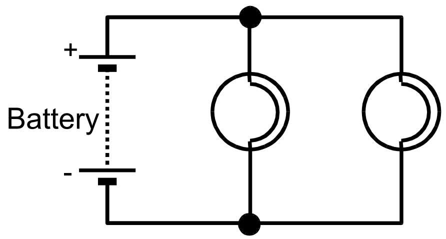
Voltage is split evenly between the bulbs and both glow dimly. Less current flows than with one bulb.



Apply ends of wire to short-circuit bulb here

Bulbs in Parallel

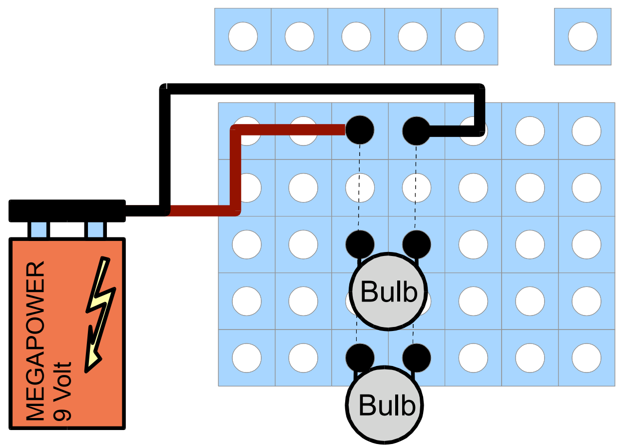
Like bulbs in your house



Joints on schematics are marked with dots

Both bulbs get the full voltage of the battery. Twice the current flows when compared to having one bulb.

Lifting one leg of a bulb out of the breadboard breaks the circuit through that bulb and allows them to be switched on and off individually. This is the same job a light-switch does.



André-Marie Ampère

20 January 1775 – 10 June 1836

Discovered many properties of electromagnetism

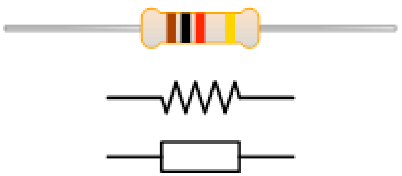
Resistors

Resistors limit the flow of electricity through part of the circuit. This can be used to control timing circuits, divide voltages in to smaller portions or protect devices that are sensitive to too much current.

Resistance is measured in Ohms (Ω),
kilohms (1,000Ω=1kΩ) or
Megohms (1,000,000Ω =1MΩ)

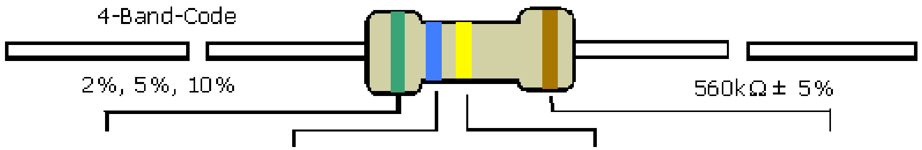
Resistors can go in the circuit either way round. The value is marked on the device with a colour code (see right), or it can be measured with almost any multimeter.

A shorthand is often used to write the value of a resistor. For example:
“100R”=100Ω
“10k”=10kΩ
“4k7”=4.7kΩ

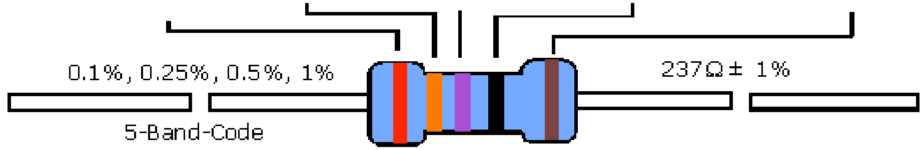


svmbol

Some resistors used in these experiments:
220R – Red, Red, Brown
1k – Brown, Black, Red
10k – Brown, Black, Orange
100k – Brown, Black, Yellow



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 2% (G)
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	±0.5% (D)
Blue	6	6	6	1MΩ	±0.25% (C)
Violet	7	7	7	10MΩ	±0.10% (B)
Grey	8	8	8		±0.05%
White	9	9	9		
Gold				0.1	± 5% (J)
Silver				0.01	± 10% (K)



Time for:
A resistor game!

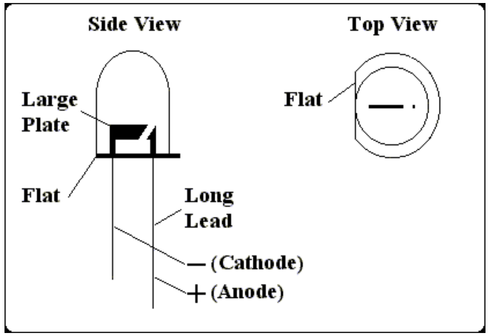
Georg Simon Ohm
(16 March 1789 – 6 July 1854)

Discovered the relationship between voltage and current in electrical circuits “Ohm's Law”.

Light Emitting Diode (LED)

LEDs are solid state devices that emit light when electricity passes through them. They are directional and need to go in the circuit the right way round.

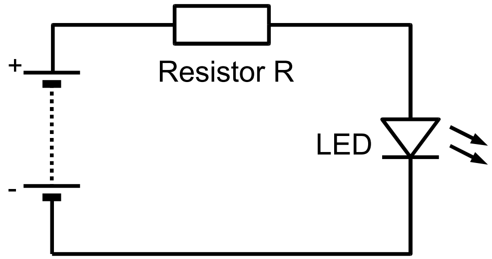
Once a certain “on” threshold voltage is reached (about 2V for a red LED) the current through an LED rises very quickly with the voltage. In most applications a resistor is needed to protect the LED from being overloaded due to this effect.



Captain Henry Joseph Round

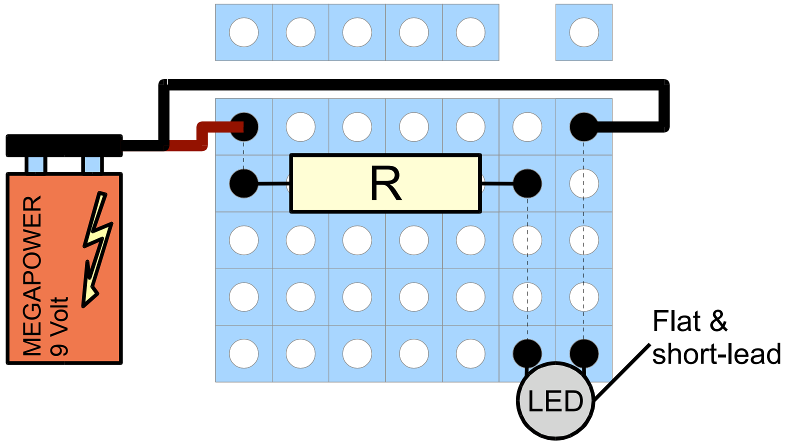
(2 June 1881 –17 August 1966)
First to observe light emitted by a solid state diode

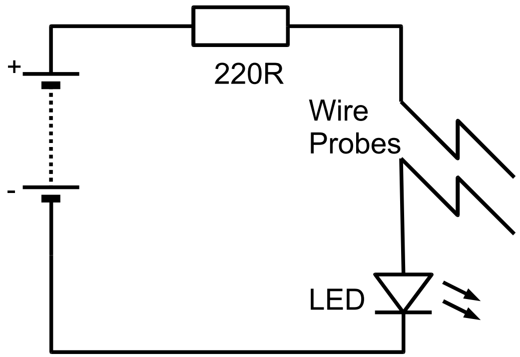
Experiments with LEDs and Resistors



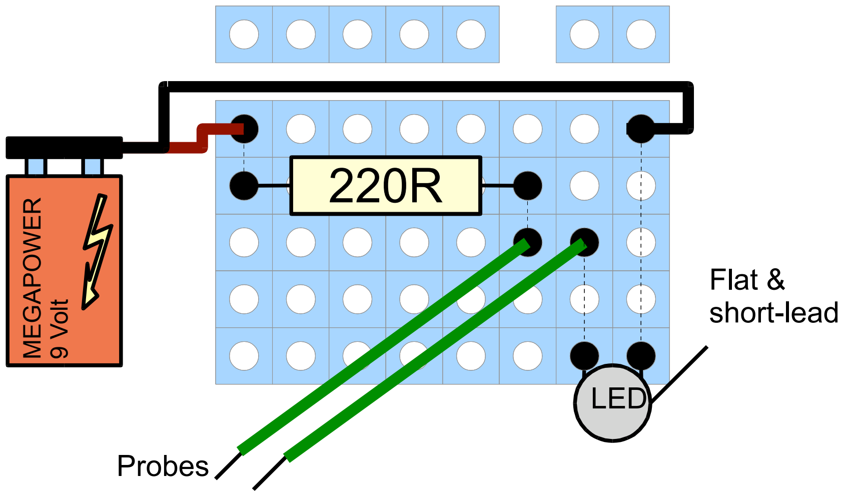
Try using different values of R in this circuit:
100k, 10k, 1k, 220R

What do you notice about the LED?
What do you notice about the 220R resistor when it is in the circuit?





Try touching the ends of the wire probes on to different objects:
- your skin
- fresh water
- salt water
- a thick line drawn with a soft pencil
- a (non light-emitting) diode (try this with the diode both ways round)



Transistors

The solid state transistor is the single component that has driven the electronics revolution. Initially they were very hard to manufacture and regarded expensive specialized parts. Improved mass production techniques gradually lead to transistors becoming cheaply and easily available. Later on a new wave on innovation was created when it was realised that multiple transistors could be manufactured on a single wafer of silicon – leading to the integrated circuit, microprocessors, microcontrollers and all the advanced toolkit available to modern electronic engineers.

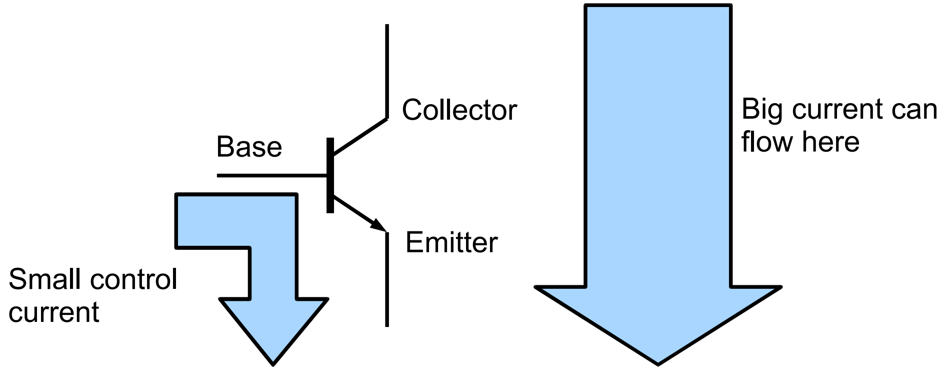
We are going to focus on one type of transistor – the *NPN bipolar transistor*. A transistor has three terminals and acts as an amplifier. For an NPN transistor the terminals are called the "collector", "base" and "emitter". A small current flowing in to the base and out of the emitter controls a much larger current flowing from the collector to the emitter. Think of the current at the base as working to control a tap that varies the flow through the collector. If no current flows in to the base then no current will flow through the collector either.

The base voltage varies between 0V when the transistor is off and about 0.7V when the transistor is on. Like an LED the input to the base normally needs to be protected by a resistor to stop the base being overloaded.

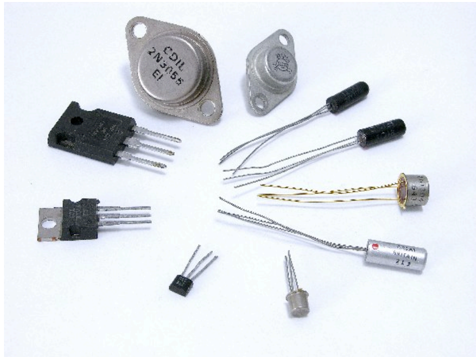
Using transistors we can build many types of circuits including amplifiers, logic circuits, oscillators, filters and power controllers.

The maximum collector current ranges from a few hundred mA to several Amps depending on the transistor. The gain of the transistor is the multiple of the base current the can flow through the collector. This is normally in the range 50-400 and is sometimes written as h_{FE}.

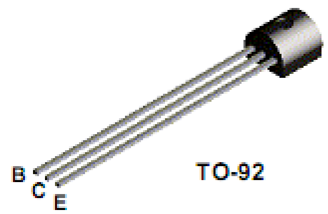
NPN Transistor

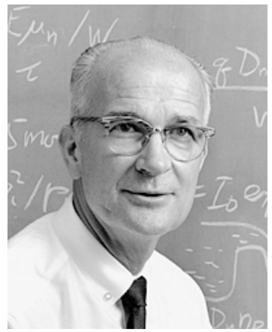


Transistor Packages



Transistor type 2N3704 pinout



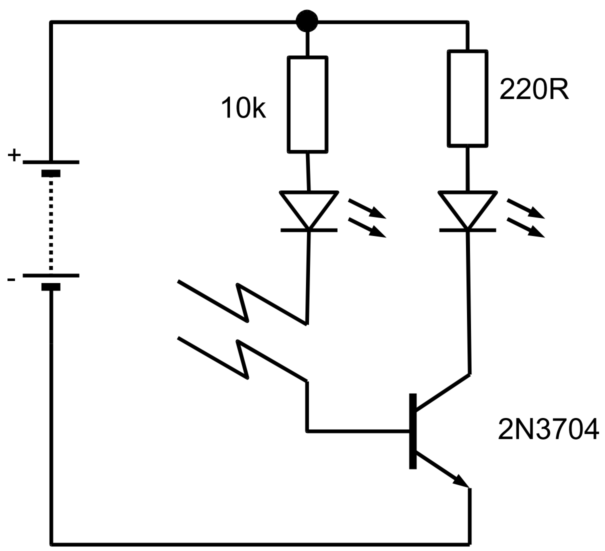


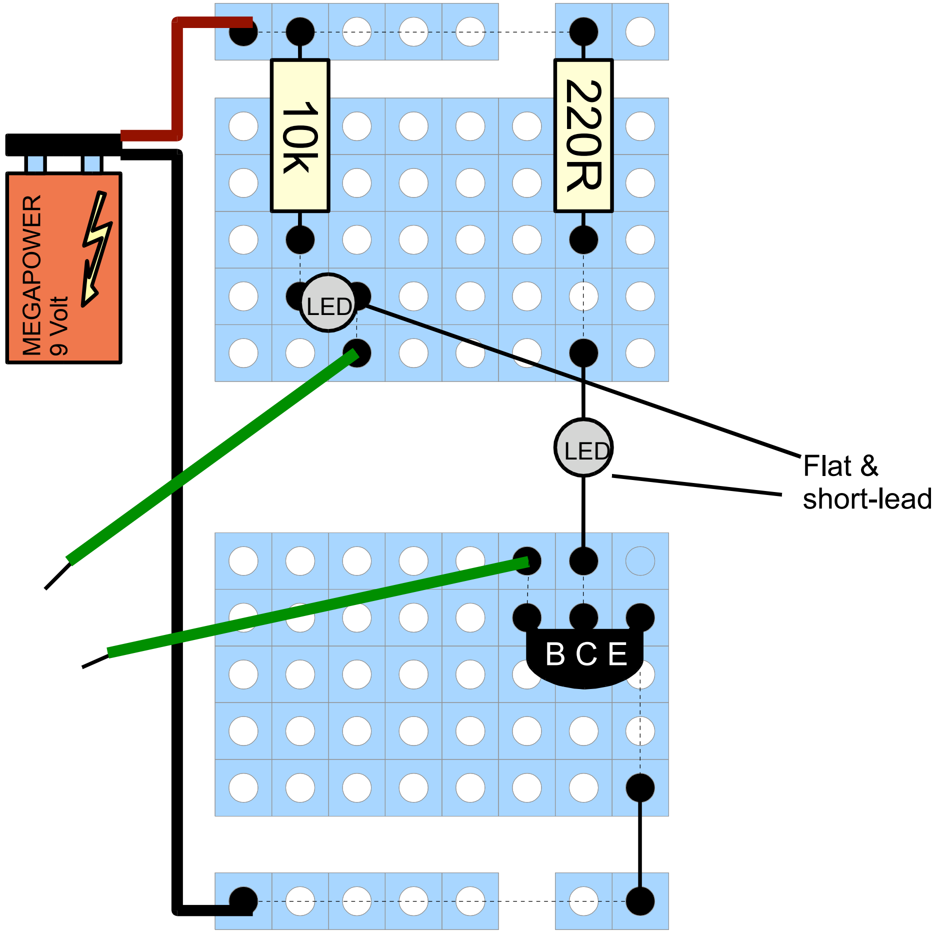
William Bradford Shockley

(February 13, 1910 – August 12, 1989)

Leader of the team at Bell Labs that developed the junction transistor. Nobel prize winner. Also described as "the notorious eugenicist and scientific racist"..

Experiments with a transistor





Connect the circuit up as shown and then try applying the probes to various items. Notice the brightness of the two LEDs. You should find the LED in the collector circuit is much brighter than that in the base.

Items to try:
- Probes open (no connection). Transistor is off and neither LED is lit.
- Probes touching each other. Transistor is fully on. The LED in the collector circuit glows brightly.
- Probes along a pencil track
- Probes on your skin

Capacitors

Capacitors store and release small amounts of electrical charge. In electronic circuits they are used to control the timing of circuits, “smooth out” electrical waveforms and to separate DC and AC components of a signal.

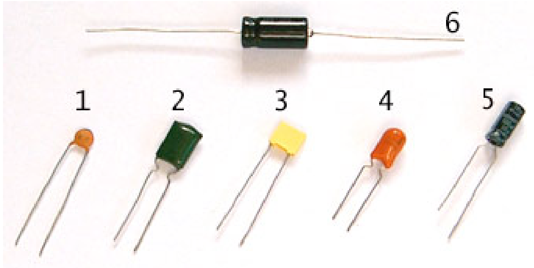
Capacitance is measured in Farads (F), but one Farad is much too big to be practical. Useful units are:
Micro Farads (µF or uF) = 1/1,000,000th of a Farad
Nano Farads (nF) = 1/1,000,000,000th of a Farad
Pico Farads (pF) = 1/1,000,000,000,000th of a Farad

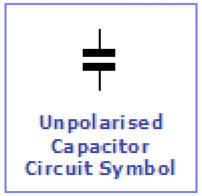
Capacitors less than 1uF can normally go in a circuit either way round. Larger capacitors normally have a polarity (normally the negative end is marked) and have to go in a circuit the right way round.

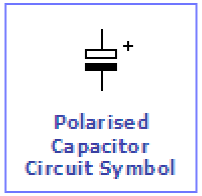
Capacitors come in a many different types that are designed for different applications. For this circuit the type used isn't important so we've used the cheap and cheerful options. The small capacitors are “ceramic discs” and the large capacitors are “electrolytics”.

Several labelling schemes are in common use for capacitors. The ceramic discs used in these circuits are labelled with three digit codes. The first two digits are the value and the third digits is the number of zeros making up the capacitance in pF.

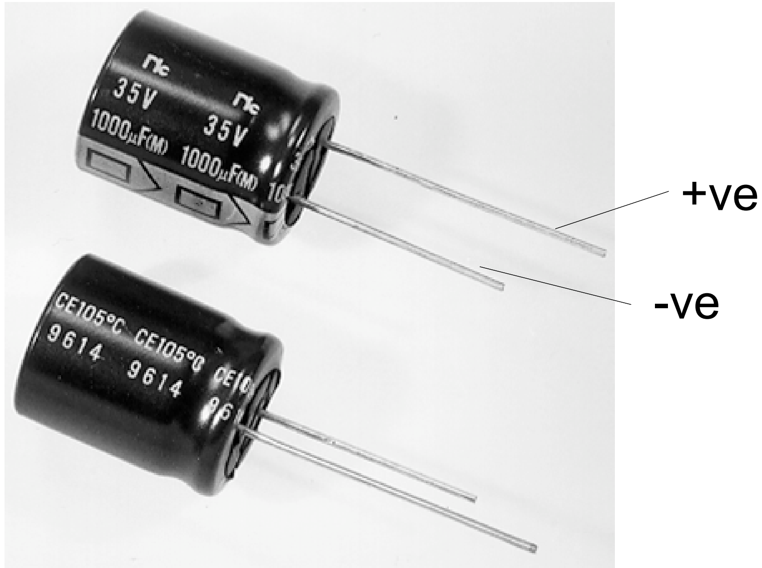
So:
10nF = 10,000 pF = “103”
100nF = 100,000pF = “104”

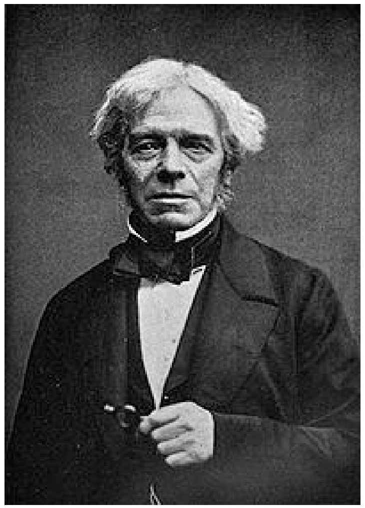






Electrolytic polarity





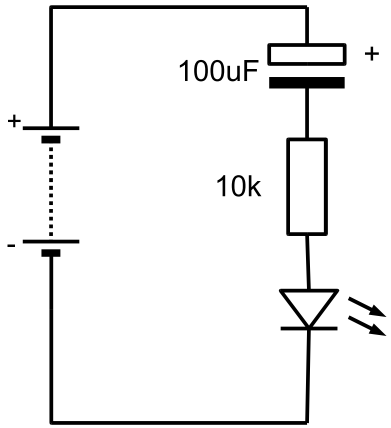
Michael Faraday

(22 September 1791 – 25 August 1867)

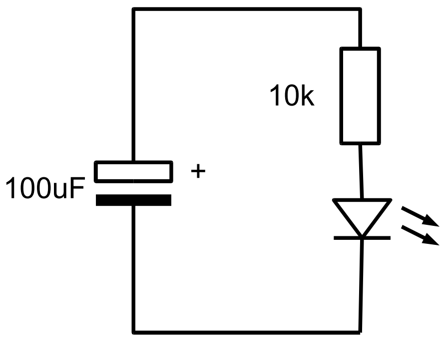
Discovered the fundamental relationship between electricity and magnetism (amongst many things).

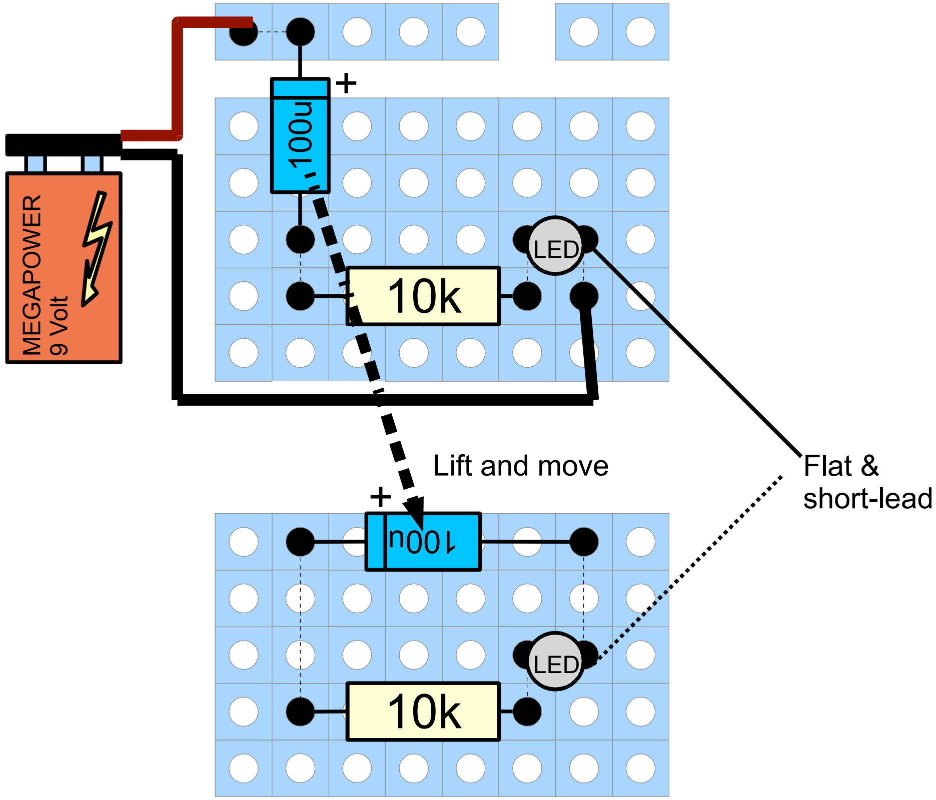
Experiments with a capacitor

Build the circuit like this with the battery disconnected.
Connect the battery and watch the LED.



Remove the capacitor and put in in this circuit without shorting out the legs.



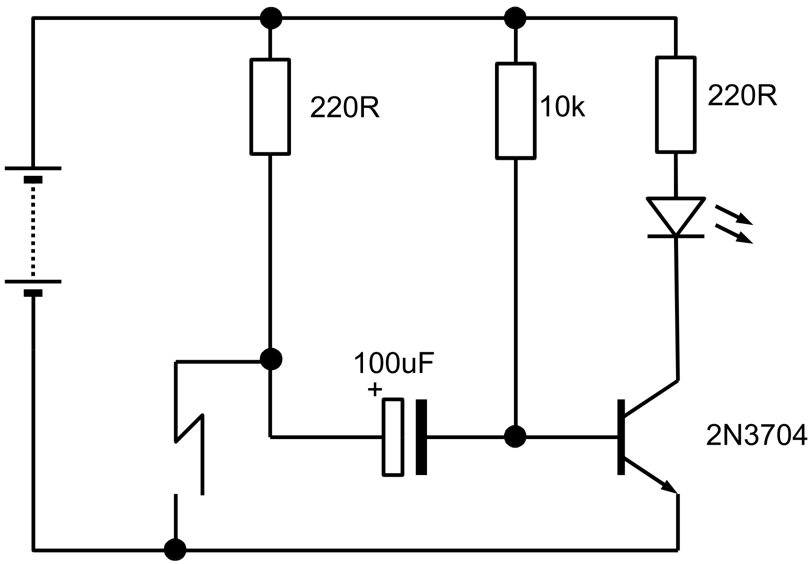


In the first circuit the capacitor charges up with current from the battery. The value of the resistor and the capacitor determine how quickly the charge builds up. As the capacitor charges it develops its own voltage that pushes against the battery. This reduces the flow of current and the LED goes out.

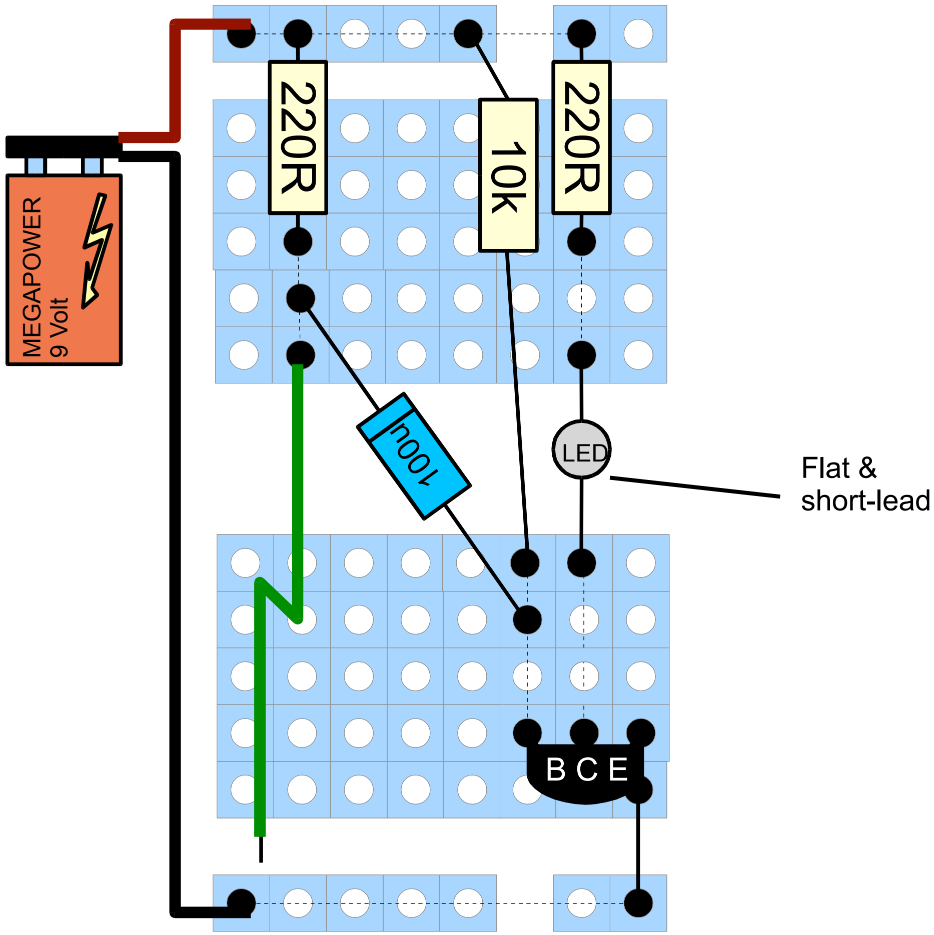
When the capacitor is moved in to the second circuit it discharges through the LED lighting it up.

Capacitors and transistors

Building timing circuits that combine capacitors with transistors offer a number of advantages over just using capacitors on their own:
- the amplifying effect of the transistor can generate a clean “on/off” effect from the gently changing voltage on the capacitor
- the transistor can isolate the capacitor from other effects allowing signals to be controlled without changing the behaviour of the capacitor timing circuit.
-



Flying lead that can connect to the negative line



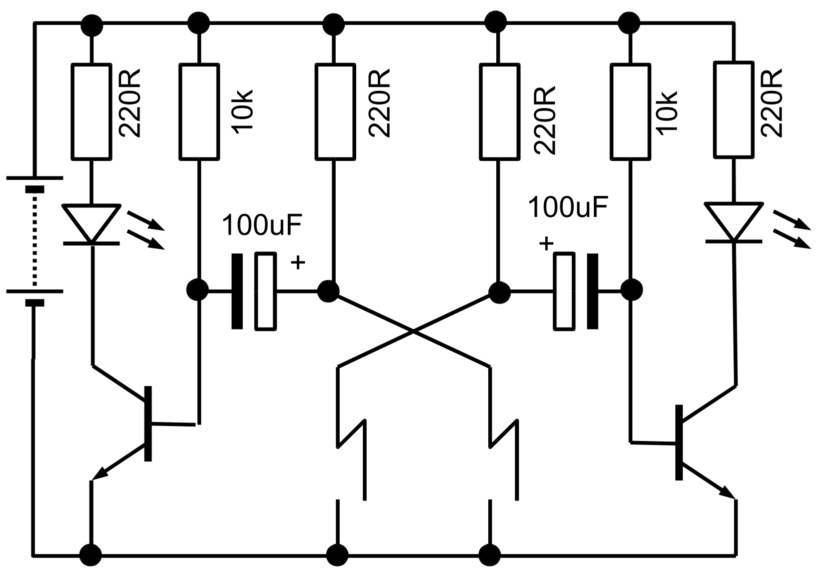
Build the circuit and then try connecting the flying lead to the negative line. The LED should go out momentarily and then relight. Disconnect then reconnect the flying lead to show this is repeatable.

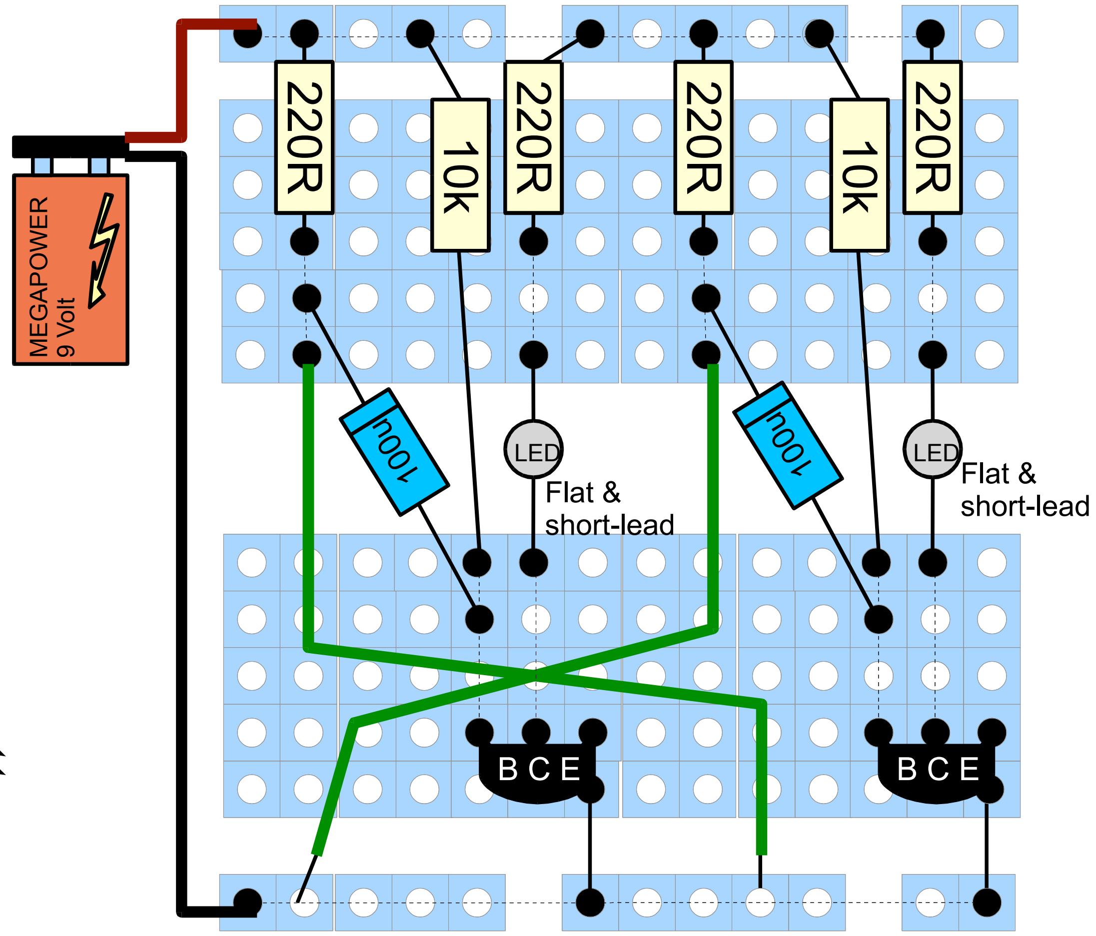
Times two

With two copies of the previous circuit you can manually make an interesting effect.

Build two versions and then cross over the flying leads. Hold the end that is now on the left in your left hand and the other end in your right hand. Connect one lead (say the one in your right hand) to the negative line. The left hand light will go out. Now follow the rules:
- if the right hand light is on connect the right hand lead to ground. If it is off then disconnect it.
- if the left hand light is on connect the left hand lead to ground. If it is off then disconnect it.

This manually makes the two LEDs flash alternately.





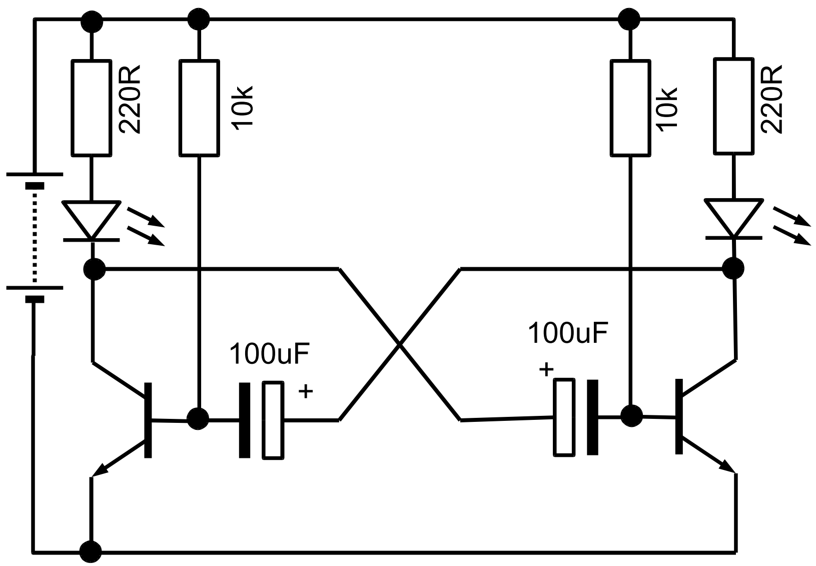
Build the circuit and then try connecting the flying lead to the negative line. The LED should go out momentarily and then relight. Disconnect then reconnect the flying lead to show this is repeatable.

Multivibrator

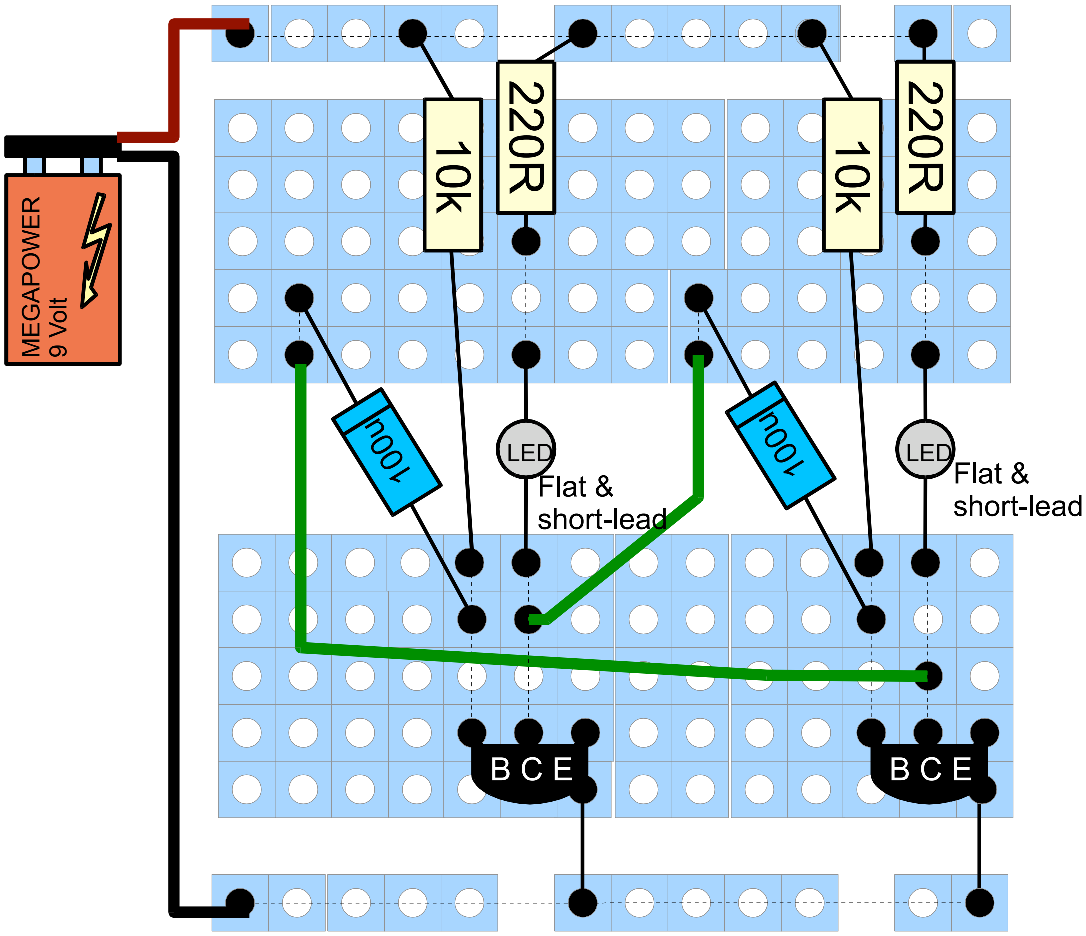
Wouldn't it be useful if you could replace the manual fiddling with leads in the previous circuit with something automatic? Well, guess what – with a few simple changes you can.

In the circuit below we've removed two of the 220R resistors and instead cross-wired what were the flying leads in to the collectors of the opposite transistor. The two halves of the circuit now work automatically against each other. When the circuit is powered up the lights will flash.

This circuit is known as a “multivibrator” and is the basis of a whole family of circuit designs. It also nicely illustrates the two sides to electronics:
1) understanding individual components and their function
2) Understanding how those components are used to create common building blocks.



Lines that cross without dots don't connect



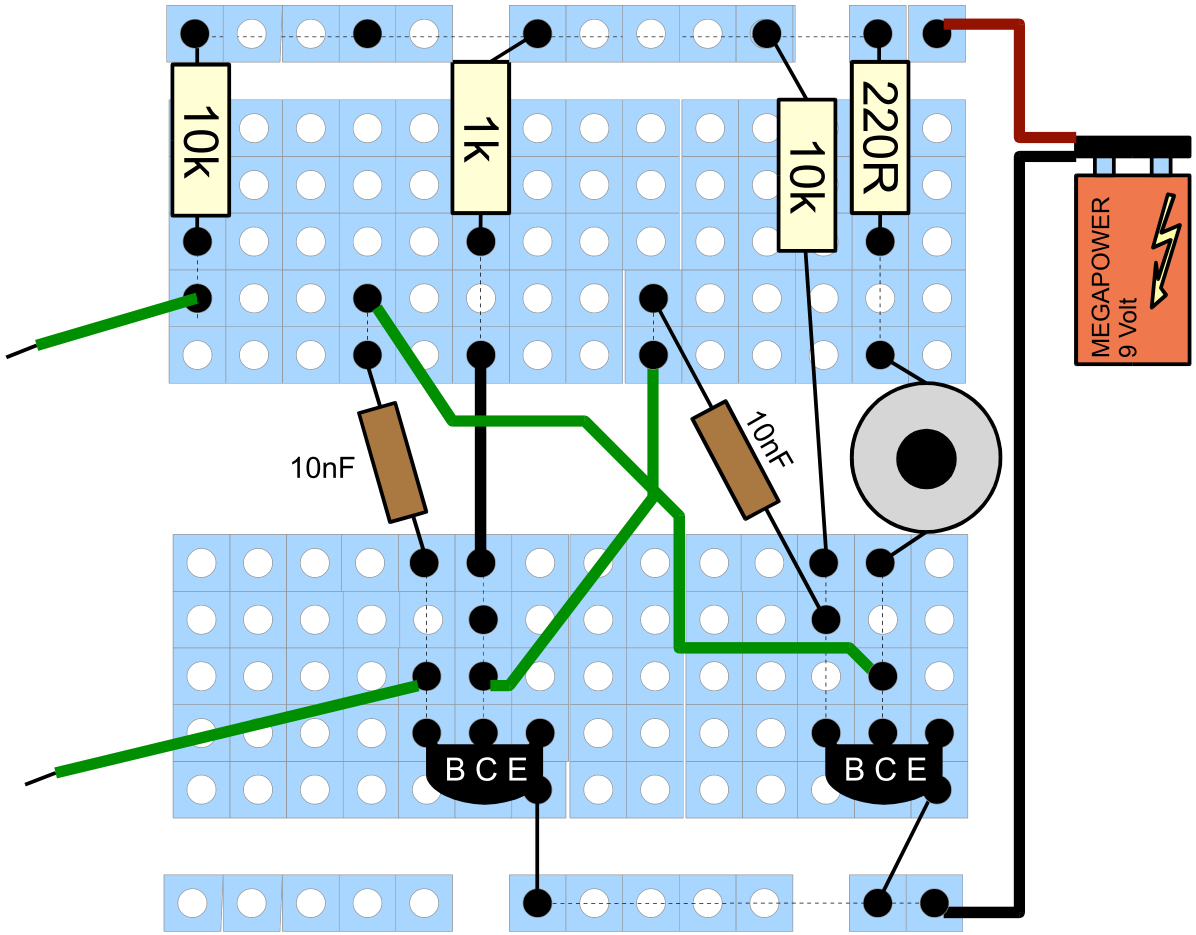
For more experiments:
1) Try changing the values of one or both of the 10k resistors. Suggested alternatives are 22k or 4k7.
2) Try changing the values of one or both of the 100uF capacitors. Try 10uF instead.

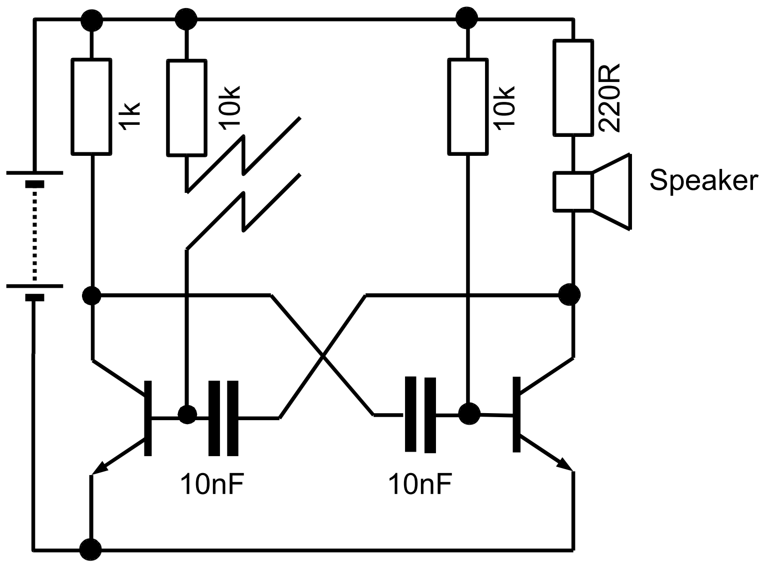
Observe the result of these changes.

Basic organ

By swapping the capacitors for much smaller values we can change the frequency of oscillation of the circuit to make it much higher – in the range your ear can hear. By connecting a speaker to the output instead of an LED this creates a basic organ. Play the organ by touching the wire probes on a pencil line.

Note about capacitor marking
10nF = 10,000pF = Normally written as “103” on capacitor

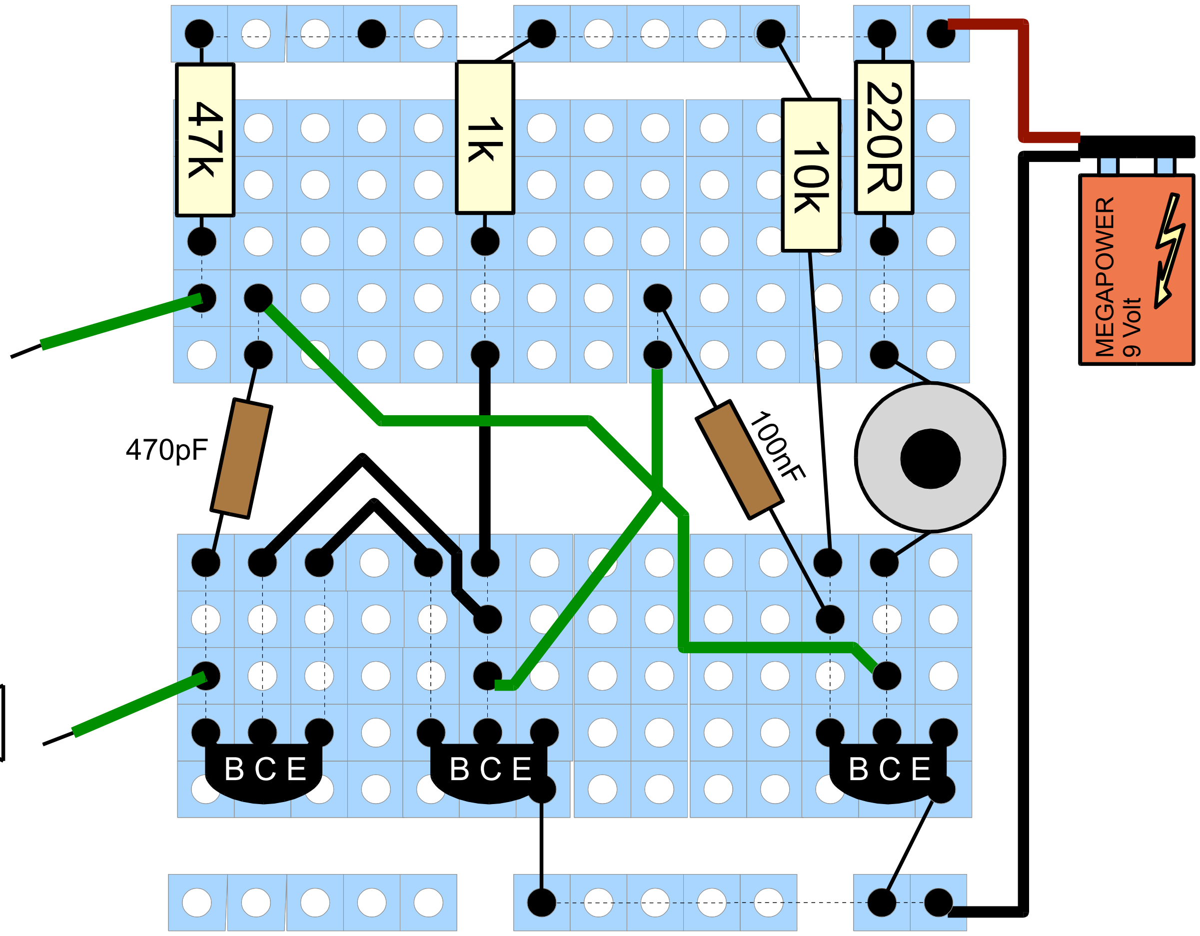


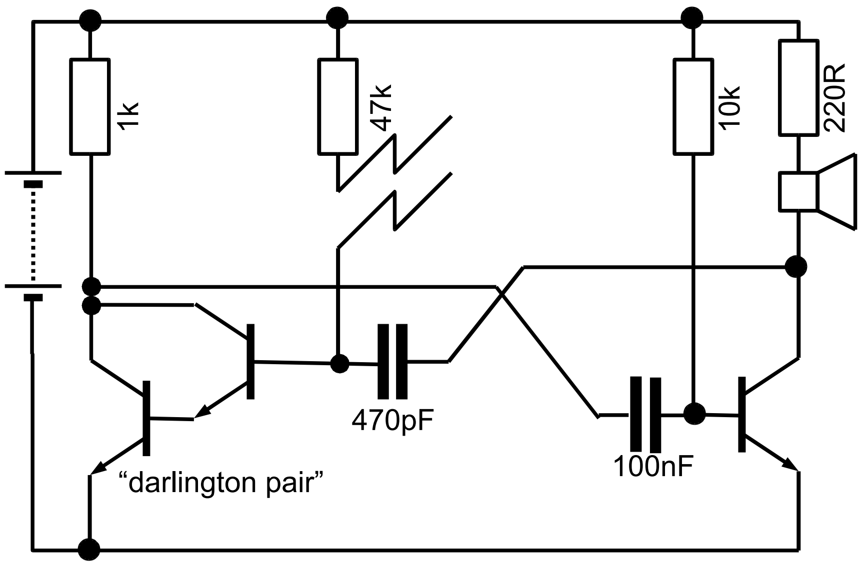


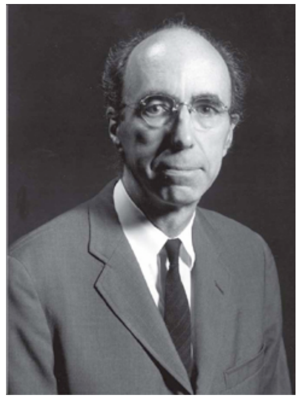
Improved organ

This circuit is an improvement on the previous design which allows longer pencil lines to be used. To do this a very high gain combination of transistors called a "darlington pair" is introduced. This allows very large resistors to be used in the base.

Note about capacitor marking
470pF = "471"
100nF = 100,000pF = "104"







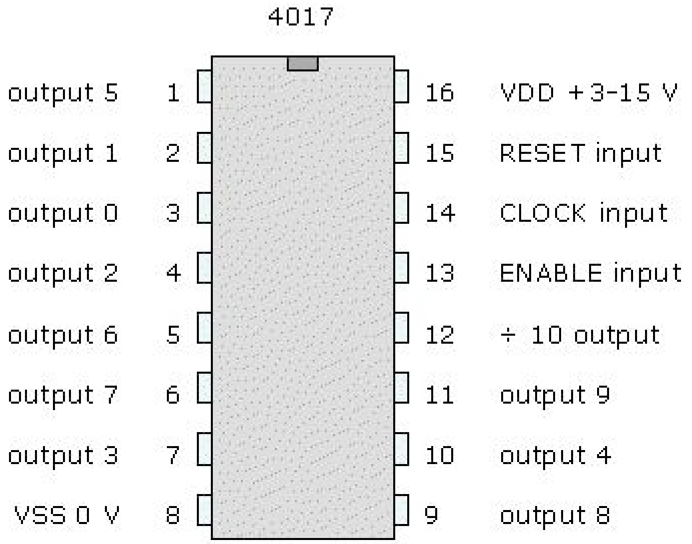
Sidney Darlington
(1906 - 1997)
Invented the "darlington pair"
and other circuit configurations and applications

Integrated Circuits

Integrated circuits ("ICs") are single packages that contain complete circuits consisting of many components. Today almost all ICs are silicon chips. Intel claims to have produced single ICs with 2,000,000,000 transistors.

For the last experiment we are going to use a "4017" decade counter. When this is driven from the output of a multivibrator it can be used to light LEDs in sequence producing a chain light effect.

Much of modern electronics is based on using ICs rather than discreet components. The skill lies in finding the right IC and understanding how to use it and its limitations. For example it's unusual to build multivibrators like the ones in these experiments in most designs – instead a timer IC like the famous "555" might be used.



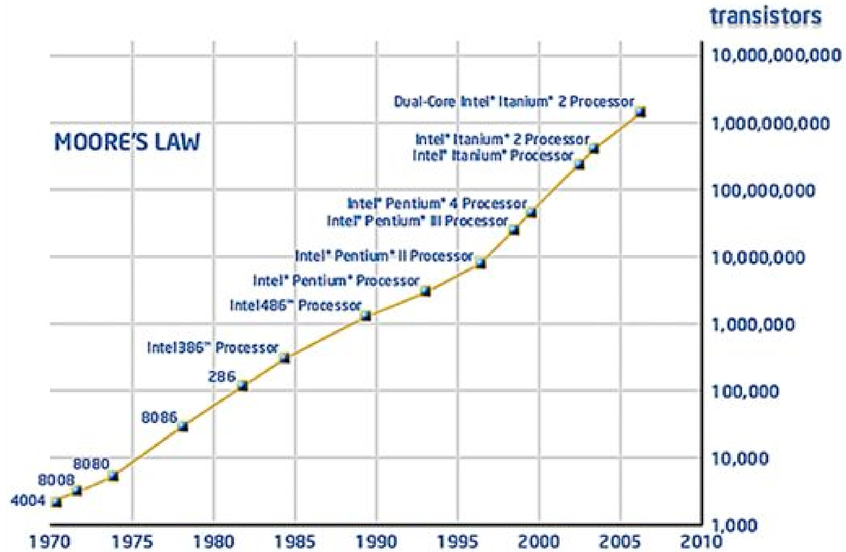
Note about IC Numbering

Numbering of ICs a pretty hit and miss. The "4017" is just the base name for the device. The full number will have other numbers or letters attached depending on which company makes it, what type of package it's put in and so on. You will often find lots of variants of the same IC with similar numbers. The IC in my parts kit says it's an "CD4017BE".

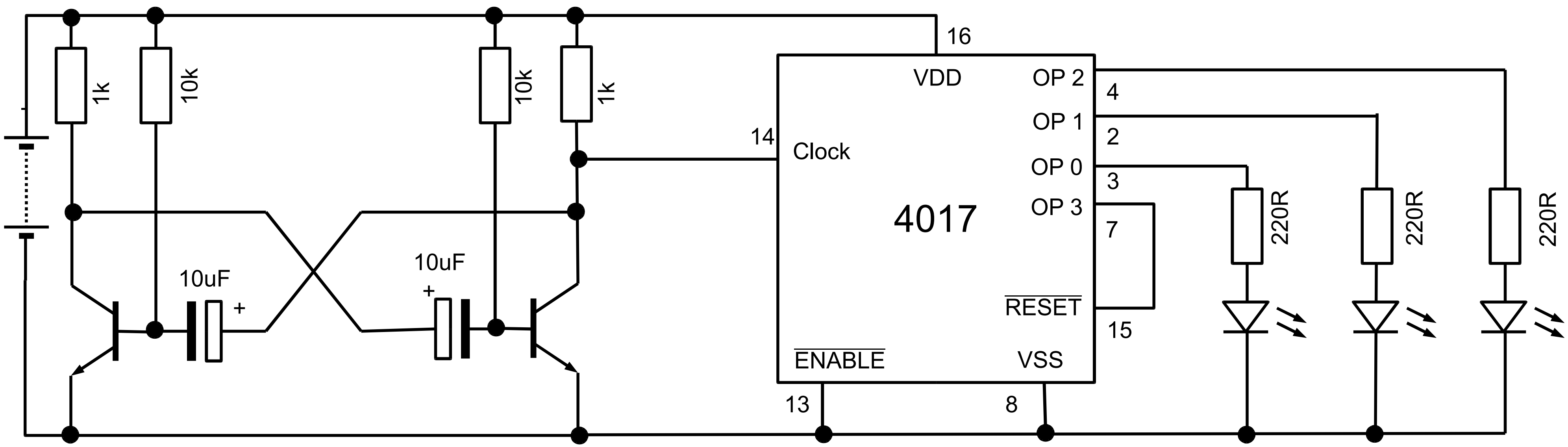
Gordon Earle Moore

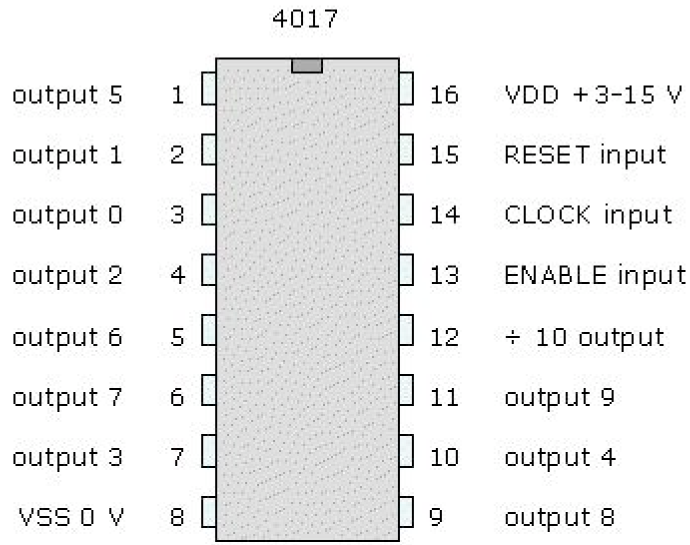
(3 January 1929-)

Observed that the capacity of economically feasible ICs doubles approximately every 2 years.



Chain Light Schematic





Chain Light Layout