Electrostatic Charging

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The Unpredictability of Electrostatic Charging**

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Plato's *Timaeus*,[1] which was written around 360 BC, is in essence a scientific review paper that addresses astronomy, the composition of materials, magnetism, and electrostatic charging (among other topics). The understanding of these topics was very rudimentary in Plato's time, but scientific progress since then has been tremendous. We now understand astronomy so well that we can send people to the moon and spaceships to other planets. Our expertise in materials is so strong that we can create new materials not found in nature, with properties tailored to our needs. And we can exploit our knowledge of magnetism in extraordinary ways, such as to produce three-dimensional images of the hidden interior of human bodies to diagnose diseases. Plato would be impressed with this progress!

But the story is different in regard to electrostatic charging. In fact, one can argue that there has been no significant progress in this field since Plato's time. Contact charging occurs when two materials are brought into contact and then are separated; as a result of the contact, charge is transferred such that one material is charged positively and the other is charged negatively. Everyone is familiar with this effect—even children, who have experimented by rubbing a balloon on their hair and seeing the balloon and hair become highly charged. But which material charges positively and which charges negatively? Despite all the progress that science has made over the millennia since Plato's time, the answer to this simple question is not really known.[2]

Scientists have been working for centuries on how to predict which surface charges positively and which charges negatively when the two surfaces are contacted, and the best that they have come up with is an empirical "triboelectric series". This series orders materials such that the relative position of any two materials determines the direction of charge transfer when these materials come into contact. Consider, for example, a subset of the triboelectric series:

(−) Teflon Polystyrene Wool Nylon (+)

From this series, polystyrene is expected to charge positively when contacted with Teflon, but negatively when contacted with wool or Nylon. Likewise, wool is expected to charge positively when contacted with polystyrene or Teflon, but negatively when contacted with Nylon. The triboelectric series is based on experimental observations, and efforts to link the triboelectric series to some material property have met only limited success.

It has long been known that the triboelectric series has flaws.[3] The ordering is not always reproducible, and different investigations find different orderings. Furthermore, some results are distinctly incompatible with the concept of a triboelectric series. For example, experiments on silk, glass, and zinc have shown that glass becomes negatively charged when silk and glass are contacted, zinc becomes negatively charged when glass and zinc are contacted, and silk becomes negatively charged when zinc and silk are contacted; these results suggest a "triboelectric ring" rather than a linear triboelectric series. Other experiments have shown that rough and smooth samples of the same material appear in different positions in the triboelectric series.

In this context, Baytekin et al. now report findings from a series of simple experiments.[4] First, Teflon beads are rolled in a polystyrene dish for about a minute. According to the triboelectric series, the Teflon beads should charge negatively and the polystyrene dish should charge positively. This is indeed what is found. However, if the Teflon beads continue to roll in the dish for more than a few minutes, the opposite result is obtained: the Teflon beads charge positively, and the polystyrene dish charges negatively!

Why does rolling the beads for longer times reverse the direction of charge transfer? While the bead-rolling experiment is simple and low-tech, Baytekin et al. answer this question using state-of-the-art surface analysis tools. They show that as the beads roll on the dish, nanoscale patches of material are torn off and transferred onto the other surface. As the rolling proceeds, the Teflon beads become partially coated with surfaces of polystyrene, and the polystyrene dish becomes partially coated with a surface of Teflon. After some time, the bead surfaces become "polystyrene-like" while the dish surface becomes "Teflon-like". Contact charging is a surface phenomenon, so now, following the tribelectric series, the "Teflon-like" dish charges negatively while the "polystyrene-like" beads charge positively.

Baytekin et al. point out that this material transfer process depends on the mechanical properties of the material, such as the material's hardness and cohesive energy. Harder materials will be more effective at tearing off pieces of a softer surface, and materials with higher cohesive energy will be less apt to have pieces torn off.

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These ideas shed light on heretofore unexplained observations. As previously noted, rough and smooth samples of the same material can appear in different positions of the triboelectric series—in particular, this was found for glass.[3] Based on Baytekin et al.'s conclusions, a rough surface of a hard material would be very effective at tearing off pieces of another surface, while a smooth surface of the same material would not be as effective. As glass is a hard material, rough and smooth samples could cause different amounts of material transfer and thus lead to different charging behaviors.

Unfortunately, the results of Baytekin et al. also lead to a somewhat depressing conclusion: perhaps contact charging may never be predictable. While it has been well-known that surface contaminants can dominate contact charging, the problems of contamination could in principle be overcome in careful experiments by thoroughly cleaning the samples before each trial. However, the results of this study indicate that the very act of contact, required for the contact charging process, leads to material transfer; this material transfer causes surface contamination that can never be avoided in contact charging experiments.

It is doubtful that the extent and consequences of material transfer will ever be predictable. First, material transfer is strongly dependent on the mode of contact which includes the force with which the surfaces are contacted, whether shear forces (for example, from rubbing) are involved, and how fast the force is applied. Second, material transfer depends on the nanoscale texture (for example, roughness) of the surface because this texture creates intersurface forces at the nanoscale that differ from the macroscale force. The surface texture intimately depends on the thermal and processing history of the material, and is generally not well characterized; even if it were characterized, it would be difficult to predict how it alters the nanoscale forces and material transfer. And third, there is no easy way to know how much material transfer is needed to affect the charging behavior. Since material transfer may never be predictable, its link to contact charging implies that contact charging may never be predictable as well.

Recent work has shown that there are other factors that may also prevent the predictability of contact charging. Baytekin et al. previously showed that the charge on a triboelectrically charged surface is not of uniform polarity, but rather the contacted surfaces have nanoscale regions of positive and negative polarity such that the net charge on a surface represents a delicate balance between the contributions from these regions.[5] Thus, a change in polarity may arise from a subtle shift in the relative contributions of positive and negative regions, which is a much more difficult effect to capture than an entire surface of uniform charge switching from one polarity to the other. In our own studies, we recently showed that material strain can reverse the direction of charge transfer.[6] Materials generally have uncharacterized nanoscale strains that depend on their thermal and processing history, and so these nanoscale strains may affect contact charging in an unknown way.

Perhaps we are now learning why the field of electrostatic charging has not followed a trajectory similar to those of the other scientific fields addressed in Plato's *Timaeus*.

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