

Electrostatics: The Shocking Truth

Important health warning for students with pacemakers or other electronic medical devices: This lab involves the use of a Van de Graaff generator, which produces small amounts of electrical charge. They are regularly used in elementary schools, high schools, colleges, and science centers. They pose no risk to health or safety. The only exception is to students with pacemakers or other such electronic medical devices. If you use a pacemaker or other such electronic medical device, please contact Dr. Hynes IMMEDIATELY to make other arrangements for lab. It is very unlikely that you will be affected, but safety is our top priority. Remember, as long as you do not have this type of medical device, you have absolutely nothing to worry about.

Pre-Lab: The Van de Graaff Generator

A Bit of History

The Van de Graaff generator is an electrostatic generator, capable of producing constant electric potential differences reaching about 10 million volts. The models that you will use (thankfully) only achieves about 1% of that. The term *Van de Graaff electrostatic generator* may sound a little foreign, but there is one electrostatic generator that you are no doubt familiar with: earth's atmosphere. In fact, some of the most famous experiments in the history of electrostatics were done using the atmosphere. In May of 1752, Benjamin Franklin performed his well-known kite experiment, an experiment which strongly suggested that lightning might not be so different from the sparks he produced using silk and glass. Interestingly, not long after Franklin completed his experiment, he learned that he had been scooped by a group of Frenchmen who had read one of his recently published books. It turns out that both groups were lucky to survive the experiments, as a Swedish scientist died the next year while attempting to replicate them.¹

The Van de Graaff generator itself has achieved great fame as a tool for demonstrating the principles of electrostatics to physics students in spectacular fashion. (The world's largest Van de Graaff generator, found at the Boston Museum of Science, exists solely for this purpose.) However, the Van de Graaff generator has also been used as a tool for doing real science ever since its invention by the American physicist Robert Van de Graaff around 1930. The high potential differences produced by large Van de Graaff generators are still used as particle accelerators around the world. While they can't accelerate particles to energies of a TeV (1 trillion electron volts) like the Large Hadron Collider at CERN, sometimes a few MeV's (millions of electron volts) is all a researcher needs. Among the many modern uses for the Van de Graaff generator are radiocarbon dating, x-ray imaging, and the production of particles for medical purposes.²

The Van de Graaff generator even played a role in a recent research project in which the Wash U physics department played a major part.³ The *Stardust* mission sent a spacecraft through a comet tail, collected particles that had blown off the comet, and safely landed back on earth. In order to calibrate their

collectors, scientists bombarded them with small grains accelerated to speeds up to 30 km/s. Such incredible speeds could most efficiently be produced using large Van de Graaff generators.

University of Virginia Van de Graaff Resource

The big piece of equipment in this week's experiment is a Van de Graaff generator powered by a hand crank. A Van de Graaff generator uses some clever tricks in order to charge a metal dome to a very high potential. (The Van de Graaff generator is described by Moore in Unit E, pages 15 and 102 and by Young & Freedman on page 743.)

The University of Virginia has an excellent virtual demonstration of the inner workings of the Van de Graaff generator. You can find a link to this demonstration on the Pre-Lab Links tab of the Electrostatics page of the lab website. Walk through the presentation (that is, watch the videos and read the slides) and answer the following questions.

PL1. What is the only quick way to discharge a fully charged Van de Graaff generator?

PL2. What is the function of the motor of the Van de Graaff generator?

PL3. Will a Van de Graaff generator work if the belt and the pulley are made of the same material? Explain briefly.

PL4. The outside of the belt carries electrons upward toward the dome. Where do these electrons come from? (You don't need to explain. We are just looking for an object.)

PL5. How can electrons jump from the outside of the belt onto the upper comb that is attached to the dome? Why aren't they repelled by the excess electrons that are already on the dome?

PL6. Is it possible to make a Van de Graaff generator with a positively charged dome? How?

Part I: Howdy Partner

The Story

What's the best way to get to know someone? We've always found that it's by delivering mild electrical shocks! Although, I suppose physicists aren't necessarily known for having the most highly developed social skills...

Equipment

- Van de Graaff generator
- Grounding wand (the wand with a wire connecting it to the base of the generator)
- Ungrounded wand (the wand with no wire connected to it)
- A new friend

1. Experiment

The goal of this first section is to get a basic understanding for how to use the Van de Graaff generator and the wands that accompany it. The first thing to understand is that these devices are not dangerous unless you have a pacemaker or other such electronic medical device. **If you have an electronic medical implant or device, please alert your TA immediately.**

Now, even though the shocks you may receive aren't dangerous, they can hurt a tiny bit. This is especially true if you get shocked through a finger since fingers are very sensitive. Getting shocked through your elbow feels a lot better. If at any point during the lab you are worried that you've built up a charge and that you'll get shocked the next time you touch anything, it is highly recommended that you touch whatever that next thing is with your elbow. This is also good advice if you happen to own one of those couches where you're always getting shocked after you watch some TV.

Read This: Make sure that the grounding wand is plugged into the Van de Graaff generator as instructed by your TA. If you are having any problems with this connection, alert your TA.

Do This: Turn the crank of the Van de Graaff generator three times. Then touch the dome with the grounding wand.

1.1. What did you observe when you brought the grounding wand toward the dome? (Keep this response short.)

Read This: Hopefully you saw and/or heard a spark jump from the dome of the Van de Graff generator to the grounding wand. (If not, try again.) That's a pretty sure sign that the dome built up some excess charge as you turned the crank. In Part II, you will determine whether that excess charge is positive or negative. Until then, forget about electrons. We'll just say that the Van de Graaff generator can build up an *excess charge* and we'll think about how that *excess charge* can move.

1.2. *Predict* what will happen if you touch the dome of the Van de Graaff generator with your elbow. (Be sure to read Appendix A about making predictions!) Explain your reasoning. This does not necessarily require equations. (Note: you will not turn the crank any more before you touch the dome.)

Do This: Test the prediction you made in Step 1.2.

1.3. Was your prediction accurate? If not, explain where your reasoning failed.

Do This: Turn the crank of the Van de Graaff generator three times. Then touch the dome with the ungrounded wand. (Not the grounding wand.)

1.4. What did you observe when you brought the grounding wand toward the dome? (Keep this response short.)

1.5. *Predict* what will happen if you touch the dome of the Van de Graaff generator with your elbow. Explain your reasoning. This does not necessarily require equations. (Note: you will not turn the crank any more before you touch the dome.)

Do This: Test the prediction you made in Step 1.5.

1.6. Was your prediction accurate? If not, explain where your reasoning failed.

Read This: If you get shocked during this lab, there's a good chance that you'll get shocked again the next time you touch a conductor (although this depends on how good your shoes are). You might be able to catch your partner by surprise!

Do This: Play around a little bit! Make a new friend!

Part II: Charging Up

The Story

There's a very funny scene in the film *Ghostbusters* where Dr. Vankman (played by Bill Murray) is testing out the effects of negative reinforcement on extrasensory perception (or ESP). A participant in the study tries to guess the shape on a card that Dr. Vankman is holding, receiving a mild shock if the guess is incorrect.

In Part II of today's lab, feel free to test the effects of negative reinforcement on your ability to solve electrostatics problems. You'll be asked to make predictions as you work through this experiment. To participate in this study, have your partner shock you whenever your prediction is incorrect. Our preliminary findings indicate that you will indeed be more knowledgeable of electrostatics after completing this set of experiments.

Equipment

- Van de Graaff generator with grounding wand and ungrounded wand
- Tape
- Plastic fork

2. Are You the Positive or Negative Type?

You'll begin this experiment by determining the sign of the charge on the dome. After that, you can use this information to predict the outcome of various experiments. These experiments can be a little finicky. With that in mind, **always test your predictions at least twice**. If your results are inconsistent or ambiguous, it is recommended that you consult your TA.

Do This: Cut a strip of tape that is about 6 inches (~15 cm) long. Fold about 1 cm of the tape over onto itself in order to make a non-tacky handle. Label this handle with a *T*. This is *tape-T*. Stick *tape-T* to the table such that most of it is dangling down over the edge. Gently brush your fingers over the tape to remove any static electricity.

Do This: Repeat the previous **Do This** but label the tape with a *U*. This is *tape-U*.

Do This: You are about to stick these two strips of tape together in a very particular fashion. Stick them together such that the tacky side of *tape-T* is in contact with the un-tacky side of *tape-U*. See Figure 1.

Do This: Now pull the two strips of tape apart. Affix each strip of tape to the table such that most of the strip is dangling over the edge. This time **do not** brush your fingers over the tape.

Read This: In the process of tearing the two strips of tape apart, you have given each a net charge! By conservation of charge, these two strips must be oppositely charged. You will figure out which one is negatively charged and which one is positively charged. This is where the plastic fork comes in handy. **FACT:** When you run a plastic comb through your hair, the comb becomes negatively charged. If you're a fan of Disney movies, you know that a fork works just as well as a comb. (Note: cotton or wool clothing can be used in place of hair.)

2.1. Describe, perform, and analyze an experiment in order to determine which of the two strips of tape is negatively charged and which strip is positively charged. Make sure your procedure and analysis are complete and easy to follow.

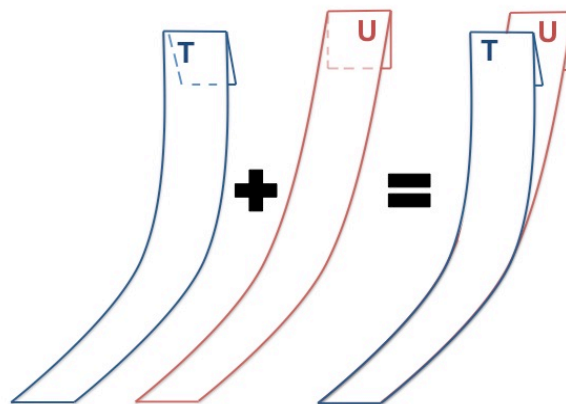


Figure 1: How to stick *tape-T* to *tape-U*.

Read This: Now that you know about the charges on each strip of tape, you will use them in tandem with the Van de Graaff generator in a series of experiments. You may recycle your fork.

Do This: Charge up the Van de Graaff generator. Grab tape-U at the folded end, remove it from the table and slowly bring it toward the dome of the generator. Make sure to start with the tape about 1 meter away from the generator.

2.2. What happens? What does this say about the charge on the dome of the generator?

Do This: Recharge your tape and repeat the previous **Do This**. Remember, we want to try everything at least twice. If this second trial agrees with your first, move on. If not, consult your TA.

Do This: Stick tape-U back on the table.

2.3. *Predict* what will happen if you remove tape-T from the table and slowly move it toward the charged dome as you did with tape-U. Explain your reasoning.

Do This: Put the prediction you made in Step 2.3 to the test. Again, make sure to start with the tape about 1 meter away from the generator. Remember to test your prediction twice. Recharge your tape in between trials.

2.4. Was your prediction correct? If not, explain where your reasoning failed. (And don't forget about negative reinforcement.)

2.5. *Predict* the results (i.e. the behavior of the strips of tape) of the following experiment and explain your reasoning: After charging the Van de Graaff generator, you touch the ungrounded wand to the dome. Then you move this wand toward each of the two dangling strips of tape, one at a time.

Do This: Just to be safe, recharge your pieces of tape and stick them back on the table. Recharging the tape is an especially good idea if either strip touches the dome or the wands.

Do This: Put the prediction you made in Step 2.5 to the test. Remember to test your prediction twice. Recharge your tape in between trials.

2.6. Was your prediction correct? If not, explain where your reasoning failed.

2.7. *Predict* the results (i.e. the behavior of the strips of tape) of the following experiment and explain your reasoning: After charging the Van de Graaff generator, you touch the grounding wand to the dome. Then you move this wand toward each of the two dangling strips of tape, one at a time.

Do This: Put the prediction you made in Step 2.7 to the test. Remember to test your prediction twice. Recharge your tape in between trials.

2.8. Was your prediction correct? If not, explain where your reasoning failed.

2.9. *Predict* the results (i.e. the behavior of the strips of tape) of the following experiment and explain your reasoning. This one's a little longer, so we'll give the steps letters:

- a) Charge up the Van de Graaff generator.
- b) Move the ungrounded wand to a distance of ten centimeters from the dome. Hold it there until (e).
- c) Touch the grounding wand with the ungrounded wand. (If the Van de Graaff generator arcs to either wand at this point, ground everything and start from the beginning.)
- d) Set the grounding wand down on the table, still holding the ungrounded wand 10 centimeters from the dome. (If the Van de Graaff generator arcs to either wand at this point, ground everything and start from the beginning.)
- e) Pull the ungrounded wand away from the generator.
- f) Bring the ungrounded wand toward each strip of tape, one at a time.

Do This: Put the prediction you made in Step 2.9 to the test. Remember to test your prediction twice. Recharge your tape in between trials.

2.10. Was your prediction correct? If not, explain where your reasoning failed.

Part III: Energy Considerations

There are many concepts that you learned last semester that are going to come back again and again during the spring. Energy is one such topic. There are all sorts of new places where we see energy changing from one form to another during second semester physics. The transformation of energy between different forms can be quite spectacular when using the Van de Graaff generator.

Equipment

- Van de Graaff generator with grounding wand and ungrounded wand
- Small fluorescent light bulb (found inside cardboard tube)
- Test lead with banana plug on one end and alligator clip on the other end

3. Transferring Energy to the Generator

Do This: Charge the generator by turning the crank a few times.

3.1. Where and in what form is energy stored before you charge the dome?

3.2. Where and in what form is energy stored after the dome is charged?

Do This: Bring the grounding wand near the dome of the generator.

3.3. Describe what happens. (No explanations of "why" needed – just describe what you see, hear, etc.)

3.4. What happened to the energy stored in the generator when you brought the grounding wand near the dome? If the energy has changed forms, which form(s) has it taken?

Read This: The dome of your Van de Graaff generator reaches an electrical potential on the order of 100,000 V when it is fully charged. Use that fact and a rough estimate of the dome's radius to answer the following Head-Scratchers.



3.5. Approximately how much excess charge is stored on the dome? Make sure to show all your work and justify any estimations and approximations that you make.



3.6. Approximately how much electrical potential energy is stored by the dome? Make sure to show all your work and justify any estimations and approximations that you make.



3.7. If you ground the dome (as you did in the experiment), then all of the excess charge on the dome will flow to the earth. How much electrical potential energy is stored by the earth if it has an excess charge equal to your response to Step 3.5? Comment on this result by considering conservation of energy. And is this result consistent with your response to Step 3.4?

4. Fluorescent Light

Let's now consider how this room is lit. Looking upward you will notice that the light is coming from a series of fluorescent light bulbs. In these systems electrical energy (which originated in a power plant of some sort) has been converted into the light energy that eventually reaches your eye.

In order to light up a room, the two ends of a fluorescent bulb must be at different electrical potentials. This potential difference accelerates electrons, giving them kinetic energy that is used to create light. (Light is produced through an interesting chain of events that you will investigate a bit in this semester's Spectra lab.)

Do This: Connect one end of the test lead to the ground plug and connect the other end, via an alligator clip, to one end of your small fluorescent bulb. Holding it by the glass tube, place the unconnected end of the fluorescent bulb near but not touching the dome of the Van de Graaff generator. (Keep the unconnected end a few millimeters from the dome.)

4.1. Describe what you observe when you crank the wheel of the generator.

4.2. Detail the energy transformations taking place as you performed the previous **Do This**. Appendix B gives specific instructions on how you should write your response to this question. It's the same format that you used during the Playing With Energy lab of the first semester.

Do This: Now connect one end of the light bulb to the dome of the generator via the test lead and alligator clip (there is a receptacle for the banana plug on the top of the dome). Bring the unconnected end of the light bulb near the dome of the generator.

4.3. Describe what you observe when you crank the wheel of the generator.

4.4. Explain your observations (Step 4.3) in terms of electrical potential.



4.5. Relate the experiments you have just done with the fluorescent light to birds standing on power lines.

Part IV: Dielectric Breakdown

Equipment

- Van de Graaff generator with grounding wand and ungrounded wand
- Test lead

5. Lil Lightnin’

You’ve probably seen some pretty fantastic little lightning bolts by now. In this Part, we’ll investigate those in a little more detail. And you probably won’t get shocked.

First, let’s be clear about what happens when you see one of those sparks. It’s the result of a phenomenon known as *dielectric breakdown*. When the electric field in air exceeds a value of about 3×10^6 V/m, air turns into a conductor as electrons are ripped from the air molecules by the strong electric field. (This critical electric field is called the *dielectric strength* of air.) We will learn more about why light is produced later in the semester.

Read This: Keep in mind during this section that as you turn the crank at a constant rate, new charge is added to the dome at an approximately constant rate.

Do This: Have one partner turn the crank at a gentle, constant rate. Have the other partner hold the grounding wand by the plastic handle. Slowly vary the distance between the wand and the dome of the Van de Graaff generator. Observe how the frequency of sparks changes as the position of the wand is varied.

5.1. Record your observations.

5.2. What is the equation for the electric field around a spherically symmetric charge distribution?

5.3. Explain the connection between your responses to Step 5.1 and Step 5.2. A complete answer will mention how excess charge is added to the dome at an approximately constant rate as the crank is turned.

Read This: You have seen that if the critical electric field is exceeded in the entire region between two conductors, a spark can jump between them. Sometimes, though, the critical electric field is reached only in a small region around a single conductor. When this happens, we get entirely different results.

Do This: Remove the grounding wand from the ground plug. Plug the long test lead in to the ground plug.

Do This: Have one partner turn the crank at a gentle, constant rate. Have the other partner hold the long test lead by part of it that's plastic. Slowly vary the distance between the tip of the test lead and the dome of the Van de Graaff generator. Observe what happens as the position of the test lead is varied.

5.4. Record your observations (what you see and what you hear).

Read This: The observations you recorded in Step 5.1 and Step 5.4 are probably different. You might guess that this difference has something to do with the difference in geometry of the wand and the test lead, and you would be correct. As it turns out, electric field lines must always intersect a conductor at a 90° angle. This fact means that the field lines will be more densely packed around an object with a small radius of curvature (such as the test lead) than they will around an object with a larger radius of curvature (such as the grounding wand) – this is another way of saying the electric field around a conductor is largest near points and other regions with a small radius of curvature. With this in mind, answer the following Head-Scratchers.



5.5. The test lead has a smaller radius of curvature than the grounding wand, allowing the electric field lines around the test lead to be more densely packed than around the wand. As a consequence, if the grounding wand and the test lead are placed a few centimeters away from the charged dome (choose one of the following)...

- A. the electric field around the test lead is not high enough to attain breakdown and no spark is observed.
- B. the electric field around the test lead is so high that the breakdown happens so fast our eyes can't see it.
- C. the electric field around the test lead is large enough to ionize the air around it, allowing excess charge to leave the test lead without producing an observable spark.
- D. as Yoda would say, "the *Force* is with the test lead."



5.6. The electrical properties of that test lead are pretty cool. And these properties can be put to good use. What is a real world scenario where something like this test lead is exploited? (If you can think of more than one, feel free to show off.)

Head-Scratchers

Don't forget to complete the following problems. They should be at the end of your lab report. If you want to work on them during lab, start a new page in your lab notebook.

- 3.5
- 3.6
- 3.7
- 4.5
- 5.5
- 5.6

References

[1] Jonnes, Jill. (2003). *Empire of Light*. Random House, USA.

[2] Hinterberger, F. (2005). "Electrostatic Accelerators". CERN Accelerator School, The Netherlands.

[3] Posteberg, F., et al. (2011). "A New View on Interstellar Dust - High Fidelity Studies of Interstellar Dust Analogue Tracks in Stardust Flight Spare Aerogel". Lunar and Planetary Science Conference, Houston, TX.

Appendix A: Making Predictions

In this lab, you are asked to make many predictions, after which you test your predictions. It's okay if your predictions are wrong! Do not erase predictions that you discover were incorrect. Incorrect predictions will receive full credit as long as you "support your prediction with a sentence or two" as requested. On the other hand, correct predictions will receive little or no credit if you do not explain how you made your prediction.

After you test your predictions, you are asked whether or not you were correct. If your prediction was correct and complete, just draw a smiley face. If your prediction was incorrect or incomplete, you must explain where your reasoning failed. Make it clear that you understand what went wrong. Learning what your misconceptions are is the best way to fix them! As mentioned previously, do not erase incorrect predictions.

Appendix B: Format for Responding to Step 4.2

In the Playing With Energy Lab of the first semester, you looked at many situations where energy changed forms over and over, much like in Step 4.2 of this lab. When responding to Step 4.2, you will be expected to state two things. First, you should state the form of energy input and the form of energy output. Then you should detail the ways in which energy is transformed in between. Here's an example of what will be expected.

Example Step:

Detail the energy transformations taking place when the battery is connected to the fan.

Example Response:

Input/Output: We start with chemical energy in the battery and end with kinetic energy in the air. [This should be a complete sentence.]

Transformations: The format is: Mechanism {input form of energy → output form of energy}

- Battery {chemical → electrical}
- Motor {electrical → mechanical} or {electrical → rotational kinetic}
- Fan blades {mechanical → mechanical} or {rotational kinetic → kinetic}