Week 4 "Tutorial" – Conceptually Understanding Conductors

Goals:

1. Understand both how *and* why charges and conductors behave (course scale learning goals 5b, 5d)
2. Apply Gauss's Law conceptually (rather than mathematically) (course scale learning goal 9)
3. Consider potential differences for various situations (course scale learning goal 10)
4. Test predictions experimentally (and resolve any disagreements) (course scale learning goal 7)
5. See the connection between physics and real life.

This tutorial is based on:

- CU Boulder original

Materials needed: big white boards, dry erase markers, Faraday Ice Pail demo (including gold foil to indicate charge), Leyden Jar, Van der Graaf generator

Tutorial Summary: Students learn the behavior/properties of conductors by analyzing a variety of situations with charges. They also consider voltage in these problems. Then, based on their previous answers, they predict the charge configurations of a Faraday's Ice Pail demo. In the end they debate the puzzling Leyden Jar demo.

A few words about running this tutorial:

The room setup has several small tables, with four chairs each. Each group was given four markers, and a big white board that covered the whole table. This allows students to easily communicate their ideas to each other and to the Learning Assistant (LA). It also helps the LA communicate with the students more effectively.

Students are advised that it should take approximately an hour to complete the tutorial. They are also advised that this is completely voluntary, so they will not be

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required to turn in the tutorial. However, they are advised that it would be in their interest to fill things out as completely as possible, since many of the topics would also be covered on the homework. The group members are encouraged to work together, and the LA wanders from group to group to see if there are any misconceptions, or if anyone is completely lost/stuck. In the words of Steve Pollock, “We will try our hardest not to give you any of the answers, but we will also try our hardest to make sure you figure everything out for yourself.”

After the students make predictions about the Ice Pail, they are shown the experiment, then asked to make sense of the results, or modify their predictions. The demo: a rod and cloth are used to transfer charge to the small metal sphere. Then the sphere is brought near the gold foil (the foil’s shadow is projected on the wall). The foil separates since the small sphere is charged, and induces a charge in the foil. Then the large hollow sphere is brought near the foil, and this time the foil doesn’t react since no charge is induced. This proves that the small sphere starts out charged, and the large hollow shell starts out neutral. Then the small, charged sphere is carefully inserted through the aperture of the large shell (without touching the edge of the opening). The small sphere is touched to the inside wall of the large shell, and then is carefully removed. The test is repeated with the gold foil, and it’s discovered that now the shell is charged. But what really throws the students off is that the small sphere is neutral!

Reflection after administering the tutorial

Number of students: 10 (2 groups of 4, 1 group of 2)
Date: Friday, February 8. Fourth week of class.

My overall reaction after the tutorial was… that this tutorial did exactly what it was designed for: solidify students’ conceptual understanding of conductors. At first, I was a little worried about this tutorial. I wanted this to be a PHYS 3310 tutorial, not a 1120

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tutorial. In the first few minutes of running this tutorial, I thought my fear (that this tutorial was too basic) would be realized, since students flew through the first questions.

However, as students worked through the tutorial, many interesting misconceptions arose. While one question might be simple, slightly changing it (by losing the symmetry), proved to be incredibly challenging for students to think about… but also incredibly clarifying once they struggled through it and we discussed it. Many students were challenged by the Ice Pail demo. It proved to be the perfect application of the concepts this tutorial addresses, and although most students were wrong in their predictions, understanding *why* they were wrong was very clarifying for them.

Part 1 – Conceptually Understanding Conductors

A coax cable is essentially one long conducting cylinder surrounded by a conducting cylindrical shell (the shell has some thickness). The two conductors are separated by a small distance. (Neglect all fringing fields near the cable's ends)

i. Draw the charge distribution (little + and – signs) if the inner conductor has a total charge +Q on it, and the outer conductor has a total charge –Q. Be precise about exactly where the charge will be on these conductors, and how you know.

Students were quick to decide the answer to this, and although they were correct, I tried to poke at them a little to see if they really understood, or if they had just memorized answers. For example, I asked why they had sketched the +Q on the surface of the inner conductor. One student replied, "because E=0 in a conductor." It seemed that that student had just memorized that E=0 in a conductor, and also memorized that charges go to the outside surface of a conductor, but didn't understand the relationship between these two properties. I told him that this is true, but it doesn't tell me much. In fact, it doesn't tell me any more than saying, "E=0 in any blue object." He smiled at this, but didn't have anything further to say about it.

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Another student explained to me (and to the first student) that you could draw a Gaussian surface in the object, and if charge was distributed within the object, there would be electric flux. And since E=0 in a conductor, the charges cannot be within the object and must therefore be on the edges. This was a much more articulate and satisfactory answer than the first student's.

ii. If you were calculating the potential difference, ΔV, between the center of the inner conductor ($s = 0$) and infinitely far away ($s = \infty$), what regions of space would have a (non-zero) contribution to your calculation?

This seemed good for them to think about, but everyone worked out the correct answer. One student initially asked me if there needed to be an E-field to have a voltage difference. Another student responded to him by writing the equation for potential difference (the integral of Edl). So he realized that there must be an E-field to have a potential difference. Another student was amazed that in order to find the potential difference from zero to infinity, all you needed to know was the E-field between the two conductors –maybe only a millimeter!

iii. Now, draw the charge distribution (little + and – signs) if the inner conductor has a total charge +Q on it, and the outer conductor is electrically neutral. Be precise about exactly where the charge will be on these conductors, and how you know.

Not every student immediately knew this, but at least one person in each group was able to explain the answer to the others.

iv. Consider how the charge distribution would change if the inner conductor is shifted off-center, but still has +Q on it, and the outer conductor remains electrically neutral. Draw the new charge distribution (little + and – signs) and be precise about how you know.

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Every student I observed initially answered this wrong. Everyone knew that the inside charges would rearrange when the inner conductor was brought closer to the inside edge of the outer conductor. However, students unanimously said that since there was a non-uniform build up of negative charges on the inside surface of the outer conductor, these negative charges would cause the positive charges on the outside surface of the outer conductor to clump together non-uniformly. This clearly showed that none of the students conceptually understood shielding.

Students knew that E=0 inside the outer conductor, so the question is: do the inner positive and negative charges create a zero, or nonzero field inside the outer conductor? If they <u>do</u> create a field, the outermost charges arrange non-uniformly to make E=0. If the inner positive and negative charges do <u>not</u> create a field, then the outermost charges must also not create a field inside, and will distribute uniformly.

The best way to see that the outermost charges are uniform is to ask the students this: If there was no outermost surface, or the shell was infinitely think (basically the problem now consists of a cavity in an otherwise-solid conductor), would E still be zero? The answer is yes; it has to be. So that implies that the inner charges cancel each other (shielding), and contribute to E=0 within the outer conductor. This implies that the outermost charges must also create zero electric field, and they do this by arranging uniformly.

(This is very similar to the asymmetry on HW5Q4f)

v. Now, instead of the total charge +Q being on the inner conductor, sketch the charge distribution (little + and – signs) if the *outer* conductor has a total charge +Q on it, and the inner conductor is electrically neutral. Be precise about exactly where the charge will be on these conductors, and how you know.

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I expected students to initially think that a charge on the outer conductor would polarize the neutral inner conductor. However, when I observed a group working on this, they said their intuition told them the charge on the outer conductor would split 50/50, half on the inside surface and half on the outside surface. However, after I left and came back, they told me they had resolved this in two ways:

1. There was no way to polarize the inner conductor and maintain E=0 inside it.

2. If 50% of the charge went to the inside surface of the outer conductor, E would not be zero within the outer conductor.

vi. What is the potential difference, ΔV, between the center of the inner conductor ($s = 0$) and the outer conductor ($s = c$)?

This was quite straightforward for them, but good to think about.

Part 2 – Faraday's Ice Pail

Faraday's Ice Pail –originally a metal pail and suspended metal ball– helped early physicists understand conductors and shielding. It consists of a hollow conducting shell, with a hole cut out to allow a smaller conducting sphere to fit inside.

i. Consider this: the conducting shell starts out electrically neutral, but the small sphere inside of it has a total charge +Q. Based on your previous answers, what does the charge distribution look like before, during, and after, if the small solid sphere makes contact with the inside surface of the conducting shell (the "ice pail"). Draw the charge configurations.

This was a very interesting debate. While I thought that the students would be split on whether the small sphere ended up positively charged or neutral, instead they were split on how positively charged it would be. One group said that

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½ of the initial +Q would end up on the small sphere, since it would equally share it with the shell. Another group said that the small sphere and the big shell would have the same σ, and because of relative size the small sphere would end up with about 1/5 Q. Two students thought it would be neutral in the end. Although these students communicated their perfect reasoning to the other students, the idea that it would give up all its charge, and become neutral, just conflicted with the other students' common sense too much for them to accept it.

After the demo, some students were seriously shocked when the small sphere was neutral. Their jaws dropped! One of the students who had predicted this now had their attention, and very clearly explained what had happened.

Part 3 – Capacitors

A parallel plate capacitor is made of two conductors that each have area A, and are separated by a distance D. There is a potential difference of 100,000V between the plates. (Neglect fringing fields near the edges)

i. There are two ways to find the work required to assemble this charge configuration. **Do not actually find the work**, but outline the two ways you could, using the given information.

No one got to this problem within the hour. In fact, it could probably be removed because it doesn't really fit with the rest of the tutorial.

(You will calculate the stored energy of a capacitor in two different ways on HW5Q5)

The original capacitor is the Leyden jar. The name "Leyden" comes from the town "Leiden" in the Netherlands, which is the location of the university where it was

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invented in 1745. Leyden jars were used for early electric experimentation. Think about where charge accumulates as you watch this demo.

Students enjoyed this demo. They also talked a lot about how a Van der Graaf generator works, and if there is an E-field inside while it's being charged. In the future, the Leyden jar demo could be removed, and instead just talk about how a Van der Graaf works, which is more relevant to this tutorial's theme.

Relevant homework problems:

Q3. GAUSS' LAW AND CONDUCTORS: Griffiths 2.35 (p. 101)

Q4. GAUSS' LAW AND CAVITIES: Griffiths 2.36 (p. 101)
Please be sure to explain your reasoning on all parts, and add to this the problem the following:
In part a, be sure to *sketch* the charge distribution.
In part c, *sketch* the E fields (everywhere in the problem, i.e. in the cavities and also outside the big sphere)
f) Lastly - if someone moved q_a a little off to one side, so it was no longer at the *center* of its little cavity, which of your answers would change? Please explain.
I really like this problem, lots of good physics in it! Try to think it through carefully, make physical sense of all your answers, don't just take someone else's word for it!

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