

 **INSTRUCTORS MANUAL: TUTORIAL 4**

Goals:

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

This tutorial is based on:

- Written by Darren Tarshis, Steven Pollock, and Stephanie Chasteen, with modifications by Ed Kinney, Michael Dubson and Markus Atkinson.

Materials needed:

Faraday Ice Pail demo (including gold foil to indicate charge). If there is time, the Leyden Jar or Van de Graaf demo may be added.

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.

Special Instructions:

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 surprises students is that the small sphere is neutral!

Reflections on this tutorial

We were originally concerned that the tutorial would be too basic, but many misconceptions are revealed during the course of this tutorial. While one question might be simple, slightly changing it (by losing the symmetry), proved to be incredibly challenging for students and very clarifying to discuss. 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 I Students are generally quick to answer **question (i)**, but it is useful to prod them for their reasons *why*. For example, why did they sketch $+Q$ on the surface of the inner conductor? One student replied “because $E=0$ in a conductor,” a rather tautological reply. This student appeared to have memorized this fact, but not full understand the relationship between the fact that $E=0$ in a conductor and the fact that all charge is on the surface. A more articulate answer is that if there were charge inside the conductor, a Gaussian surface drawn inside the conductor would have nonzero flux through its surface. And since $E=0$ in a conductor, the charges cannot be within the object.

In **question (ii)**, students are asked to calculate the potential difference. Students generally arrive at the correct answer though it appears to be a useful exercise to think about it. One student initially asked if there needed to be an E-field to have a potential difference. Another student was amazed to realize 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! While not every student immediately knew the answer to **question (iii)**, at least one person in every group was able to explain it to their fellow students.

When the symmetry of the situation was changed in **question (iv)**, students struggled. Every student observed initially answered it 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 shows the challenges of a conceptual understanding of shielding. Students knew that $E=0$ inside the outer conductor, so the question is: do the inner positive and negative charges create a nonzero field inside the outer conductor, which would cause the outer charges to rearrange into a non-uniform manner?

A good way to recognize that the outermost charges are uniformly distributed is to ask the students this: If there was no outermost surface, or the shell was infinitely thick (changing the problem to that 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 and the outer charges must therefore be uniform.

On **question (v)**, some students indicated that their intuition told them that half the charge on the outer conductor would reside on the inner surface and half on the outer surface. They resolved the issue by realizing that (a) there was no way to polarize the inner conductor and maintain $E=0$ inside, and (b) if half of the charge resided on the inner surface of the outer

conductor, E would not be zero within the outer conductor. **Question (vi)** was fairly straightforward.

Part 2 – Faraday’s Ice Pail

This demonstration sparked a very useful debate. Students did not debate 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 $\frac{1}{2}Q$ 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 $\frac{1}{5}Q$. Two students thought it would be neutral in the end. Although these students communicated their reasoning well to the other students, the idea that the small sphere would be drained of charge and become neutral 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. One of the students who had predicted this now had their attention, and very clearly explained what had happened.

Relevant Homework Problems

Gauss’s law and conductors

Griffiths 2.35 (p. 101)

Gauss’s 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)

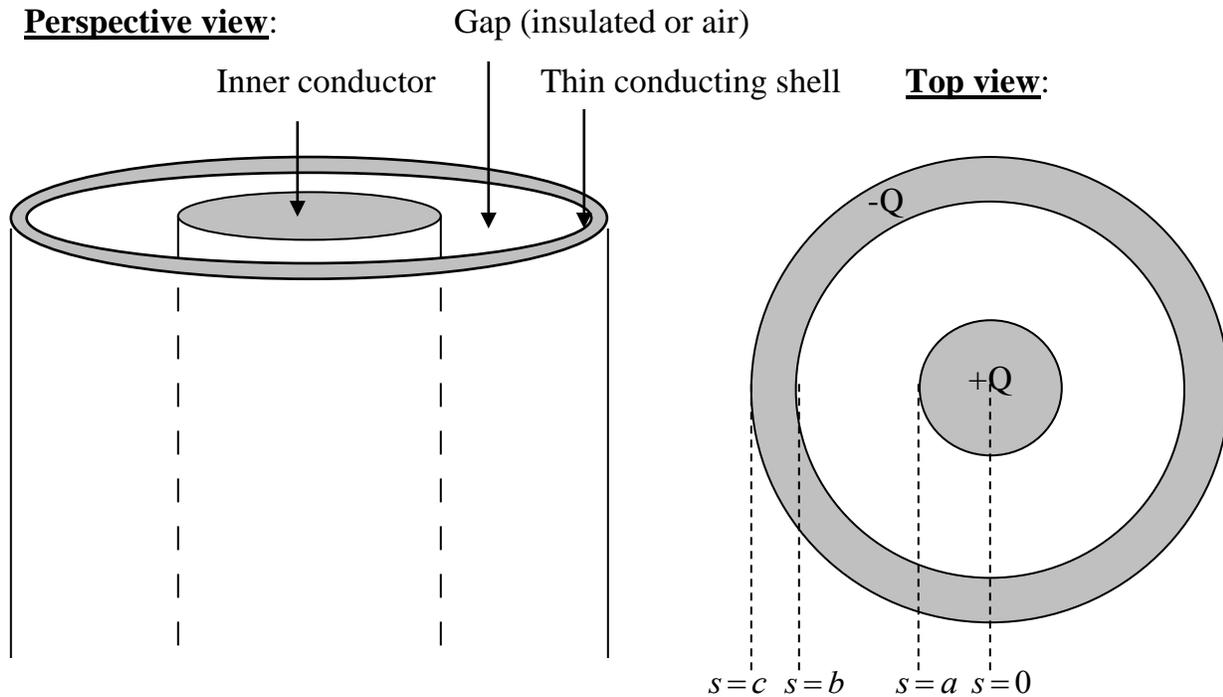
f) Lastly - if someone moved q_a a little off to one side, so it was no longer at the *center* of its little cavity, which of your answers would change? Please explain.

★ TUTORIAL 4: CONCEPTUALLY UNDERSTANDING CONDUCTORS ★

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).

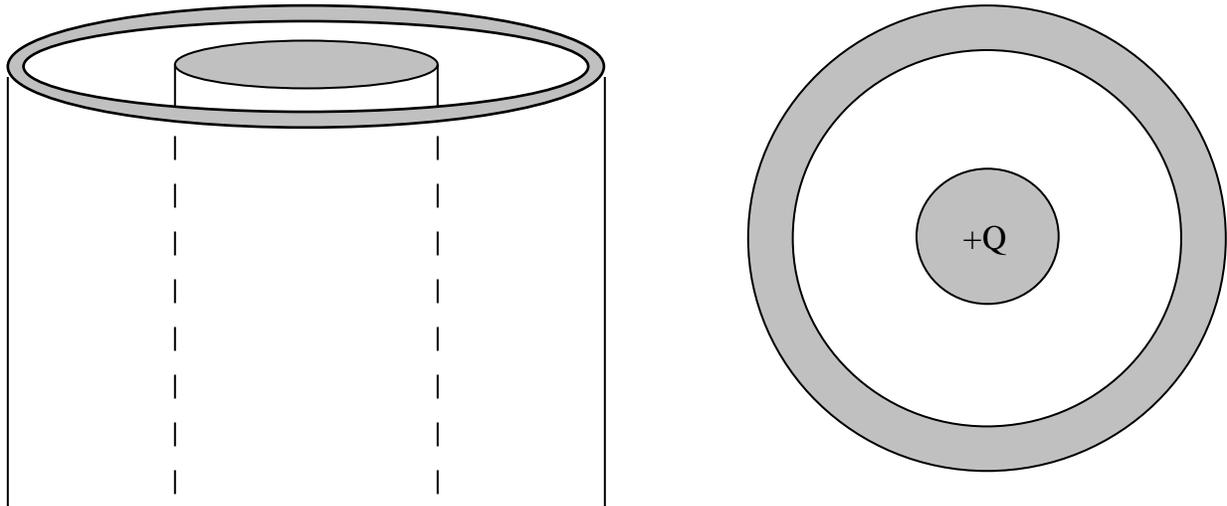
Draw the charge distribution (little + and – signs) if the inner conductor has a total charge $+Q$ on it, and the outer conductor has a total charge $-Q$. Be precise about exactly where the charge will be on these conductors, and how you know.



TUTORIAL 4: CONCEPTUALLY UNDERSTANDING CONDUCTORS

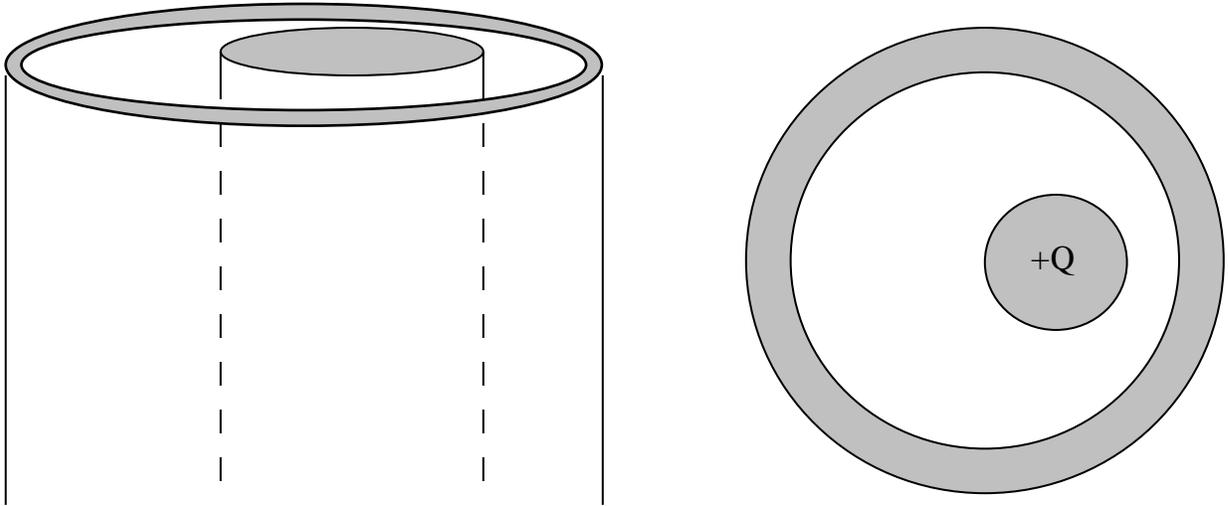
- i. If you were calculating the potential difference, ΔV , (for the configuration in part (i.)) between the center of the inner conductor ($s=0$) and infinitely far away ($s=\infty$), what regions of space would have a (non-zero) contribution to your calculation?

- ii. 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.



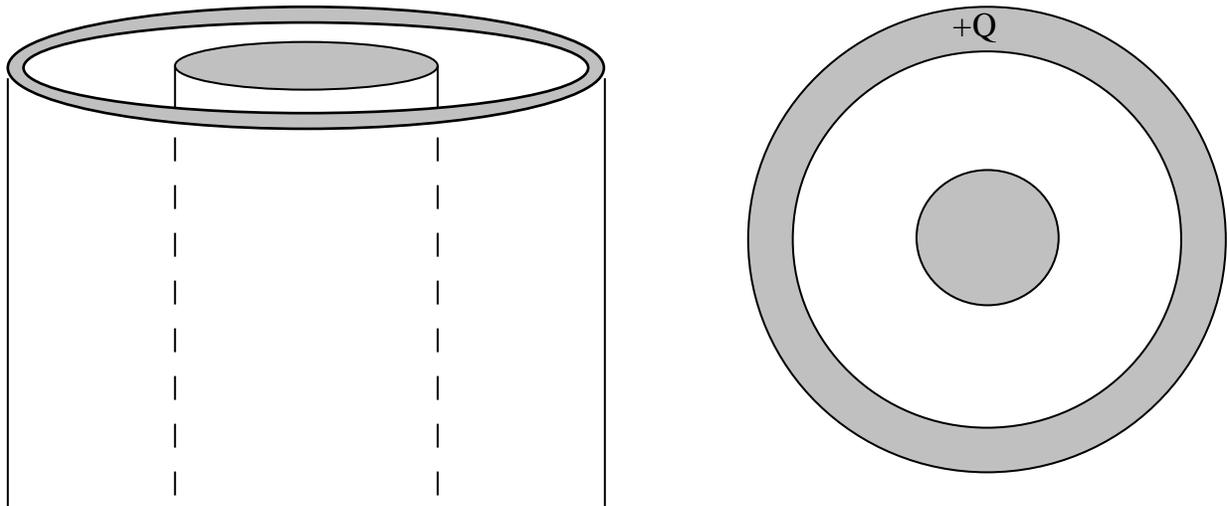
TUTORIAL 4: CONCEPTUALLY UNDERSTANDING CONDUCTORS

- iii. 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.



TUTORIAL 4: CONCEPTUALLY UNDERSTANDING CONDUCTORS

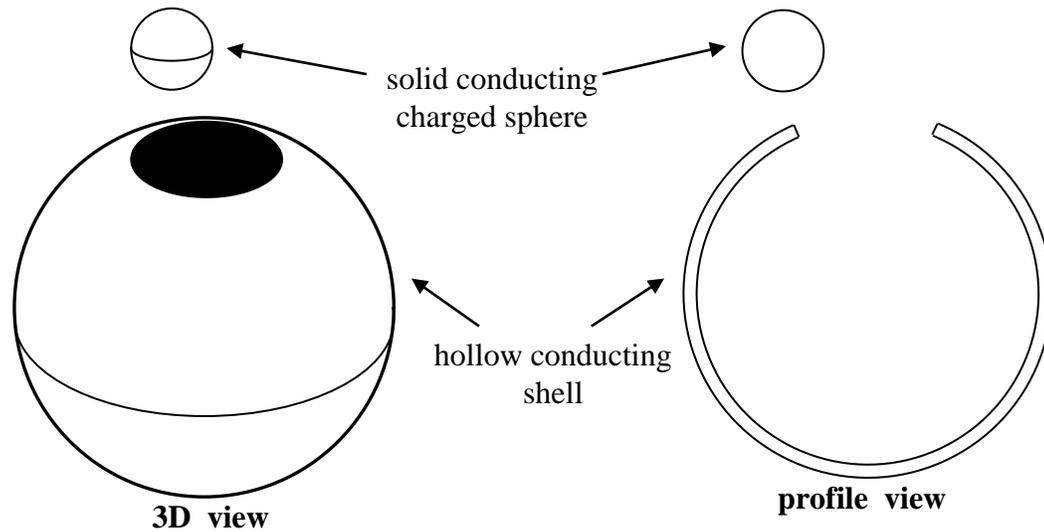
- iv. Now, instead of the total charge $+Q$ being on the inner conductor, sketch the charge distribution (little $+$ and $-$ signs) if the *outer* conductor has a total charge $+Q$ on it, and the inner conductor is electrically neutral. Be precise about exactly where the charge will be on these conductors,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



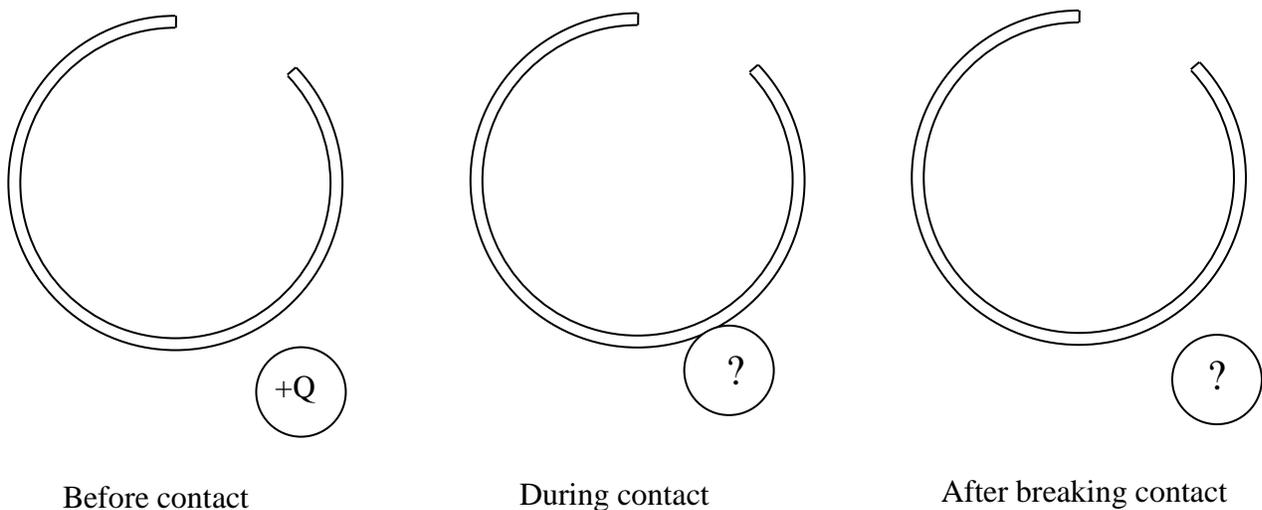
- v. For the case v ($+Q$ on outer conductor, inner conductor neutral) what is the potential difference, ΔV , between the center of the inner conductor ($s=0$) and the outer conductor ($s=c$) ?

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. First consider the charged sphere as it approaches the electrically neutral hollow shell from the outside. What does the charge distribution look like before contact, while in contact, and after contact, if the small solid sphere makes contact with the outside surface of the conducting shell (the “ice pail”)? Draw the charge configurations.



TUTORIAL 4: CONCEPTUALLY UNDERSTANDING CONDUCTORS

- ii. Now consider this: the conducting shell starts out electrically neutral as before, but the small sphere with total charge $+Q$ is brought inside the shell. What does the charge distribution look like before contact, while in contact, and after removal, if the small solid sphere makes contact with the inside surface of the conducting shell? Draw the charge configurations.

