Van De Graff Machine

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Introduction:

Robert Jemison Van de Graaff discovered that it should be possible to generate a high volume of voltage by transferring charge to an ungrounded, conducting sphere from a ground potential. He built the first model of the Van de Graaff machine out of a can, a silk ribbon, and a small motor in 1929. This original model generated 80 kilovolts (Bygrave, Treado, and Lambert 1970, 3).

The goal of this project was to create a Van de Graaff machine using simple materials that could easily be purchased at a common convenient store. This machine would be able to use the belt and rollers to create a net charge on the top conductor. This net charge should be detectable using an electroscope or by inducing a shock. However, after using three types of rollers, two different belts, and three different designs, the Van de Graaff machine did not create a net charge.

The physics of a Van de Graaff Machine

A Van de Graaff machine is an electrostatic generator. It uses an insulating belt to collect charge by rubbing against rollers and then discharging them into a large metal conductor (Cleveland and Morris 2006, 471). A typical Van de Graaff machine is built using a motor, a belt, two rollers, a conducting sphere, two conducting combs, and something to hold the structure together. It is important to have a powerful enough motor to turn the belt quickly, since the amount of charge generated relies on the belt's ability to move. The belt needs to be an insulating material, like a rubber band. One roller needs to be a material from one side of the triboelectric series, like a plastic, while the other roller needs to be either a conductor, like a metal rod, or a material from the opposite side of the triboelectric series than the first roller, such as human hair in opposition to plastic. The conducting combs need to be sharp edged, like a wire. Ideally the conductor on top should be a sphere; however any smooth conductor should work (Dufresne 2012).

A Van de Graaff machine is able to generate charge onto the conducting surface due mostly to triboelectrification, or charging by rubbing. Triboelectrification is caused by the fact that when two insulating materials are pressed against each other a chemical bond called adhesion occurs. When adhesion happens, certain qualities existing is a material cause a change in its surface charge. These triboelectric qualities cause an exchange in surface charge between the materials based on their position in the triboelectric series. Then when these materials are separated from each other they retain their net charge because they are insulators (Zavisa 2012). This same concept has been used in early physics II labs where an oven bag was used to charge a golf tube.

The Triboelectric effect is thought to be caused by many factors, one of which is surface contact effects. Certain qualities of a surface can increase or decrease the amount of charge produced from rubbing. In particular, surface roughness can be a large factor in determining how much charge is produced. A rougher surface will have many sharp edges on the nano-scale; therefore if you place a rough surface on a smooth surface, the rough surface will only make contact with the smooth surface at its peaks. In contrast if you lay a smooth surface on top of another smooth surface, more of the surface is going to be in contact with the other, and therefore there is a greater opportunity for the two surfaces to exchange charges (Allen 2000, 2-3). Therefore it is important to choose a belt that is rough enough to keep the rollers turning, but not so rough that the belt barely makes contact with the roller.

The Triboelectric series list materials by their ability to become charged by rubbing. Examples of positive materials, charge positively, on the triboelectric series include: rabbit fur (more positive), glass, human hair, nylon, wool, fur, lead, silk, aluminum, paper, and cotton (less positive). While examples of negative materials, charge negatively, on the triboelectric series include: Teflon (more negative), Silicon, PVC, Scotch Tape, Saran Wrap, Styrofoam, polyester, Gold, Platinum, Copper, Brass, Silver, Nickel, Hard rubber, and Wood (less negative). (Zavisa 2012) Thus if you rubbed two materials together their charge would correlate to their property given in the triboelectric series. Notably, rubbing two materials that are further away from each other in the triboelectric series provides a much larger net charge than two materials closer in the triboelectric series. All materials on the triboelectric series that are less conductive tend to be able to be charged easier by rubbing.

In a Van de Graaff machine, triboelectrification comes into play when the inside of the belt rubs against bottom pulley, which causes the pulley to become charged. The charge of the pulley then repels the like charge onto the outer side of the belt, while the bottom conducting comb brings the repelled charges to ground, causing the outer side of the belt to become charged. The belt then travels to the upper pulley where it attracts the opposite charge from the top conducting sphere through the top conducting comb, leaving the conducting sphere charged. Meanwhile the belt rubs with the second oppositely charged roller, bringing the belt back to a neutral charge. The now neutral belt then travels down to the bottom and starts the process over (Gedney 1998). The concept of surface contact, as discussed above, can be applied on a larger scale to the Van de Graaff machine. The wider the belt of the Van de Graaff machine, the more surface area will come in contact between the belt and the rollers, which will allow a greater exchange of charge.

Design Van de Graaff machine for this project

The plan for this project was to create a Van de Graaff machine using a coffee can for the large top conductor, one wooden dowel wrapped in nylon yarn for one of the rollers, another wooden dowel wrapped in vinyl electrical tape for the other roller, two lengths of wire for the conductive combs, aluminum foil for a conductive ground, a hand drill to act as the motor, a box and several dowels for the structure, a silk ribbon as the belt, and duct tape to hold the machine together. A silk ribbon was used for two reasons. Firstly, it is only slightly positive on the triboelectric series, which is useful because it then has a greater charging ability on both the nylon and vinyl. Secondly, a silk ribbon was used as the belt in Van de Graaff's original machine, and thus historically works. Nylon was selected as one of the roller materials because nylon yarn is easy to obtain and it is decently positive on the triboelectric series. In opposition to the nylon, vinyl tape was chosen for the other roller because it is very negative in the triboelectric series and it can easily be applied to a wooden dowel.

The original frame had the Van de Graaff machine operating in the upright position, that is, with one roller several inches above the other and the coffee can placed on top. This is a more classic style of Van de Graaff machine and is the most common type of set-up found throughout all the research for this project. Figure 1 gives an example of this type of set-up.

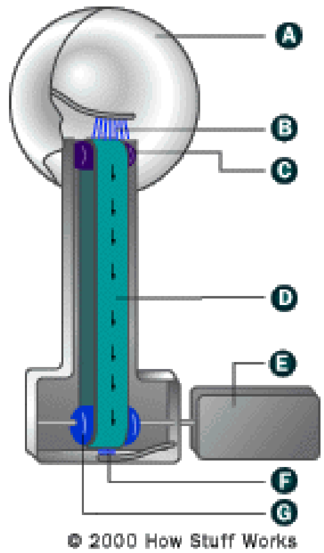

Figure 1: A typical set-up for a Van de Graaff machine. Note how the belt travels vertically up the machine. (Zavisa 2012)

The machine was constructed by covering the base of the machine, the box, with aluminum foil. Then four large dowels were placed vertically on the box as to support the weight to the top coffee can and the rollers. Next the bottom roller was secured into place a few inches above the box. Then the bottom wire was set so that one end was in contact with the aluminum foil, acting as ground, and the other was very close, but not touching, the bottom roller. The end of the wire close to the roller was spread out to create a more comb like appearance. The top roller was then placed near the top of the vertical dowels. Then the coffee can was placed on top of the dowels with the other wire set up so that one end of it was in contact with the interior of the can and the other end was spread out near the top roller. Next, the belt was wrapped securely around the two rollers and the hand drill was attached to the bottom roller to power the machine, as shown in figure 2.

Figure 2: The high power drill is attached to the end of the vinyl roller to rotate the belt and cause a net charge.

The initial issue with the machine was the motor. A hand drill was used that had very low number of rotations per minute, which caused the belt to move very slowly. This caused there to be significantly less friction between the belt and the rollers and therefore a significant loss in triboelectric charging. Thus the belt did not become charged. This problem was solved by buying a more powerful drill capable of rotating at 325 and 650 rotations per minute.

After the more powerful drill was integrated into the machine, there was another problem. The silk ribbon was not able to withstand the speed of the hand drill and tore at its seam after a few second of being turned. This was largely due to the inefficiency of fastening the ends of the belt together. Originally, the ribbon was tied so that it was complete belt; however that caused issues with the knot scratching against the wires. Then instead the ribbon's ends were fastened with tape to keep the belt completed. Silk material, though, is not particularly adhesive, which caused the tape to fail within seconds of the motor turning it. Lastly, the silk ribbon was stitched together using thread; however the ribbon was much too thin for it to be stitched. The ribbon was ripped to shreds by the stitching. Thus a new belt was in order.

The belt replacement would be rubber bands as they are already completed circuits. Also rubber bands are hard rubber which is only slightly negative in the triboelectric series and is a strong insulator. Three rubber bands laid side by side were used for the new belt. Yet, this belt had its issues as well. The rubber bands were new and therefore carried a lot of tension in them. Due to their tension the rubber bands caused the entire structure to collapse as it dragged the top roller down with such a force that its support gave.

A new structure was created after the first one collapsed. This time the machine was built horizontally instead of vertically. The coffee can was now behind the belt which moved laterally. Figure 3 shows how the machine was set up.

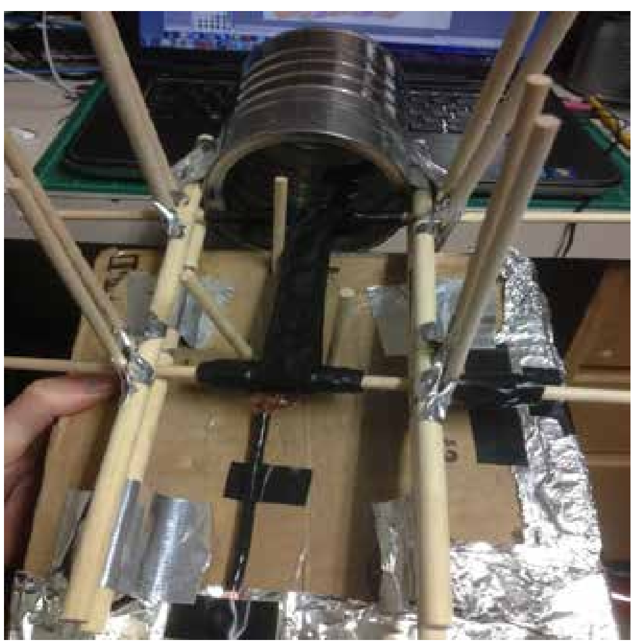

Figure 3: The Van de Graaff machine is lying flat instead of standing vertically.

By having the Van de Graaff machine move laterally, there was a lot less strain on the support dowels. The whole structure was more secure than with a vertically standing one. In Figure 3, the machine is shown using the silk belt again. The silk belt worked considerable better when the machine was lying down. But the biggest problem with the silk belt was the extremely large amount of slipping going on between it and the rollers. The slipping was chiefly due to the fact that the silk belt was loose on the rollers and therefore did a poor job of making them turn. This causes a substantial loss in surface rubbing, which causes the system not to create a charge. Therefore the silk belt was retired from this project at that point.

Another issue that rose was the fact that the wire used in the machine was not very maneuverable. It was very thick wire and therefore moved frigidly and with great difficulty. The size wire used in the project was much larger than it should have been. One of the big problems with this wire was that it would not make contact with the coffee can very easily. Keeping the wire in contact with the can while the motor was running was certainly challenging as the wire would easily slip out of its electrical tape fixture. In order to compensate, the wire was pinned to the can by a layer of aluminum foil, which is also conductive. This way, the wire was in contact with a conductive surface that led to the coffee can at all times.

Although the frame was better, there were still several issues with it. For instance, the rubber band belt, although it was better with the machine lying flat, still pulled the rollers with enough force to cause a loss of structural integrity. After only a few trial runs, it was clear that the structure was being ripped apart by the rubber bands. Even after stretching the rubber bands for a long period of time, around twenty four hours, they still had enough tension to cause damage. Eventually the duct tape fastening gave and a new structure was in order.

The third structure was simpler and more stable. Slits were cut in a box to support the rollers. Then the conducting coffee can was placed on top of the box with a wire running through the top of the box to act as the conducting comb. Similarly, another wire ran from beneath the box up close to the bottom roller. The bottom of the box was covered in aluminum foil to act as ground. The high power drill was attached to the bottom nylon roller. The top roller was replaced with a metal bronze roller, as its conductive properties as a metal should make the belt go to ground as it passes over it. Figure 4 shows this step up for the machine.

Figure 4: The frame of the machine was replaced with a box with the rollers running vertically above each other. The coffee can conductor is placed on the top of the machine and the hand drill motor it attached to the right side of the bottom roller.

Reasons for failure

Throughout the three structure changes, the machine never seemed to produce any sign of charging. This may be to the design.

In order for the Van de Graaff machine to work, the conducting combs have to be very close, but not touching, to the rollers in order for the charge to transfer between them. That distance could have been too large for the amount of charge produced by the machine. However, the distance between the wire and the rollers was about 1 centimeter, so getting any closer would have been unreasonable. Figure 5 shows the distance between the roller and the wire end.

Figure 5: The wire end is about 1 cm away from the roller.

Another possible factor for the failure of the device is that coffee can could have had an interior coating which would prevent the flow of charge to take place. Though, this seems like an unlikely cause for failure since during the third reconstruction of the structure, shown in figure 4, the wire was attached to the outside of the can and still produced no change in the machine.

Therefore the most probable error occurred in the belt and roller interaction. By observing the speed at which the bottom roller, the one attached to the motor, rotates and comparing it to the speed at which the top roller rotates, the amount of slipping that occurs between the rollers and the belt is observed. Since the bottom roller turns at a considerably faster rate than the top roller, the top roller spins at about one sixth the rate the bottom roller spins, the belt and rollers must have a large amount of slipping taking place. The slipping of the belt on the rollers disrupts the flow of the machine and causes a lot less surface area becoming charged. Thus, the Van de Graaff machine built for this project is likely producing a miniscule amount of charge that is too small to be transferred to the conducting dome or ground through the combs.

Conclusion

The goal of this project was to produce a Van de Graaff machine that could generate enough charge to cause a visual shock. However, the Van de Graaff machine produced did not work because of the slipping of the belt. In order to create a working Van de Graaff machine, the belt needs to be at just the right tension so that it has enough friction with the rollers to produce a net charge. If the belt is too loose on the rollers, like the silk ribbon belt was, there will not be enough friction to even get the top roller to turn. Likewise, if the belt is too tight, as the rubber band belt was, it will pull the rollers, keeping them from turning, instead of turning them.

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