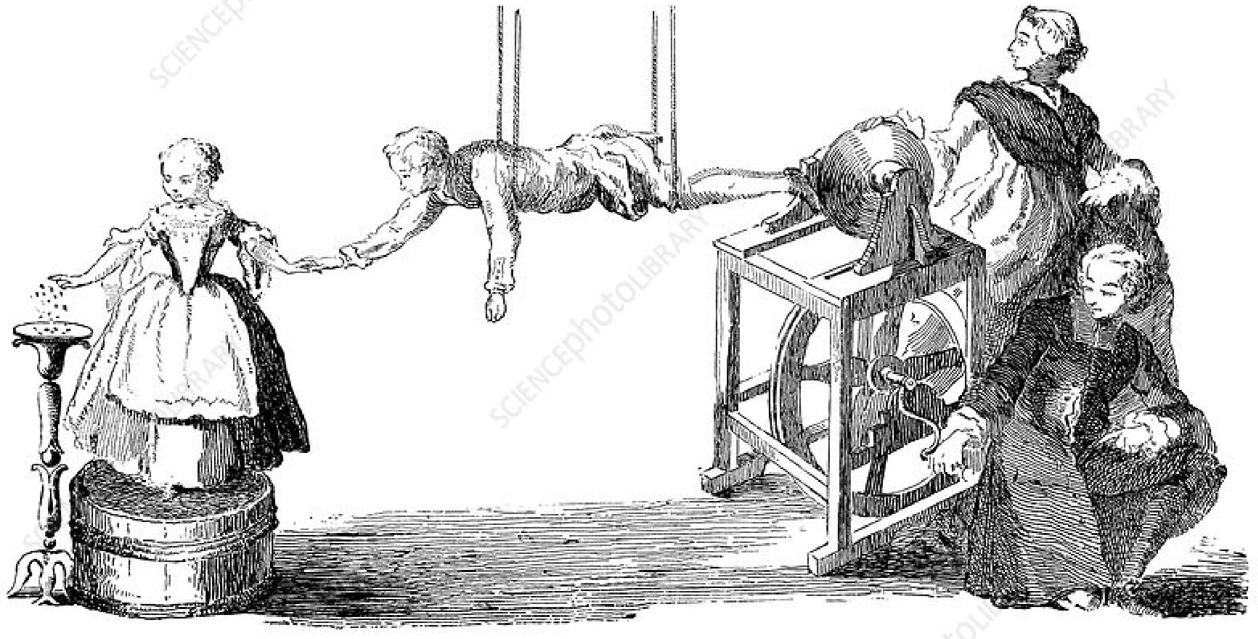
The Wimshurst Machine

History



During the eighteenth century, electrostatic demonstrations were hugely popular. The illustration above shows the sort of thing which amused the gentry of the day. The lady of the house is gently holding her hand on the surface of a glass globe which is being rapidly rotated by a footman. A boy – perhaps her son? - is suspended from the ceiling by silk threads and his feet are picking up the charge which is being generated by the friction between the glass globe and the ladies hand. This charge is transferred through his body (which is effectively an electrical conductor and also a capacitor) to the girl who is standing on a tub of pitch (to insulate her from the ground). She demonstrates that she is electrically charged by waving her hand over some wheat chaff which obligingly dances in the air.

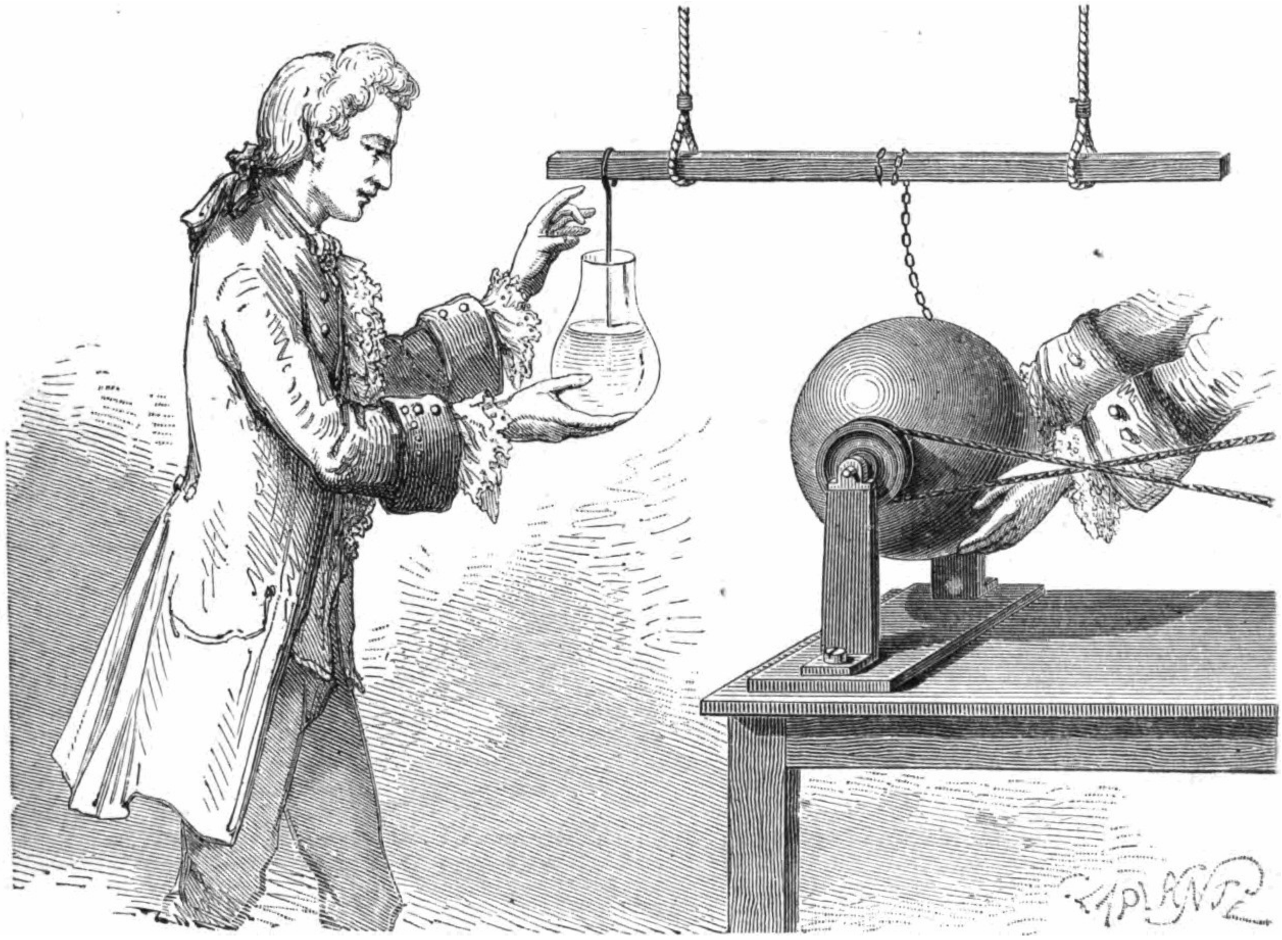
On a good day, a simple machine like this could produce sparks of 1 or 2 mm in length at the most. This translates into a potential difference of 2 – 4 thousand volts. If we assume that the boy and the girl have a combined capacitance equivalent to a sphere of radius 0.5 m, then the electrical capacitance of the system is of the order of

$$C = 4\pi\epsilon_0 r \approx 6 \times 10^{-11} \text{ Farads} = 60 \text{ pF} \tag{1}$$

and the energy stored will be:

$$W = 1/2\,CV^2 = 6 \times 10^{-11} \times 4000^2 = 0.0005 \text{ J} = 0.5\,\text{mJ} \tag{2}$$

This is much smaller than the recommended value of 390 mJ which is considered safe and will only deliver the mildest of shocks.



In 1745 a German dean, Edward Georg von Kleist, conceived of the idea of collecting electric charge in a bottle. A few years later, the same idea occurred to Pieter van Musschenbroek, the physics professor at Leiden University. The illustration above shows the Dutch scientist's assistant holding a glass bottle filled with water, supposedly collecting the 'electric fluid'. Once 'full' the bottle could be removed and on touching the electrode inserted in the top, a quite severe shock could be felt. What Musschenbroek did not realise was that the combination of the electrically conducting water inside the bottle, the assistant;s hand outside it and the insulating glass between made a very effective capacitor. The fact that the device was (and continued to be) shaped like a bottle was irrelevant. Never the less, these so-called 'Leyden Jars' were used for many years.

The natural successor to the eighteenth century friction machine is the Van de Graaf generator which was used in the 1930's to power the first particle accelerators. Here, charges generated by friction or other means are carried by a continuously moving belt into the interior of a metal sphere. This greatly increases the efficiency by which the charges are collected and the maximum voltage which can be achieved is limited only by the corona discharge from the sphere. Air breaks down at under an electric field strength of about 20,000 V per centimetre (2 MV m^{-1}) and the Electric field at the surface of a sphere of radius r is

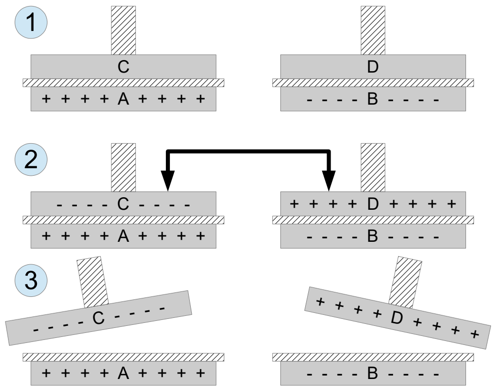
$$E = \frac{Q}{4\pi\epsilon_0 r^2} = \frac{Q}{Cr} = \frac{V}{r} \qquad (3)$$

Putting E = 2 MV m^{-1} we see that typical Van de Graaf generator as used in schools with a sphere whose radius is 0.06 m can generate a maximum voltage of around 120 kV and a maximum energy of 0.05 J .or 500 mJ. In practice, it is not possible to generate sparks longer than about 5 cm (100,000 V) with such a small machine which is considered perfectly safe.

Electrostatic Induction

The ideas which led to the development of the Van de Graaf generator date back to the 1870's. At around the same time, James Wimshurst, an employee of Lloyd's Insurance company and amateur inventor, became interested in designing a machine which, like the Van de Graaf generator, would produce a continuous supply of charge but which used a totally different method of producing charge called electrostatic *induction*. To see how this works, suppose we have two insulated metal plates A and B; suppose also that one (A) is charged positively and the other (B) negatively. Now we place two similarly sized but uncharged plates with insulating handles (C and D) on top of each one (1). Nothing of note happens because the insulation separates the plates.

But if we momentarily connect the two uncharged plates together with a piece of wire, the positive charges on disc A will attract negative charges on disc C, and the negative charges on disc B will attract positive charges onto disc D (2). We can now lift the plates C and D off the plates A and B (incidentally, doing work in the process) (3). We now have two oppositely charged plates whose charge we can transfer to some other object such as a capacitor or a leyden jar.



What Wimshurst saw was that if the plates A and B and the plates C and D were placed on counter-rotating insulating discs, each could provide the charge necessary to induce the opposite charges on the opposing disc. Also the momentary contact needed to connect the opposite plates together could easily be furnished by fixed contacts on each side. (These fixed contacts have come to be known a 'neutraliser bars' but they are badly named because the function of the bars is the *create* opposite charges on the two plates at each end.) It is worth pointing out here that the charge induced on plates C and D can never be greater than the total charge on each of the plates A and B and in practice it will be significantly less. On the othet hand, the process can be repeated indefinitely because the charges on A and B remain unchanged by the process.

A Simple Wimshurst Machine

Our simple machine consists of two counter-rotating insulating discs, each carrying two metal plates. We shall suppose that the front disc is rotating clockwise and the rear one anti-clockwise. The two discs are synchronised so that the plates coincide when they are at the 45 degree angle. There are two neutraliser bars, also at 45 degrees to the vertical, which momentarily connect the plates together when they coincide. The bar at the front is angled from top left to bottom right and the bar at the rear is angled (when seen from the front) from top right to bottom left. Pickup electrodes are placed on the left and right hand sides of the machine which collect charge from both the front and the rear discs. These contacts are connected to the poles of two earthed capacitors (or Leyden jars).

Fig. 1 shows the position when the two front plates C and D have just given up their charge to the two Leyden jars, and the two rear plates are vertical, A being positively charged and B negatively charged:

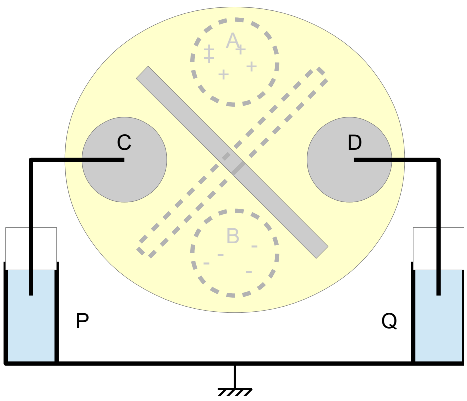


fig. 1

The two discs now rotate by 45 degrees. A moves behind C and B moves behind D. C and D are momentarily connected together: C acquires a negative charge by induction, D a positive charge. After a further 45 degrees of rotation, C and D are now vertical, A dumps its positive charge into jar P, while B dumps its negative charge into jar Q. This is the situation now:

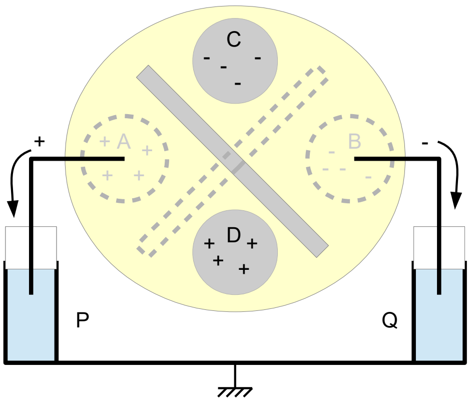


Fig. 2

After another 45 degree turn, the negatively charged plate C moves in front of plate B while the positively charged D moves in front of A; A acquires a negative charge while B acquires a positive charge due to the rear neutralising bar and after a further 45 degree rotation, D dumps its positive charge into jar P while C dumps its negative charge into Q. Now we are effectively back where we began and the whole process repeats indefinitely with P acquiring positive charge and Q negative.

There are a number of things to say about this simple machine. The first is – where does the initial charge come from? We assumed that A was originally positively charged and that B was negatively charged. What if they were the other way round? Obviously, the polarity of P and Q would be reversed. What if they were neutral? Then, in theory, no voltage would be developed. In practice, however, there is always sufficient charge (caused by friction with the air etc.) to get the process going one way or the other.

Secondly, it was assumed that the rotating discs were synchronised. What if they were out of sync? It is vital that at the instant that two plates are connected by the neutraliser bar that the opposing plates should be somewhere near in order for induction to occur.

Thirdly, what if the neutraliser bars are at some other angle? In our analysis we have assumed that they are at 45 degrees to the horizontal. What if they were horizontal? In that case, at the instant the two plates were connected, they are also in contact with the two Leyden jars which would then be short-circuited. What if they were both vertical? All four discs would be neutralised at the same time and no voltage would be generated. So, provided that the bar is sufficiently far away from the pickup contacts so that they are not in simultaneous contact and provided that neutralising bars are never in contact simultaneously, the machine should work.

Fourthly, if we assume that the induced charge is exactly equal to the charge on the opposing plate, then at each half revolution a single unit of charge will be dumped into each of the Leyden jars and the machine will produce a continuous (and tiny) direct current. If, however, the induced charge is anything less than 100% of the inducing charge (i.e. what we might call the 'generating factor' is less than 1), then the machine will quickly discharge itself and the current will cease. Clearly there is something missing from the analysis we have presented so far (and there is something missing from virtually all the articles on the web which purport to explain how the Wimshurst machine works including the article on Wikipedia.)

The missing principle

In order for the machine to produce the very high voltages which we know it generates, it must be the case that somehow the charge which is induced on the plate C is *greater* than the charge on plate A and the 'generating factor' must be greater than 1. In other words, there must be some other mechanism which induces charge on plate C over and above the charge on plate A. Let us therefore consider an even simpler machine with only one rotation disc (the one carrying plates C and D) and one neutralising bar.

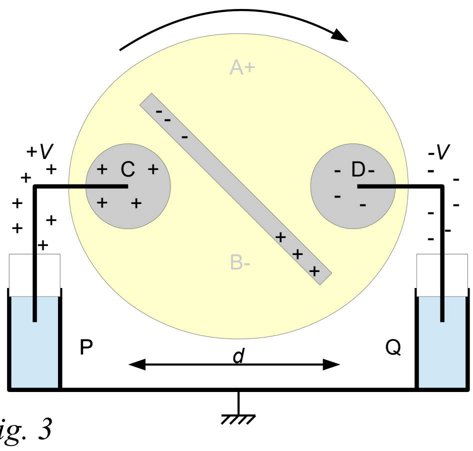


Fig. 3

The above diagram shows the situation at the point when the plates C and D are in contact with the poles of the Leyden jars. We shall assume that the jars have already acquired a voltage of $+V$ and $-V$ respectively. This creates an electric field across the apparatus equal to $2V/d$ where d is the width of the machine and the jars are at $\pm V$. Now within this electric field there exists a conducting bar – the neutraliser bar. This bar becomes strongly polarised with negative charges on its left hand end and positive charges on its right. As the disc rotates (clockwise) the plates C and D become disconnected from the poles of the Leyden jars but still retain their respective equal and opposite charges. At the instant that they come into contact with the neutraliser bar they mutually discharge – but owing to the electric field across the machine, they end up being part of the conducting bar and become polarised like this:

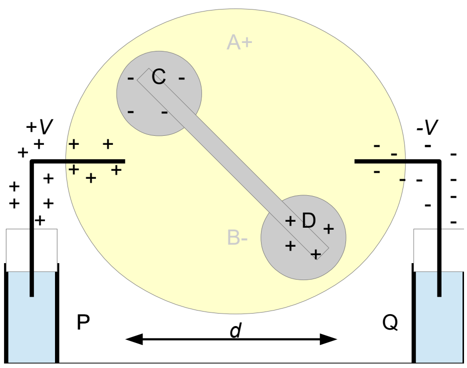


fig. 4

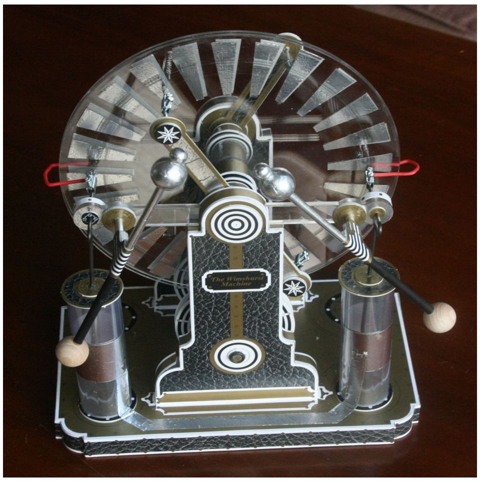
When the two plates lose contact with the neutraliser bar, plate C carries negative charge and plate D carries positive charge. Note that the greater the potential difference between the poles, the more strongly the plates will get charged.

We can now see why the angle of the neutraliser bar makes a difference to the operation of the machine. If the (single) neutraliser bar is vertical, it will not be polarised by the electric field across the machine and the plates will simply discharge. The plates will only pick up opposite charge when the neutraliser bar is angled towards the pickups in the opposite direction to the direction of rotation of the disc. Maximum polarisation and therefore maximum induction will occur when the bar is nearly horizontal (without ever shorting the poles, of course).

Getting the machine going

It will be appreciated that there is some difficulty getting all this induction started. We have seen that it is not sufficient just for some of the plates to carry charge. It is essential for the whole process to get going that there exists a potential difference across the machine. - i.e. the Leyden jars must contain some charge. (It is the failure to realise this that is the cause of some frustration when a Wimshurst machine fails to work.) However, since the degree of polarisation is proportional to the voltage across the poles, it is easy to see that the rate of increase of voltage will be exponential so it hardly matters how small the voltage is to start with. (This initial voltage could well be provided by the small current which is generated by charges initially present on the plates.)

The standard Wimshurst Machine



A standard Wimshurst machine with 12 pairs of segments

I do not know if anyone has tried to get a Wimshurst machine with a single disc and one pair of plates to work. In practice, it is much more efficient to use a pair of discs and at least 8 pairs of plates or segments. The machine illustrated above is made from a cardboard kit marketed by Astromedia[1] for about £50 and produces very satisfactory sparks of up to 30 mm in length (~60 kV)

The use of multiple pairs of segments has the following advantages.

Firstly, it makes it relatively unimportant if the rotating discs are out of sync. Even if, at the instant that a segment is in contact with its neutralising bar, there is no segment immediately opposite, since all the segments on the other discs are charged, induction will still occur provided that the segments are not too far apart. Induction due to the electric field across the machine will occur regardless.

Secondly, and rather obviously, a machine with 12 pairs of segments will charge up 12 times faster than a machine with only one pair.

1 https://www.astromediashop.co.uk/JTL-Shop/

The effect of altering the angle of the neutralising bars

As we have seen, the polarising effect of the electric field across the machine is greatest when the neutralising bars are nearly horizontal. This means that the 'generating factor' will be relatively large and the machine will charge up quickly. If your Wimshurst machine will not start, then it is best to put the bars in this position in order to maximise its chances of getting going.

There is, however a downside of putting the bars in this position. You can see from fig. 4 that at the instant one of the segments comes into contact with the neutraliser bar, there will be a large potential difference between the segment and its neighbour (which is still in contact with the Leyden jar). In fact, since the neutralising bar is at zero potential all the time, the potential difference will be equal to V. Roughly speaking therefore, the maximum length of spark which can be obtained between two electrodes will be twice the distance between adjacent segments on the disc, because, if the voltage is greater than this, currents will flow across the surface of the disc rather than sparking across the air gap.

By moving the bars towards a more vertical position, providing the 'generating factor' does not fall below 1, the potential difference is spread across a greater number of gaps between the segments and the length of the spark you can achieve will be greater. Ultimately, therefore, the maximum voltage which the machine is capable of generating is limited by the maximum voltage which can exist across all the segments between the neutraliser bar and the nearest pole. If the discs are at all damp, this voltage is greatly reduced. Gentle warming of the discs with a hair dryer will help.

Carr Bank: January 2025