



The enduring puzzle of static electricity

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Even though it lacks a complete explanation, the small-scale, everyday effect is being exploited for various applications.

Volcanic eruptions of ash instigate lightning discharges in the atmosphere. Flows of grain dust in agricultural silos trigger spontaneous explosions. Sandy dunes on Saturn's moon Titan that stretch for kilometers withstand the dense atmosphere's prevailing winds. In all those seemingly disparate contexts, vast numbers of tiny particles collide, rub against each other, and exchange tremendous amounts of electrostatic charge. But you don't need to see an eruption or an explosion to witness triboelectricity (the prefix "tribo" means "rub" in Greek). If you battle a spray of static-laden coffee grounds pouring out of a grinder in the morning, you can experience the effect firsthand. Figure 1 shows the aftermath: triboelectrically charged espresso grounds clinging to a coffee grinder.

Triboelectric charging occurs when two surfaces make contact or slide past one another—one surface becomes positively charged, while the other becomes negatively charged. Beyond coffee preparation, you've experienced contact and frictional electrification if your hair stands on end after you rub a balloon on your head or if you receive a sharp jolt after walking across a carpet and then touching a doorknob. But even though static electricity is an everyday phenomenon and has been studied for millennia, researchers still lack a fundamental understanding of why and how charge transfers between two or more interacting surfaces.

The modeling (or lack thereof) of triboelectricity

For metal-metal contacts, theoretical and experimental evidence suggests that triboelectrification is driven by an electronic process in which charge flows from the metal with the lower work function to the one with the higher work function. A material's work function is the amount of energy needed to remove an electron from the surface and bring it to a point just outside the material, where the electron has zero kinetic energy. The situation is more complicated for insulators. Unlike metals, insulators lack free charge carriers and therefore do not have work functions. Although electron transfer has been implicated in metal-insulator contacts, some investigators have also argued that tribocharging arises from the transfer of ions or small bits of material.

In the absence of a physics-based model, researchers treat metal-insulator and insulator-insulator triboelectrification phenomenologically. That is, both metal and insulator materials get ordered in a list, known as a triboelectric series, according to the polarity of charge that they acquire when brought into contact with another material. The material that becomes



FIGURE 1. COFFEE GRINDERS in busy cafés are often coated in grounds held in place by electrostatic forces. Besides messy workspaces and increased waste, the absence of charged grounds in the brewing process may result in weaker espresso. (Photo courtesy of Robert Asami.)

positively charged is placed above the one that becomes negatively charged. Glass, for example, sits near the top of the list, and Teflon generally sits near the bottom. If a bit of Teflon tape is dragged across a glass rod, the tape will become negatively charged, and the glass rod will become positively charged.

Unfortunately, a lack of reproducibility diminishes the predictive power of a triboelectric series. Two experiments using the same sets of materials may yield two distinct orderings of the materials. Furthermore, triboelectric series cannot account for electrification between chemically identical surfaces. Charging has been observed when two pieces of the same material repeatedly touched one another. The two pieces formed a triboelectric series: The surface of one gained a positive charge, and the surface of the other gained a negative charge. The finding hints that nanoscale morphological changes may be a crucial factor that affects the polarity acquired by an object.

Lastly, triboseries do not account for the effects of ambient conditions, such as temperature, relative humidity, pressure, and external electric fields, all of which have been shown to

influence triboelectrification. Yet even though a detailed understanding of triboelectrification is lacking, its scaling relationships are known—and offer insights.

Small-scale interactions, big consequences

It's unsurprising that granular flows of volcanic ash plumes and foodstuffs in grain elevators display rich triboelectric effects. After all, systems consisting of large populations of particles collectively have extensive surface areas that allow for the particles to repeatedly transfer charge between each other. When charged, the constituent particles experience electrostatic forces. For particles with large diameters d and high mass densities, such forces are often negligible, because electrostatic forces scale with d^2 , whereas body forces, such as gravity, scale with d^3 .

When particle size and mass are small, however, electrostatic interactions can be several orders of magnitude stronger than body forces (see figure 2) and substantially affect particle–particle and particle–surface dynamics. Espresso aficionados might be intimately familiar with the transition to an electrostatically dominated regime. Although electrostatic forces are muted when coffee beans are coarse ground for French press or filter preparations, fine grinding for espresso has the tendency to produce coffee grounds that cling and scatter uncontrollably because of electrostatic forces.

Be it the result of electrons, ions, or bits of material, the charge transfer between interacting particles occurs at scales of nanometers to micrometers. In addition, electrostatic forces between particles act over relatively short ranges and decay proportionally to the square of the interparticle separation. Despite the limited range, electrostatic forces can have collective effects that manifest across much larger spatial scales, from millimeters to sometimes even kilometers.

The charging in volcanic plumes, for example, can drive fine ash particles to electrostatically cluster together. Although ash aggregates typically have diameters of at most a few millimeters, their clumping significantly changes the atmospheric residence time of ash. In some cases, fine ash particles may form rafts that allow them to settle slowly like feathers. In others, clumping may create dense, heavy aggregates that deposit more quickly. Aggregation ultimately helps regulate the effect that volcanic eruptions have on the amount of dust in a region and across the globe.

Designing charged materials

Despite a limited understanding of triboelectricity, researchers are increasingly shifting their roles from observers to designers. Even without a complete knowledge of the underlying mechanism, electrostatic interactions can be tuned in granular materials for beneficial applications. Researchers have, in some cases, shut off electrostatic attractions by tailoring particle surface chemistry or morphology to produce antistatic coatings. In other cases, the goal has been to exploit triboelectric charging to create structures from heterogeneous building blocks. In one proof-of-principle demonstration, two millimeter-sized beads of different polymer compositions were shaken over a conductive substrate material, and one polymer charged negatively and the other charged positively. After some time, the attraction led to the emergence of a checkerboard lattice.

The precise self-assembly of nanometer- to micrometer-sized particles has implications for the development of re-

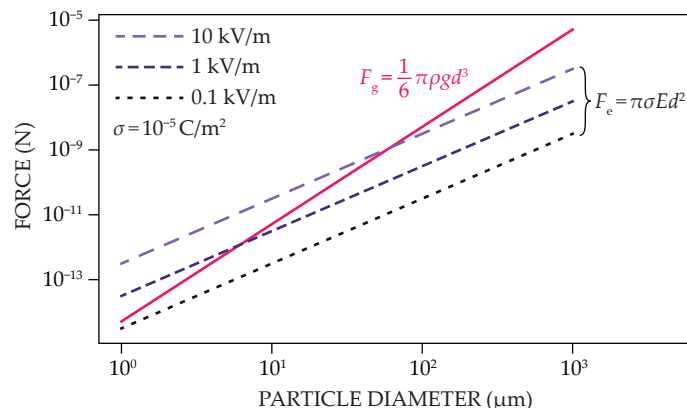


FIGURE 2. COMPETITION BETWEEN GRAVITATIONAL FORCES F_g AND ELECTROSTATIC FORCES F_e determine the behaviors of many granular materials. In this plot, a particle with a fixed density ρ of 1000 kg/m³ and a charge density σ equal to the theoretical maximum in air is exposed to an electric field E of 0.1–10 kV/m. Particles with a large diameter d experience gravitational forces that easily exceed electrostatic forces (g is the standard acceleration of gravity). As d decreases, electrostatic forces can surpass gravitational forces by a couple orders of magnitude. The shift in force balance has important implications for the aggregation, behavior, and mobility of fine particles in natural and engineered systems.

sponsive materials, bioanalytical devices, efficient solar panels, and triboelectric nanogenerators. A granular-interfaced triboelectric nanogenerator can convert ambient kinetic energy into electricity. That could be one way to develop self-powered sensors for internet-of-things devices.

The diversity of research in triboelectric charging has led to tremendous progress over the past few decades. Consistent and reproducible triboelectric behavior, however, remains challenging to observe because of subtle variations in environmental conditions, surface chemistry, and local electric fields. All three variations cause large fluctuations in the magnitude and polarity of the generated charge. The unpredictability underscores the persistent absence of a unified model to describe the transfer and stability of charge at contacting interfaces. Although researchers can apply triboelectricity without a full understanding of the underlying mechanism, developing reliable triboelectric technologies will require solving one of the oldest unresolved problems in physics.

Additional resources

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